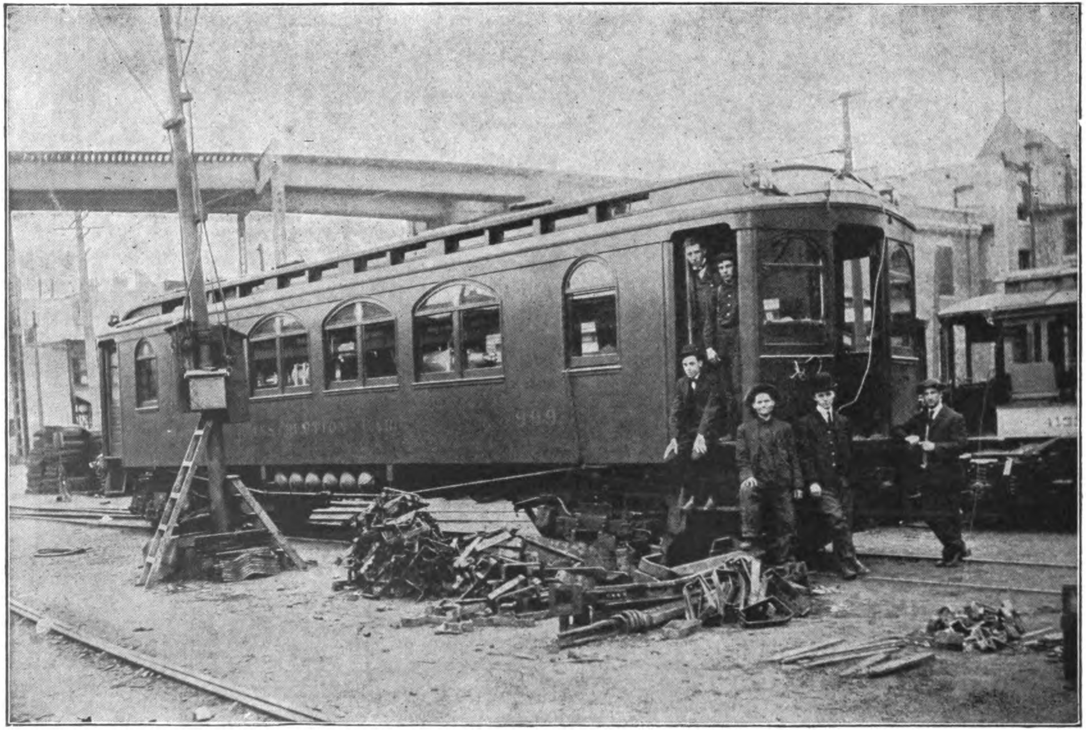

TESTING THE B. R. T. CO.'S INSTRUCTION CAR.

Frontispiece

Electric Railways

THEORETICALLY

AND

PRACTICALLY TREATED

BY

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Volume Two

Engineering Preliminaries and Direct-Current Sub-Stations

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PREFACE.

REALIZING the absence of a suitable text on Electric Railways, treating of the Engineering Preliminaries and Direct-Current Sub-Station Operation, it has been the purpose of the writer to prepare such a volume. The method of treatment is similar to that followed in "Electric Railways — Rolling Stock," by Ashe and Keiley, except that an attempt has been made to increase the value of the volume as a reference by the insertion of problems, tables, and operating data, restricting the descriptive matter pertaining to apparatus.

Through the courtesy of the American Institute of Electrical Engineers the author has been able to incorporate in this volume the contents of the railway papers of Messrs. Cary T. Hutchinson, C. W. Ricker, and by the writer.

Opportunity is also taken to acknowledge the co-operation of Prof. Frank W. Chandler in the correction of proofs, and Mr. William B. Kouwenhoven for assistance in the preparation of part of the text. The writer also feels indebted to Mr. Charles F. Scott for the preparation of a number of unique views of the construction details of converters which form part of the text.

The author regrets that press of work prevented Mr. Keiley's participation in the preparation of this second volume. He hopes, however, to be able to secure his aid in the preparation of the third and final volume.

S. W. ASHE.

POLYTECHNIC INSTITUTE OF BROOKLYN, *August, 1907.*

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ELECTRIC RAILWAYS.

THEORETICALLY AND PRACTICALLY TREATED.

ENGINEERING PRELIMINARIES AND DIRECT-CURRENT SUB-STATIONS.

CHAPTER I.

PRELIMINARY CONSIDERATIONS.

ELECTRIC railway problems have assumed such extensive proportions during the past few years as practically to eliminate all "rule of thumb" engineering methods. Such problems are now considered from an engineering standpoint. They are solved on a per capita basis, with a view to the probable annual revenue per unit of population served. A schedule is prepared to accommodate the traffic most economically, and then the electrical features are approached. These embrace questions of motor capacity, location and magnitude of power house, location of sub-stations, feeder calculations, and construction. Throughout the solution of these problems, the elements of reliability of service, the safety of passengers, and the schedule speed are considered primarily with reference to the road's probable earning capacity. Such other elements as first cost, maintenance, and operating expenses are also considered with a view to earning a suitable revenue upon the original investment.

Electric railway problems are usually of two kinds ; those relating to improvements or extensions of existing systems, and those relating to new systems. The latter problems are more difficult of solution than the former, as they involve the careful consideration of a number of variables. A new problem may be dealt with advantageously in the order indicated by the following table: *

Table of Considerations.

Preliminary Matters.

Population of community under consideration;
Probable future growth of community;
Determination of miles of track which the community can economically support;
Riding habit;
Gross income per year;
Car miles to be operated per year;
Determination of number of cars;
Passengers per car per day;
Number of miles per car per day;
Number of trips per car;
Size, type, seating capacity of cars.

Electrical Features.

Determination of motor capacity for cars;
Relation of schedule speed to motor capacity;
Graphic time tables;
Speed time and energy curves;
Effective current values;
Tonnage tables;

* For convenience in treatment this table is discussed in several chapters.

Load diagrams;
Total load diagrams;
Electrical center of gravity of load of track sections;
Electrical center of gravity of load of entire system;
Location of main power house;
Location of sub-stations;
Feeder calculations;
Construction data.

A new electric railway undertaking may conform to one of three types; namely, a local city problem, an inter-connecting railway problem, or a trunk line problem. These problems often merge into one another. The method of treatment outlined in the table applies directly to a city problem. For an inter-connecting railway, the treatment would be modified by certain fixed conditions, such as the distance between towns, the schedule speed, the number of cars in a train, and the frequency of traffic, the purpose being to excel parallel steam roads. There are also modifications to be considered in a trunk line problem. Later these features will be discussed in detail.

TABLE No. 1. — *Table Showing Relation of Trackage and Traffic to Population in Selected Urban Centers with Population of Less than 25,000, 1902.*

Name of Center.	Population of Center.	Number of Passengers.		No. of Miles of Track.	
		Total.	Per Unit of Population.	Total.	Per 1,000 of Pop.
Fort Smith, Ark.	11,587	731,553	63.1	8.93	0.77
Riverside, Cal.	7,973	547,051	68.6	9.52	1.19
San Diego, Cal.	17,700	2,220,000	125.4	16.60	0.94
Santa Barbara, Cal.	6,587	814,405	123.6	8.50	1.29
New London, Conn.	17,548	1,320,791	75.3	8.51	0.48
Stamford, Greenwich, Conn.	18,417	1,327,617	72.1	12.69	0.69
Pensacola, Fla.	17,747	998,290	56.2	9.00	0.51
Athens, Ga.	10,245	356,969	34.8	6.53	0.64

TABLE NO. 1. — *Relation of Trackage and Traffic to Population* — Continued.

Name of Center.	Population of Center.	Number of Passengers.		No. of Miles of Track.	
		Total.	Per Unit of Population.	Total.	Per 1,000 of Pop.
Alton, North Alton, Upper Alton, Ill.	17,487	1,497,130	85.6	12.25	0.70
Cairo, Ill.	12,566	870,838	69.3	9.67	0.77
Kankakee, Bradley, Bourbonnais, Ill.	15,708	714,769	45.5	12.78	0.81
Vincennes, Ind.	10,249	450,000	43.9	8.00	0.78
Burlington, Ia.	23,201	1,600,000	69.0	14.50	0.62
Muscatine, Ia.	14,073	865,120	61.5	8.60	0.61
Ottumwa, Ia.	18,197	1,211,028	66.6	10.00	0.55
Atchison, Kan.	15,722	533,867	34.0	9.00	0.57
Wichita, Kan.	24,671	1,460,000	59.2	18.50	0.75
Shreveport, La.	16,013	1,450,000	90.6	8.80	0.55
Biddeford, Saco, Maine	22,267	728,909	32.7	8.15	0.37
Benton Harbor, St. Joseph, Mich.	11,717	1,198,826	102.3	10.50	0.90
Marquette, Mich.	10,058	373,672	37.2	7.00	0.70
Menominee, Mich.	12,818	529,764	41.3	6.71	0.52
Vicksburg, Miss.	14,834	1,188,289	80.1	8.75	0.59
Springfield, Mo.	23,267	1,700,715	73.1	19.10	0.82
Great Falls, Mont.	14,930	939,436	62.9	11.90	0.80
Concord, N. H.	19,632	1,510,856	77.0	12.71	0.65
Laconia, N. H.	8,042	436,171	54.2	8.87	1.10
Long Branch, Deal, Allenhurst, Asbury Park, Bradley Beach, Neptune City, Belmar, N. J.	16,148	3,737,541	231.4	23.68	1.47
Perth Amboy, Metuchen, N. J.	19,485	880,128	45.2	9.06	0.46
Dunkirk, Fredonia, N. Y.	15,743	681,770	43.3	7.00	0.44
Kingston, N. Y.	24,535	2,217,334	90.4	9.16	0.37
Ogdensburg, N. Y.	12,633	478,283	37.9	10.00	0.79
Ashtabula, Ohio	12,949	999,857	77.2	5.75	0.44
Lima, Ohio	21,723	1,375,979	63.3	18.55	0.85
Tiffin, Ohio	10,989	482,000	43.9	7.33	0.67
Zanesville, Ohio	23,538	1,800,000	76.5	10.00	0.42
Sayre Athens, Pa.; Waverly, N.Y.	9,481	1,059,507	111.8	9.11	0.96
Tarentum, New Kensington, Pa.	10,137	622,447	61.4	6.61	0.65
Greenville, S. C.	11,860	537,603	45.3	7.00	0.59
Austin, Tex.	22,258	1,213,703	54.5	13.38	0.60
Waco, Tex.	20,686	1,605,525	77.6	16.29	0.79
Ogden, Utah	16,313	861,910	52.8	11.00	0.67
Burlington, Winooski, Vt.	22,423	1,270,136	56.6	11.22	0.50
Everett, Wash.	7,838	971,650	124.0	9.65	1.23
Ashland, Wis.	13,074	503,658	38.5	7.68	0.59
Janesville, Wis.	13,185	304,398	23.1	7.41	0.56
Totals	718,254	49,179,495	68.5	485.95	0.68

Table No. 2. — *Table Showing Relation of Trackage and Traffic to Population in Selected Urban Centers with Population of from* 25,000 *to* 100,000, 1902.

Name of Center.	Population of Center.	Number of Passengers.		Number of Miles of Track.	
		Total.	Per Unit of Population.	Total.	Per 1,000 of Pop.
Montgomery, Ala.	30,346	1,849,395	60.9	20.00	0.66
Little Rock, Ark.	38,307	3,841,415	100.3	20.70	0.54
Sacramento, Cal.	29,282	3,948,791	134.9	23.50	0.80
Pueblo, Col.	28,157	4,065,162	144.4	36.25	1.29
Meriden, Wallingford, Conn.	31,033	2,589,737	83.5	19.50	0.63
Augusta, Summerville, Ga.	42,686	2,360,674	55.3	31.02	0.73
Peoria, Averyville, North Peoria, Peoria Heights, Ill.	60,340	6,750,000	111.9	41.25	0.68
Quincy, Ill.	36,252	2,127,623	58.7	17.38	0.48
Rockford, Ill.	31,051	1,989,080	64.1	23.00	0.74
Springfield, Ridgely, Ill.	35,328	3,532,013	100.0	23.83	0.67
Evansville, Howell, Ind.	60,428	3,629,534	60.1	30.50	0.50
Dubuque, Ia.	36,297	2,391,355	65.9	20.85	0.57
Sioux City, Ia.; South Sioux City, Neb.	34,000	4,138,944	121.7	43.00	1.26
Topeka, Kan.	33,608	2,730,287	81.2	28.63	0.85
Lexington, Ky.	26,369	2,350,682	89.1	15.13	0.57
Bay City, West Bay City, Essexville, Mich.	42,386	1,986,982	46.9	23.30	0.55
Duluth, Minn.; Superior, Wis.	84,060	9,418,517	112.0	73.84	0.88
Dayton, Ohio	85,333	14,667,094	171.9	52.88	0.62
Springfield, Ohio	38,253	3,784,338	98.9	28.13	0.74
Altoona, Gaysport, Juniata, Bellwood, Pa.	46,034	4,759,279	103.4	27.50	0.60
Williamsport, South Williamsport, Pa.	32,085	2,582,297	80.5	16.41	0.51
Dallas, Tex.	42,638	6,574,773	154.2	46.30	1.09
Galveston, Tex.	37,789	2,851,603	75.5	35.86	0.95
San Antonio, Tex.	53,321	5,268,627	98.8	45.51	0.85
Salt Lake City, Murray, Utah.	56,833	10,631,591	187.1	78.04	1.37
Richmond, Va.	85,050	16,313,560	191.8	43.96	0.52
Spokane, Wash.	36,848	5,028,388	136.5	36.55	0.99
La Crosse, Onalaska, Wis.	30,263	1,706,728	56.4	17.11	0.57
Oshkosh, Neenah, Wis.	34,238	1,973,843	57.7	32.00	0.93
Totals.	1,258,615	135,842,312	107.9	951.93	0.76

TABLE NO. 3. — *Table Showing Trackage and Traffic in Urban Centers of* 100,000 *Population and Over in* 1902.

Urban Center.	Population.	Miles of Track.	Miles track per 1,000 Pop.	Fare Passengers Carried.	Passengers per Inhabitant.	Passengers per Car Mile.
Albany, Troy, Rensselaer, N.Y.	216,530	75.83	0.35	26,417,076	122	3.5
Baltimore, Ellicott City, Md...	510,288	365.12	.72	96,763,878	190	4.1
Boston, Cambridge, Chelsea, Everett, Malden, Newton, Somerville, Brookline, Waltham, Mass..............	927,994	451.68	.49	228,179,308	246	4.8
Buffalo, Niagara Falls, Lockport, North Tonawanda, N.Y.	421,694	320.48	.76	74,136,881	176	4.3
Chicago, Ill.; Hammond, Ind..	1,769,951	1,036.24	.58	410,284,094	232	4.0
Cincinnati, O.; Newport, Covington, Ky...............	429,137	263.57	.61	86,208,384	201	3.6
Cleveland, O., and vicinity....	405,359	237.04	.58	81,370,202	201	4.3
Columbus, O., and vicinity ...	127,022	106.43	.84	26,489,927	208	4.7
Denver, Col................	133,859	149.77	1.12	31,085,443	232	4.8
Indianapolis, Ind............	169,164	109.86	.65	30,005,026	177	4.3
Jersey City, Elizabeth, Hoboken, Paterson, Passaic, Newark, Bayonne, Orange, N. J.	969,736	463.54	.48	148,094,623	153	6.0
Kansas City, Independence, Mo.; Kansas City, Argentine, Rosedale, Kan.........	237,042	181.24	.76	57,148,083	241	3.6
Los Angeles, Pasadena, Santa Ana, Orange, Cal..........	118,746	164.16	1.38	30,803,086	259	3.2
Louisville, Ky...............	204,731	147.13	.72	34,503,388	168	3.6
Memphis, Tenn.............	102,981	71.88	.70	16,598,823	161	4.5
Milwaukee, Whitefish Bay, Wauwatosa, Wis...........	301,701	145.50	.48	46,974,373	156	5.1
Minneapolis, St. Paul, Stillwater, Minn..............	378,923	251.02	.66	63,009,957	166	4.9
New Orleans, La............	287,104	180.31	.63	53,184,273	185	3.0
New York, Yonkers, White Plains, Mt. Vernon, New Rochelle, Pelham, N. Y.....	3,548,096	1,299.10	.37	943,687,316	266	5.2
Oakland, Alameda, Berkeley, Hayward, Emeryville, Cal...	101,872	122.80	1.20	17,247,022	169	3.2
Omaha, South Omaha, Dundee, Neb.; Council Bluffs, Ia.	155,268	105.95	.68	21,418,791	138	3.4

TABLE No. 3. — *Trackage and Traffic in Urban Centers* — Continued.

Urban Center.	Population.	Miles of Track.	Miles track per 1,000 Pop.	Fare Passengers Carried.	Passengers per Inhabitant.	Passengers per Car Mile.
Philadelphia, Pa.	1,293,697	517.53	.40	331,304,685	256	5.4
Pittsburg, Allegheny, McKeesport, Bellevue, Sharpsburg, McKees Rocks, Carnegie, Wilkinsburg, Braddock, Homestead, Connellsville, Uniontown, Pa.	640,380	469.47	.73	168,632,339	263	4.9
Providence, Pawtucket, R. I.	268,946	137.05	.51	45,163,704	168	5.6
Rochester, Irondequoit, N. Y.	178,333	95.86	.54	20,171,260	113	3.9
St. Joseph, Mo.	102,979	35.15	.34	8,534,278	83	3.9
St. Louis, Mo.; East St. Louis, Granite, Ill.	614,328	396.21	.64	129,596,027	211	4.2
San Francisco, San Mateo, Cal.	344,614	276.50	.80	117,357,877	340	5.7
Scranton, Dunmore, Olyphant, Jermyn, Carbondale, Pa.	155,655	76.68	.49	8,331,663	54	3.6
Syracuse, Onondaga, Geddes, DeWitt, N. Y.	123,776	68.16	.55	14,234,508	115	3.8
Toledo, Ohio.	135,271	97.78	.72	20,104,076	149	3.6
Washington, D. C.	279,940	139.67	.5c	63,829,752	228	4.1

NOTE. — Population shown for 1902 is that reported at the census of 1900.

TABLE No. 4. — *Table Showing Relation of Trackage and Traffic to Population in Groups of Urban Centers,* 1902.

	All centers over 500,000 population.	All centers of 100,000, but under 500,000 population.	Twenty-nine selected centers of 25,000, but under 100,000 population.	Forty-six selected centers of less than 25,000 population.
Total population served	10,274,470	5,380,647	1,258,615	718,254
Number miles of track	4,998.89	3,559.82	951.93	485.95
Miles of track per 1,000 of population	.49	.66	.76	.68
Number of passengers	2,456,542,270	994,327,853	135,842,312	49,179,495
Number of rides per inhabitant	239.1	184.7	107.9	68.5

Population of Community under Consideration.*— The population of small communities may readily be ascertained, and statistics are often issued bearing on the population of larger cities. As an illustration, tables 1, 2, 3, and 4, showing the relation of traffic and trackage to population in a number of urban centers in the United States, are here inserted from the U. S. Census Reports for 1902, compiled by S. N. D. North.

Probable Future Growth of Community.—Having selected a site for the location of a railway, it is desirable to study the community's growth. This may be done by plotting a curve of its past growth in terms of years and population, and from this an idea of its future can be gained. It is well to compare with this the actual growth of similar but older communities of the same industrial development, especially when interpolating the curve of future growth of the community under consideration. As an example, curves are here plotted for New York City; Portland, Oregon; Albany, N. Y.; and San Francisco, illustrated by Figs. 1, 2, 3, and 4. These curves indicate population values as given in the U. S. Census Reports.

Statistics also give the rate of increase of population for different cities for every ten years. In order to determine the rate of increase of population of a given city for any particular year, a tangent should be drawn to its population curve, the tangent touching the curve at a point corresponding to that year. The intercepts of the tangent should then be noted. The relation of these intercepts will be equal to the rate of increase of population. This rate of increase will be either positive or negative as it shows the community's growth or decline. Suppose that the rate of

* See article in *Electrical Review* by writer, June 2, 1906.

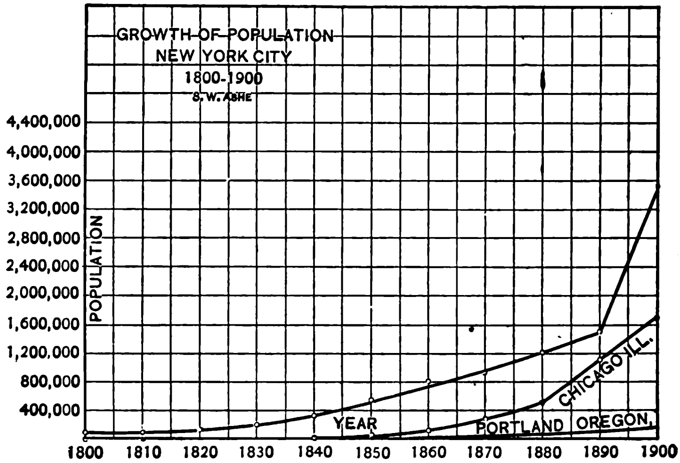


Fig. 1. — POPULATION CURVES OF NEW YORK, CHICAGO, AND PORTLAND, OREGON, COMPARED, 1800–1900.

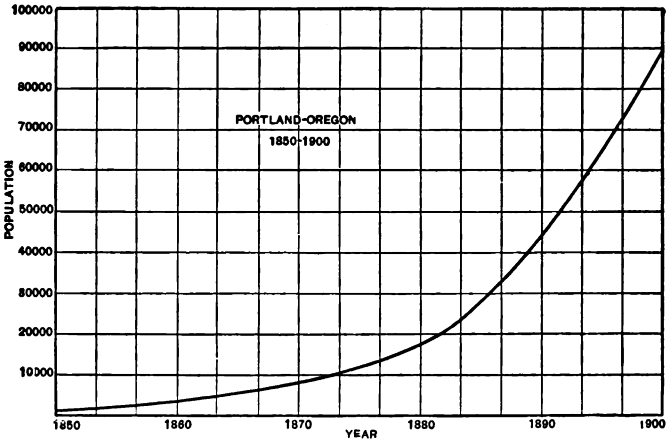


Fig. 2. — POPULATION CURVE OF PORTLAND, OREGON, 1850–1900.

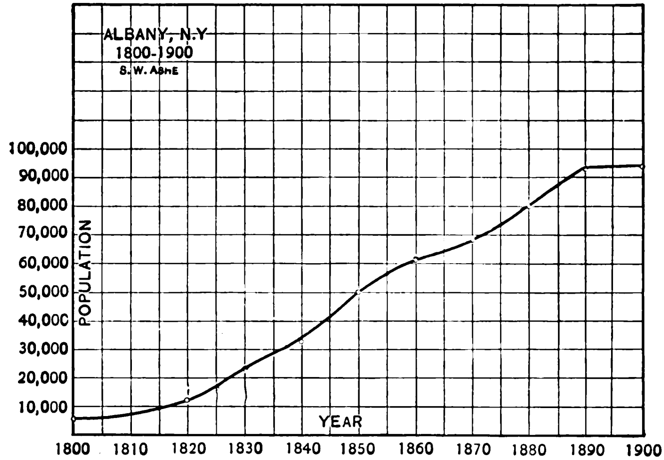


Fig. 3.—POPULATION CURVE OF ALBANY, N. Y., 1800–1900.

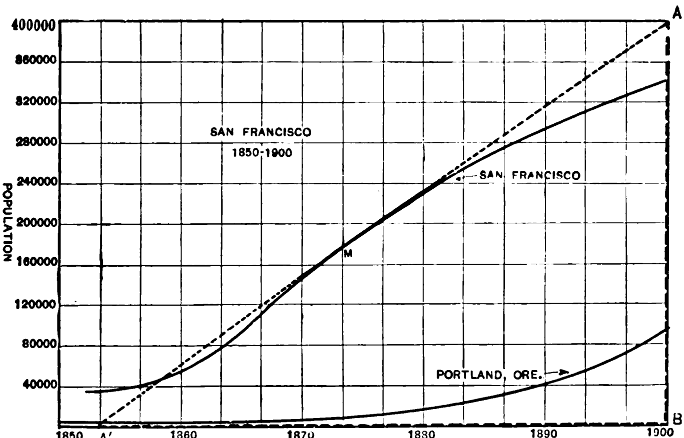


Fig. 4.—POPULATION CURVE OF SAN FRANCISCO, 1850-1900.

increase of population for San Francisco for the year 1874 is desired. Draw a tangent $A.A'$, as illustrated in Fig. 4, touching the population curve at the point M, which corresponds to the intersection of the coördinates representing the year 1874 and the population 180,000. The intercepts in this case, designated as AB and $A'B$, are a population value of 400,000 inhabitants and a time value of 46 years. This is obviously equivalent to the slope of the curve at this point. The slope is usually expressed in the form

$$\frac{dy}{dx} = \text{tangent}.$$

The percentage increase may then be determined by dividing the increase of population, 8,695 in this case, by the population corresponding to this year, namely, 180,000 inhabitants. This yields a value of 4.83% = (8695/180,000 = 4.83%).

A small source of error in drawing such tangents will be evident on trial. The method is sufficiently accurate for all practical purposes, however, provided care be taken. It is necessary to employ this method only in cases where there is a sudden change in the population curve at the last point corresponding to the last census report. These changes sometimes occur, as is evident from an examination of the population curve of Albany, N. Y., Fig. 3. The rate of increase of population for this city has fallen rapidly in the past twenty years to .8 of 1%. Moreover, in the case of what are termed "boom" cities, such as mining towns, sudden changes are likely to occur. For instance, it is interesting to study the percentage increase of population of San Francisco, in each decade from 1860 to 1900. The values are as follows:

Years.	Percentage Increase
1860–1870	163.0
1870–1880	56.5
1880–1890	27.8
1890–1900	14.6

It usually follows that the rate of increase of population in cities lowers as the population increases. An instance of this is New York City which has the following rates of increase:

Years.	Percentage Increase.
1790–1800	82.7
1800–1810	59.3
1810–1820	28.4
1820–1830	63.8
1830–1840	54.4
1840–1850	64.9
1850–1860	57.8
1860–1870	15.8
1870–1880	28.6
1880–1890	25.6
1890–1900	126.8

The large rate of increase between 1890 and 1900 was obviously due to the formation of Greater New York. The retarding effect of the War of 1812 and the Civil War is also evident.

Another interesting study is the case of Chicago whose rates of increase are as follows:

Years.	Percentage Increase.
1840–1850	570.3
1850–1860	264.6
1860–1870	173.6
1870–1880	68.3
1880–1890	118.6
1890–1900	54.4

Determination of Miles of Track. — Granting that the future population that it is desirable to accommodate has been determined, the next important step is to decide upon the maximum number of miles of track that the community in question can economically support. A population value corresponding to a ten years' growth may be taken as a safe working basis. In deciding upon this future time value, due consideration must be had for depreciation and the time necessary to operate a road from the beginning of the engineering preliminaries. With large propositions the construction period may extend over three years, but in smaller propositions it may be considerably reduced.

To determine the miles of track, refer to Fig. 5, curve 1, which indicates the miles of track per 1,000 of population for various population centers. This curve has been plotted from values taken from Table 4 and from the Census Report on Electric Railways.

Example — Assume the case of a city which has a population of 31,200 inhabitants and is not equipped with any railway service. (It is worth noting here that there are few such cities in the United States.) This city could economically support .72 miles of track per 1,000 of population, or a total number of miles of 22.46 (31,200 × .72 = 22.46).

Miles of Track = Population × Track Factor.

The number of miles of track having been determined, this track should be laid out with a view to earning the best revenue, care being taken to avoid, so far as possible, steep grades and sharp curves.

Riding Habit.—Statistics show that, with the increase of population of cities and the corresponding improvement of transit facilities, passenger traffic is considerably increased. This increased traffic per unit of population has been designated by the term "Riding Habit." Curve 2, Fig. 5,

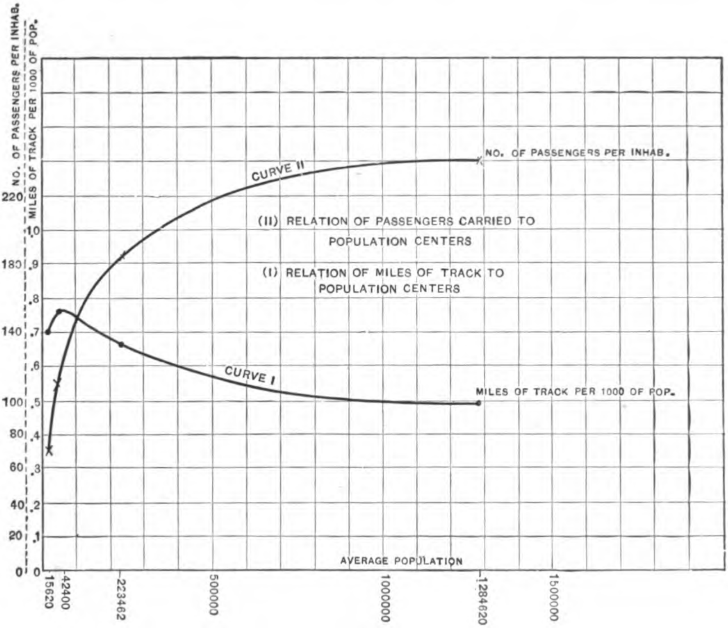


Fig. 5.—RELATION OF TRAFFIC AND TRACKAGE TO POPULATION.

indicates this point clearly, the curve being plotted in terms of population and the number of passengers per inhabitant. Referring to this curve and to the original problem, it may be noted that for a population of 31,200 each unit of population will ride 69 times per year, corresponding to a total annual traffic of 2,152,800 passengers (31,200 × 69 = 2,152,800).

Passenger Traffic (yearly) = Population × Riding Habit.

Gross Income per Year. — Throughout the United States, the average fare per passenger carried for trolley systems is five cents. Steam railways have a method of charging two to three cents per mile per passenger carried, but where the distances are short, as with trolley service, the average fare is five cents. Assuming a five cent fare, the gross income from the passenger traffic is equal to the product of the passengers carried and the average fare, namely, five cents. This, in the example in question, would be 2,152,800 × .05 = $107,640.00.

Gross Yearly Income = Total Passengers Carried × Fare.

Car Miles per Year. — A well-conducted road will earn approximately twenty cents per car mile operated. The number of car miles to be operated may then be readily determined by dividing the gross income per year by the gross earnings per car mile. In the example at hand, this would amount to 538,200 car miles in a year, or, assuming the road to be operated 19 hours per day for 365 days, 77.6 car miles per hour.

$$\text{Car Miles per Hour} = \frac{\text{Gross Earnings per Year}}{\text{Gross Earnings per Car Mile} \times 365 \text{ days} \times \text{No. Hours per Day}}.$$

TABLE No. 5.—*Income and Operating Expenses per Car Mile of a Number of Electric Railways, Year ending June 30, 1905.*

Company.	Income from Operation.	Income per Car mile.	Total Exp. per Car mile.
		Cents	*Cents*
Albany and Hudson	$200,671.65	28.50	24.30
United Traction Co. of Albany	1,714,848.82	22.35	15.35
Auburn and Syracuse Co.	268,507.78	25.12	16.24
Binghamton Ry. Co.	258,819.85	20.14	11.23
International Tr. Co. of Buffalo	3,694,339.01	25.16	14.90
Rochester & Eastern	212,668.51	27.88	21.36
Cortland Traction Co.	49,139.86	22.95	16.06
E. W., L. & R.R. Co., Elmira	192,921.47	16.06	11.61
City Ry., L. & R. Co., Fishkill	41,474.56	24.17	16.34
Dunkirk & Fredonia	44,457.88	26.92	22.57
Hudson Valley Ry. Co., Glens Falls	499,148.09	25.89	18.13
Hornell Elec. Ry., Hornellsville	16,919.70	9.30	9.06
Ithaca St. Ry. Co., Ithaca	91,817.90	23.21	17.87
King. Consol. R. R. Co., Kingston	123,632.92	23.08	14.57
Orange County Trac. Co., Newburgh	119,270.85	20.04	15.39
Ogdensburg St. Ry. Co.	27,240.09	9.78	7.86
Oneida Railway Co.	13,528.65	9.22	10.01
I. C. & R. S. Ry. Co., Oneonta	103,862.05	15.97	13.82

For further details as to the distribution of operating and maintenance expenses, see Table in Street Railway Journal of Sept. 29, 1906, pages 406 and 407, compiled by H. M. Beardsley, Elmira, N. Y.

Determination of Number of Cars. — The number of cars necessary for a given service depends upon the schedule speed at which the cars are to operate and upon the number of car miles per hour. The car miles per hour divided by the schedule speed in miles per hour will give the number of cars. In this example, assuming a schedule speed of 6 miles per hour equivalent to a maximum speed of about 8 miles per hour, the car service would call for approximately 13 cars. It is understood that this simply refers to cars actually operating and does not include reserve cars for summer and winter.

$$\text{No. of Cars} = \frac{\text{Car Miles per Hour}}{\text{Schedule Speed in Miles per Hour}}.$$

In many cities the schedule speed is fixed by law.

Many methods have been suggested and used with varying success for determining the number of cars required to serve a given population. The foregoing method, in the writer's opinion, excels all others. It was proposed by Mr. Lardner in a lecture before the students of the Polytechnic Institute of Brooklyn, but it has been amplified by the writer.

Passengers per Car per Day. — The total number of passengers carried per year divided by the number of days in the year and the number of cars operated, will give the passengers per car per day. In the example in question, this will be 453 passengers per day (2,152,800 / 365 × 13 = 453).

$$\text{Passengers per Car per Day} = \frac{\text{Total Yearly Passengers}}{\text{No. of Cars} \times 365 \text{ Days}}.$$

Number of Miles per Car per Day. — The schedule speed in miles per hour times the number of hours a car is operating will yield the number of miles a car will travel in a day.

In the example at hand this will be 114 miles per day (6 × 19 = 114 miles).

Miles per Car per Day = Schedule Speed × Number of Hours car operates.

Number of Trips. — The number of miles operated per day by a car, divided by the length of the line will yield the number of trips a car will make in a day. In the example in question this will be 5.07 trips (114. / 22.46 = 5.07, or approximately 5 trips).

$$\text{No. of Trips} = \frac{\text{Miles per Car per Day}}{\text{Length of Road in Miles}}.$$

Size, Type, Seating Capacity of Car. — The seating capacity of cars varies for trolley cars, from 22 to 90 persons as indicated by standard tables. In the example under consideration each car carries, as previously stated, 453 persons per day and makes 5 trips. This would create an average of about 90 passengers per trip. Assume that the town is located at the middle of the line and that the car line operates through the town from one end to the other. Going towards the town each car would carry an average of 45 passengers. This of course would vary. Obviously it would be poor economy to design a system so that its cars would be large enough to seat its maximum passenger traffic. In this case a car seating 22 passengers and accommodating the remaining passengers standing would be sufficient. The fact must not be forgotten that all passengers are not through passengers.

An example would be a Brill 16-foot closed car, figured on the basis of 17 inches per passenger. The total weight would be 10,700 lbs. including car body, trucks, and running gear. Figuring the weight of an average passenger as 130 lbs., this would amount to 10,700 + (32 × 130) = 14,860 lbs. or 7.43 tons. The motor capacity may then be determined.

"For full time electric railway service without commercial lighting, the largest urban centers show 4.92 fare passengers per passenger-car mile, and the smallest 3.26. Between the two extremes there is a steady graduation in the density of traffic per car mile." (Extract from Census Reports in Electric Railway.)

Interurban Electric Railways. — The primary factor which usually governs the engineering preliminaries of an interurban electric railway is its ability to compete with a steam road already covering the same territory. The success of an interurban proposition, therefore, depends upon the frequency and high speed of the service it can offer.

To use the curves for city traffic, Fig. 5, to determine the most suitable service for an interurban proposition would lead to erroneous results. There are two population values to be considered in an interurban railway, — the population of the towns through which the railway passes, and the population of the rural districts surrounding the railway. Of the former population about $\frac{1}{3}$ are passengers, and of the latter the proportion is much less. As an illustration, statistics secured by the Muncie, Hartford and Fort Wayne Railway Co. show that 82.7% of their passenger traffic is furnished by the towns in inter-city traffic, whereas but 17.3% of the traffic is supplied by the rural districts.

Assuming a high-speed service as a necessity, other limiting factors enter into consideration, such as large energy consumption at high speeds for cars of few units. This tends to eliminate single-car operation. In the experiments performed upon the Buffalo and Lockport Line of the International Railway Co., in March, 1900, it was discovered that with trains of one or two units operating at maximum speeds of 75 miles per hour, the watt hour consumption per ton mile was 137, as compared with 47 watt hours per ton mile for a train of several units.

Another factor must be considered, namely, that the maintenance of high speeds calls for very low grades, say a maximum of 3%, and the elimination of most curves, and all sharp ones. Long curves are undesirable, as a motorman cannot see sufficiently far ahead to prevent accidents.

CHAPTER II.

ELECTRICAL FEATURES.

DETERMINATION OF MOTOR CAPACITY.

FOUR methods are in common use for determining the motor capacity required for a given service. These methods may be characterized as,

1. — The Rule of Thumb Method;
2. — Armstrong's Method;
3. — Storer's Method;
4. — Hutchinson's Method.

The Rule of Thumb Method.*— This method consists in having at hand data in tabulated form upon all of the principal railway installations throughout the world. The problem under consideration is compared with this table, and from the table is selected an installation of a somewhat similar nature. The motor capacity of this installation is then noted and considered with reference to the problem at hand. Care is taken in such cases to select a system in which the profile and the contour of the road are somewhat similar to those in the problem at hand, and also to note that the total weight of the equipment, including passenger load, and the schedule speed compare favorably in both systems.

The Rule of Thumb method is based upon the assumption that a motor capacity which has proven adequate in

* See article in *Electrical Review* by writer, Oct. 14, 1906.

one service will serve equally well in a similar service. This assumption is justifiable, and in fact is followed almost unconsciously by many technical engineers. The data for such a table may be readily obtained by reference to the technical journals for past years in which descriptions may be found giving data upon almost every installation of note. Such journals contain also descriptions of new rolling stock representing improved methods installed on old systems. Data of this kind may be arranged both alphabetically and according to total h.p. of motor per car installed. Table 6

TABLE 6. — *Car Motor Equipments used by Various Railway Companies.*

	Company.	No. of Motors.	H. P. Rating of Motor.	Total H. P.	Length of Car. Ft.	Length of Car. In.	Width of Car. Ft.	Width of Car. In.	Estimated. Max. Speed in Miles per Hr. outside City Limits	Estimated. Max. Speed in Miles per Hr. in City Limits.
1	Atlantic City (Short line)	1	40	40					10	8
2	Austin, Texas.........	2	25	50	30	7	7	9	16	10
3	Atlantic City..........	2	40	80	....		......		16	8
4	Chicago and Indianapolis	2	55	110	41		8	4	20	12
5	Conneant and Erie....	4	35	140	41		......		20	10
6	Easton, Pa...........	4	40	160	40	1	8	4	20	10
7	Warren and Jamestown.	4	50	200	52	141	9		50	..
8	North Shore R. R., Cal.	4	125	250	56	4	......		60	..
9	Chicago and Milwaukee	2	65	260	46	9	......		40	20
10	Indianapolis and North-western.............	4	75	300	60		8	8	42	20
11	Los Angeles, Pacific R.R.	4	80	320	55		.....		60	8
12	Interborough Rapid Transit, N. Y.......	2	200	400	....		......		Interurban	
13	Schenectady Rail., N. Y.	4	125	500	51		8	9	70	12
14	N. Y. C. & H. R. R. R.	4	550	2200	Locomotives				60	..

illustrates the latter method. Referring to this table, it may be noted that the motor capacity per unit ranges from one single 40-h.p. motor to four 550-h.p. motors, or a total of 2,200 h.p. The maximum speeds range from about 16 miles per hour to 70 miles per hour. As case 14, Table 6, includes locomotive service, a truer comparison of h.p. would be with case 13. The number of motor units varies from 1 to 4, depending upon the amount of traction desired. Where the traffic conditions are severe, a four-motor equipment is often preferable.

Referring to Table 6, and to the original problem worked out in Chapter I, in which a car having a length of 16 feet, a total weight including passengers of 14,860 lbs., and operating at a schedule speed of 6 miles per hour, it is obvious that two 25-h.p. motors would be ample. The service, in other words, would correspond to that of Austin, Texas.

The foregoing method does not meet with success, however, when applied to an original problem of widely different nature, such as a trunk-line problem, owing to the lack of available data. Applying this method to such a problem would be expensive and probably result in improper design, as the heating of a motor under these conditions is entirely different from an interurban problem. Fortunately in solving such problems the practical engineer has at his disposal the immense engineering resources of the larger manufacturing companies.

Table 7 gives data upon some modern railway car equipments. The table gives in connection with cars, the length over all, the width, the weight without motors, the total weight, the seating capacity, the diameter of the car wheels, the number of motors to the cars, and the h.p. capacity of the motors. The table is not complete, but it gives considerable general information such as one would find in the technical publications, and which one would naturally tabulate.

TABLE 7. — *Data on Electric Car Equipments in Use.*

Name of Company.	Length Over All. Ft.	In.	Width. Ft.	In.	Weight Without Motors. Lbs.	Total Weight. Lbs.	Seating Capacity.	Diameter Wheels. In.	No. of Motors to Car.	H.P. Capacity per Motor.
Central Kentucky Traction Co.	44	44	......		28,000	......	...	33	4	40
Warren and Jamestown R. R.	52		9		......	66,000	59	33	4	50
Alexandria Electric Ry.	27		8	3½	12,300	17,700	...	33	2	25
Iowa Interurban Co.	50		8	10	......	......	50	35	4	75
Toledo Railways	30	1	8		17,900	......	...	33	...	...
Columbus Railway	43	4⅜	7	11¼	......	......	...	......		40
Lehigh Valley Trac. Co.	41	11	8	4	......	......	...	......	...	...
Milwaukee and Chicago R. R.	46	7	......		......	......	56	......	4	...
Memphis Railway Co.	40	6	7	11½	33,300	45,700	...	33	...	50
Johnstown, Pa.	29		7	10	......	......	...	33	...	...
Toledo and Chicago Interurban	......		......		......	......	...	......	...	75
Spokane R. R. Co.	30	8	......		......	......	...	......	...	...
Public Service Corporation of N. J.	39	3¾	......		17,000	......	...	......	4	40
Toledo, Detroit Interurban	52		......		......	......	...	......	...	75
Indianapolis and Cincinnati	55		......		......	......	...	......	4	75†
Stark Electric Railway	50		8	8	47,000	......	56	......	4	...
Philadelphia, Sight-Seeing Cars	34	9	8	2	34,140	......	...	......	4	...
Portland R. R.	39		7	1	......	......	48	......	4	...
Indianapolis Northern	55	5½	8	6	......	......	...	......	4	...
Joliet, Aurora and Plainfield	51		......		......	......	52	......	4	...
Chicago and Milwaukee	46	9	......		......	......	...	......	4	65
Green Bay, Wis.	45	5	8	6	......	......	...	......	4	...
Biltmore	32	11	7	10	14,500	......	...	......	...	...
Sciota Valley R. R., Ohio	60		8	6	94,000	......	72	......	4	125
Erie, Pa.	29	5	7	6	......	......	...	......	...	...
Aberdeen and Hogerion, Wash.	45		......		......	......	...	......	...	...
Northern Texas R. R.	30	1	8		......	......	32	......	...	...
Memphis, Tenn.	29		7	6	......	......	...	......	...	25
Augusta and Aiken R. R., Ga.	42	9	8	4	34,460	......	48	......	4	50
Washington, D. C.	35	1	8	4	......	......	...	......	...	...
Union Railway N. Y. C.	36		7	6	18,390	......	...	*	...	55
Easton, Pa.	40	1	8	4	......	39,244	...	......	4	40

* 30 and 20 † 44–56

Table 7. — *Data on Electric Car Equipments in Use* — Continued.

Name of Company.	Length Over All. Ft.	In.	Width. Ft.	In.	Weight Without Motors. Lbs.	Total Weight. Lbs.	Seating Capacity.	Diameter Wheels. In.	No. of Motors to Cars.	H. P. Capacity per Motor.
Fort Wayne and Rosen Hight R. R.	39	9	8	4			†			40
Oklahoma City	31		6	3					2	25
Evansville Suburban and Newbury	46		9						4	55
Petaluma and Santa Rosa R. R.	47	9	8	8					4	40
Oregon Water Power R. R. Co.	40	1	8	2			44–56		4	50
Escanaba, Mich.	28		9				32			
Atlantic Shore Line, Me.	45									40
Dayton, Covington and Piqua Tract. Co.	45								4	*
Seattle, Renton and Southern R. R.	38	5	8	2			40			50
Indiana, North'n Tract. Co.									4	75
Punxsutawney R. R.	26	4	8				28			45
Washington, D. C.	28	4	7	9		21,500				50
Hartford and Springfield R. R.	42								4	40
Levin City Shops	45	2							4	40
New York, Trenton, P. S. Co.							48		4	50
Los Angeles, Pacific E. R. R. Co.	55					62,500			4	80
Boston and Worcester	41	6			35,660	35				
Evansville E. R. R	28						40		4	40
Schenectady R. R.	51		8	9					4	125
Atlantic City, N. J.	41	11	8	2	34,200				2	40
Springfield, Troy, Piqua	50	1	8	6	26,000					
Cleveland, Painsville and Ashtabula	53	1½	8	9					4	50
North Shore R. R., Cal.	56	4			60,000		66.		2	125
Jackson and Battle Creek R. R.	50								4	50
Grand Rapids	28				30,000		40		2	125
Interurban, Western, N. Y.	52		8	6					4	†
Austin, Texas	30	7	7	9			30		2	25
Indianapolis and Northwestern Traction Co.	60		8	8			60		4	75
Chicago Union R. R.	41						40		4	40
Chicago, Indianapolis	41		8	4			44		2	55
Conneant and Erie R. R.	45				20,000				{4 {4	35 50
Syracuse	37	6	8	2			40		4	38

* 40–50 † 65 or 75

Armstrong's Method. — In a paper presented by Mr. A. H. Armstrong at the 20th Annual Convention of the American Institute of Electrical Engineers at Niagara Falls, N. Y., June 30, 1903, was given a set of curves, Figs. 6, 7, 8, from which could be determined the required motor capacity for a given service. These curves were plotted for

A. Trains of Twenty Cars or more;
B. Trains of Two Cars;
C. Single Cars.

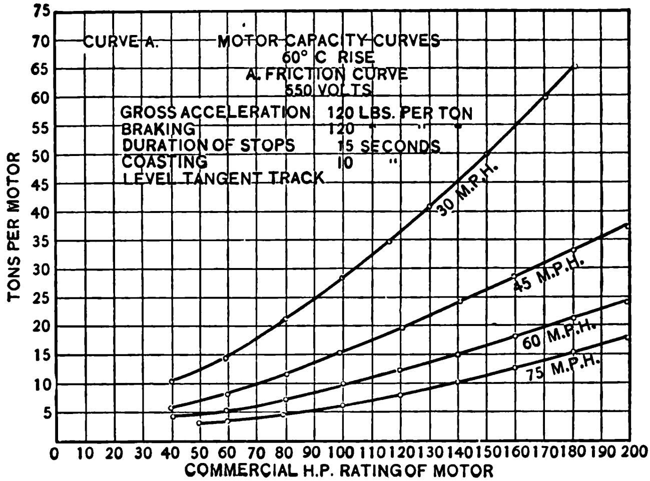


Fig. 6.—MOTOR CAPACITY CURVES FOR TRAINS OF TWENTY OR MORE CARS.

The curves are based upon a service rating which shows the relation between the commercial rated h.p. of a motor, and the weight in tons of the car which it can propel at any speed without heating more than 65° above the temperature of the atmosphere. These curves are plotted for a level track, gross acceleration of 120 lbs. per ton, braking 120

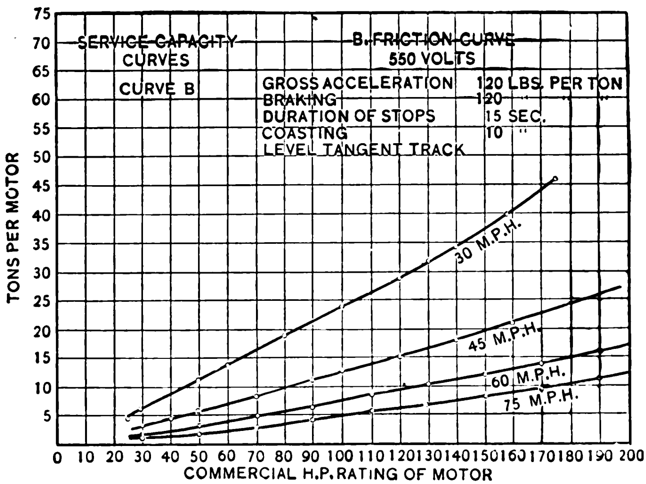


Fig. 7.—MOTOR CAPACITY CURVES FOR TRAINS OF TWO CARS.

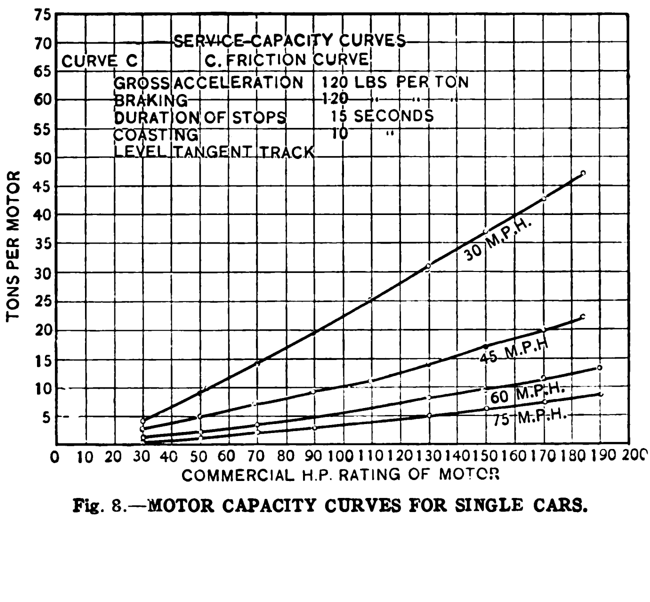


Fig. 8.—MOTOR CAPACITY CURVES FOR SINGLE CARS.

lbs. per ton, duration of stops 15 seconds, coasting 10 seconds. To use curves, apply the following example.

Example. — Given a 40-ton single car moving at 30 miles an hour, to determine the required motor capacity for a four-motor equipment. Refer to curve sheet *C*, Fig. 8, for single cars. The tons per motor would be 10 (40/4 = 10). Note the intersection of the 30 mile per hour curve with the ordinate 10 tons per motor. By referring this point vertically to the lower scale on the abscissa, there may be found the required rated commercial h.p. per motor, in this case, 52 h.p. If there is considerable lay-over at the ends of the lines, the motor of the next smaller size manufactured by standard companies may be employed. If the service is heavy, the next largest size could be employed. Table 8 indicates a number of the standard size motors manufactured by the General Electric Co. and the Westinghouse Electric Mfg. Co. In the problem at hand, four 50-h.p. motors would be ample. Table 9 gives the weights of standard types of control manufactured by the General Electric Co. The curves of Mr. Armstrong are based upon the friction curves, plotted from the Davis formula. A more recent set of friction curves obtained by Mr. Armstrong is given in Figs. 9 and 10. They are based upon the formula

$$R = 4 + .07V + \frac{.0025}{T} V^2 A \ [1 + .1\ (N - 1)]$$

where

R = train resistance in pounds per ton.
T = weight of train in tons.
A = cross-section of car in square feet.
V = speed in miles per hour.
N = number of cars in train.

TABLE 8. — *Railway Motors. Standard Sizes and Ratings.*

Type.	Make.	Horse-Power Rating.	Weight.
12 "a"	Westinghouse	30	....
49	do.	35	....
92	do.	35	....
68	do.	40	2280
101	do.	40	....
38 B.	do.	45	....
56	do.	50	....
93	do.	50	....
112	do.	65	....
76	do.	75	3840
83	do.	110	....
50 F.	do.	150	....
86	do.	200	....
800	General Electric	25	1800*
52	do.	25	1725
1000	do.	35	2180
67	do.	40	2385
70	do.	40	2530
80	do.	40	2530
57	do.	50	2972
74	do.	65	3534
73	do.	75	4022
66	do.	125	4378
55	do.	160	5415
69	do.	200	6100

* Including gear case and gears.

TABLE 9. — *Weights of Railway Equipment. Includes Control, Car Wiring and Motors.*

Type Motor.	Number Motors.	Type Control.	Weight in Pounds.
G. E. 800	2	K 10	4750
800	4	K 6	8740
52	2	K 10	4380
52	4	K 12	8100
1000	2	K 10	5310
1000	4	K 6	10,290
67	2	K 10	5710
67	4	K 6	11,090
57	2	K 11	6884
57	4	K 14	14,108
74	2	Train Type M	9000
74	4	do.	16,586
73	2	do.	11,044
73	4	do.	20,768
66	2	do.	13,230
66	4	do.	23,760
55	2	do.	13,680
55	4	do.	26,640
69	2	do.	13,600
69	4	do.	26,600

In Fig. 9, the curves have been plotted in terms of speed in miles per hour, and train resistance in lbs. per ton for a car weight of 45 tons and a cross-section of car of 110

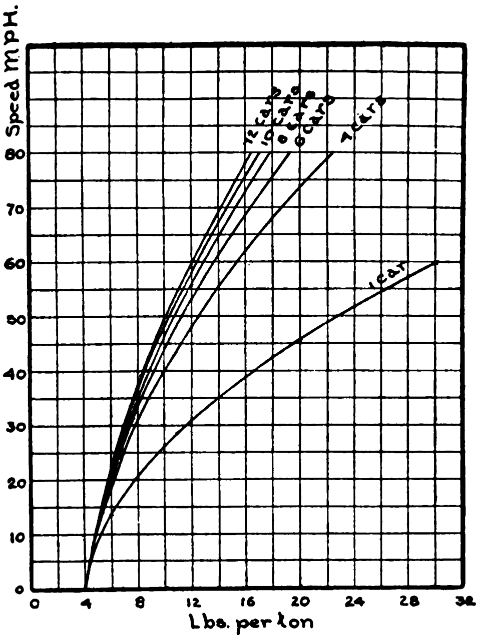


Fig. 9.—TRAIN RESISTANCE CURVES, MULTIPLE UNIT TRAIN OPERATION.

square feet. The curves indicate values for trains of 1, 4, 6, 8, 10, and 12 cars. Fig. 10 shows locomotive service.

Mr. Armstrong also presented a series of curves based upon tests which gave the energy consumption in watt hours per ton mile for trains of units, corresponding to pre-

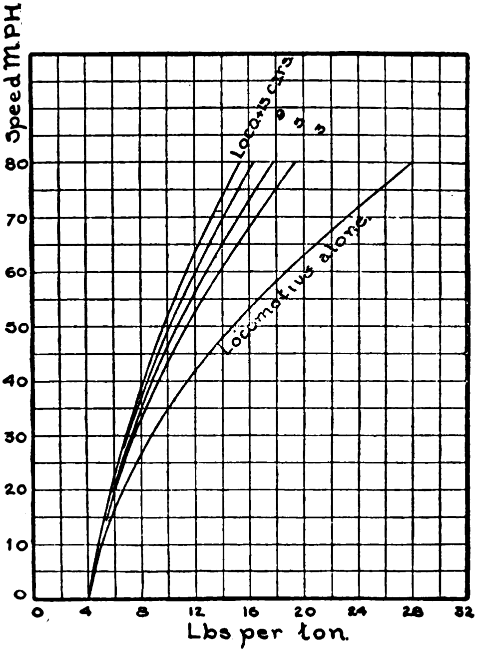


Fig. 10.— TRAIN RESISTANCE CURVES, ELECTRIC LOCOMOTIVE SERVICE.

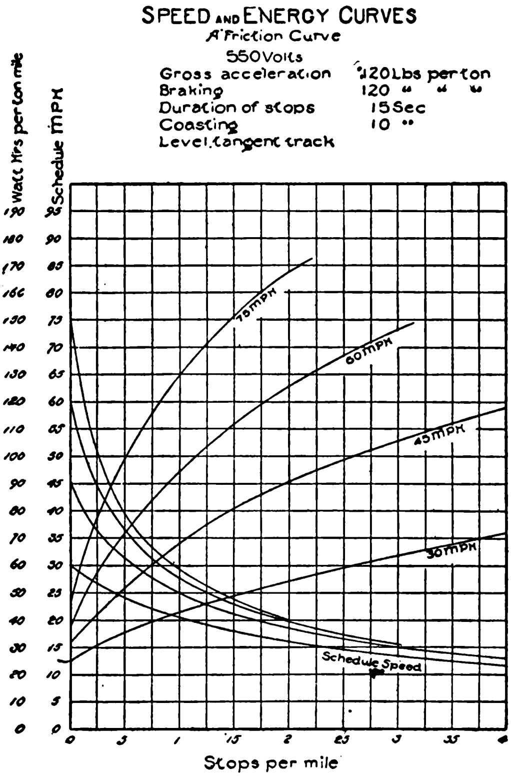


Fig. 11.—SPEED AND ENERGY CURVES FOR TRAINS OF TWENTY OR MORE CARS.

vious motor capacity curves. These energy curves, Figs. 11, 12, and 13, are plotted for maximum speeds of 30,

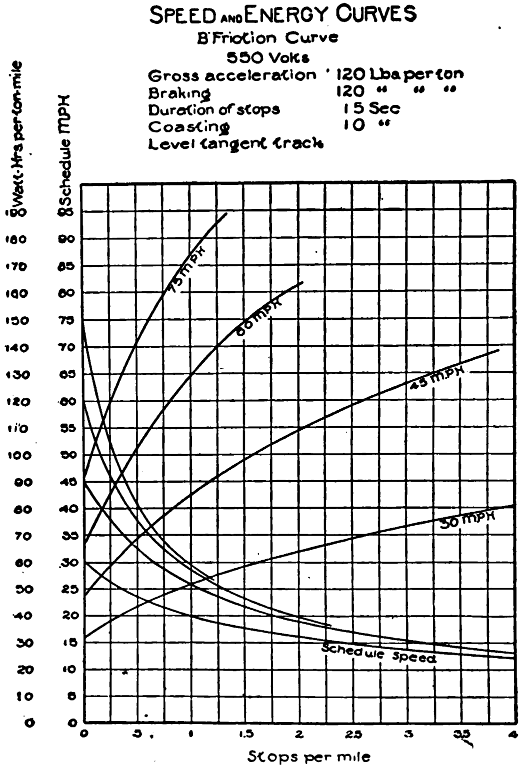


Fig. 12.—SPEED AND ENERGY CURVES FOR TRAINS OF TWO CARS.

45, 60, and 75 m.p.h. in terms of watt hours per ton mile, and stops per mile ranging from 0 to 4.

To apply curves, assume as an example the case previously cited of a single 40-ton car, moving at 30 m.p.h., to

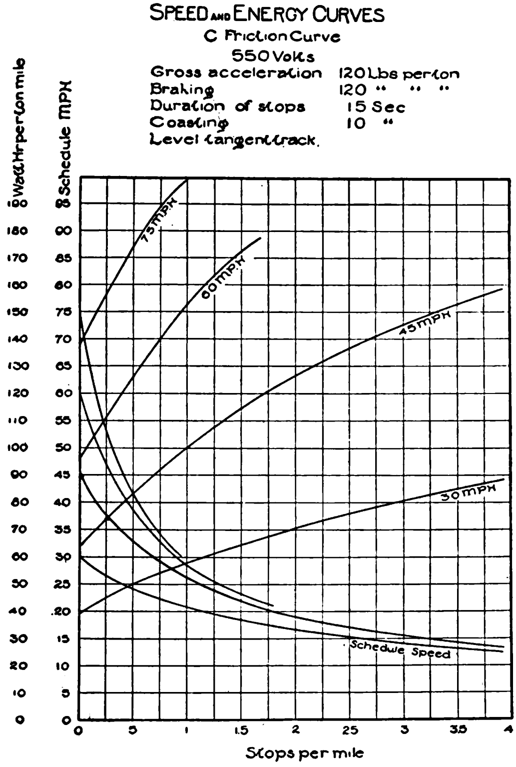


Fig. 13.—SPEED AND ENERGY CURVES FOR SINGLE CARS.

determine the energy consumption in watt hours per ton mile, making 2 stops per mile, at a schedule speed 16 m.p.h. Referring to Fig. 13, to the curve of schedule speed: This curve passes through the coördinates, 2 stops per mile and 16 m.p.h. As a maximum speed would correspond to 0 stops per mile, the curve of schedule speed, if followed, intersects the 0 stops per mile ordinate at 30 m.p.h. Following the maximum speed curve of 30 m.p.h. until it intersects the coördinate 2 m.p.h. it will be noted that this corresponds to 70 watt hours per ton mile.

Storer's Method. — This method serves in the case where a given motor has been selected for a given service, and it is desirable to determine whether or not it has the proper capacity. Average speed time and power curves are drawn for this motor and the effective current value is determined. The average motor voltage over a whole cycle is determined. The effective current value and this voltage value are referred to the characteristic curves of the motor. As the average voltage value will be in the vicinity of either 400 volts or 300 volts, the continuous current capacity at these two values will be given (see Fig. 14) for Westinghouse No. 89 Railway Motor. Usually a motor selected in this manner will have about 25% excess capacity owing to the fact that the ventilation is much better when the motor is mounted under a car than when it is mounted on a stand. This excess is on the safe side, however, and is particularly advantageous to the motor when operated by an incompetent motorman. Where greater accuracy is desired with this method, the original I^2R losses of the motor and its core loss at that particular voltage value are considered and the total loss calculated. This value is compared with the heating value of the motor under similar conditions and its adaptability for the service determined. An excellent description of this method is here inserted as originally published by Mr. Storer in the "Street Railway Journal" of January 5, 1901.

"The rational way to decide what further information is necessary is to analyze the actual work the motor has to do, to locate and determine the amount of loss it sustains in

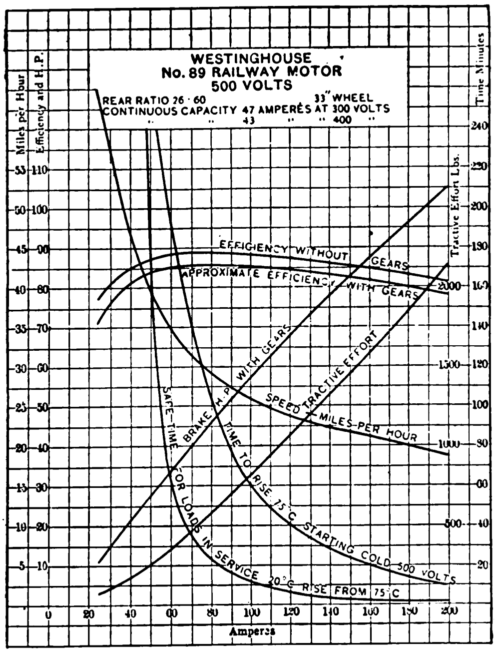


Fig. 14.—CHARACTERISTIC CURVES OF WESTINGHOUSE NO. 89 RAILWAY MOTOR.

service, and then to find what shop test will reproduce the losses and other important conditions of such service. This involves:

First. A definite knowledge of the service for which the motor is to be used, including the schedule speed, the profile of road or a statement as to its grades, etc., the number of stops, and the accurate weights of cars loaded and unloaded:

Second. A knowledge of the characteristics of the motor, including speed, tractive effort, resistance of windings, and the iron losses at all voltages and currents within its capacity.

With this information at hand, a set of curves may be drawn that will show very closely the variations in load and speed of the motor throughout the different cycles of work it will have to perform. From these load curves the losses in the motor may be calculated.

In order properly to illustrate the method of doing this, a practical example is given. The assumptions in regard to operating conditions in the case are as follows:

Track — level.

Schedule Speed — 14.2 miles per hour.

Weight of Car Equipment with Load — 15 tons.

Frequency and Duration of Stops — 4 per mile, 5 seconds each.

Average Line Voltage — 500.

Rate of Acceleration — 1½ miles per hour per second.

Rate of Braking — 2 miles per hour per second.

Rolling Friction — 20 lbs. per ton.

The characteristic curves of the motor to be applied to this case are shown in Fig. 15. The iron loss curves of the same motor, plotted in terms of watts and voltage on the motor, for a number of different currents, are shown in Fig. 16. From these curves and the foregoing assumptions the curves shown in Fig. 17 are constructed. (See Vol. 1, "Electric Railways," on Plotting of Speed Time Curves, pages 37 to 46 inclusive.)

The speed-time curve is plotted in terms of speed in miles per hour and time in seconds. The current and voltage are also plotted with reference to time in seconds.

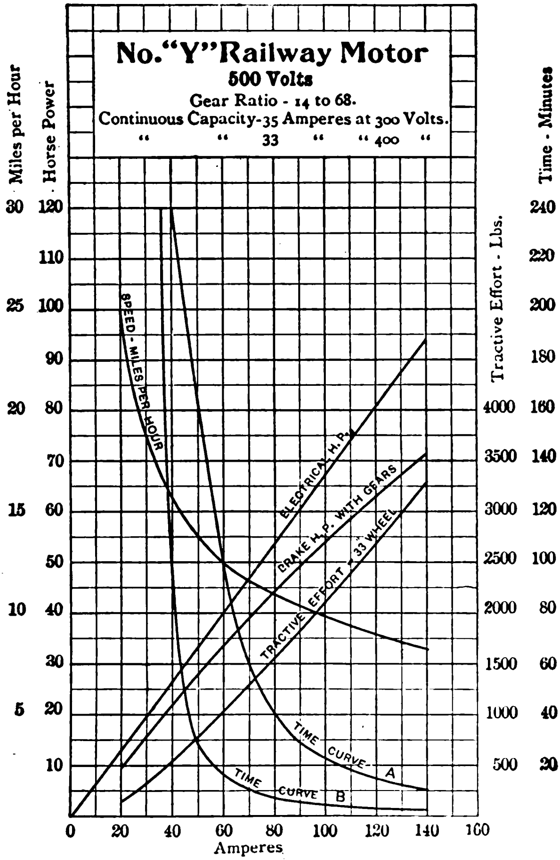


FIG. 2.

Fig. 15.—CHARACTERISTIC CURVES FOR "Y" MOTOR.

The current curve corresponding to the speed curve may be plotted at the same time as the acceleration portion of the speed-time curve. It will be noted that in Fig. 17 it is plotted in terms of amperes per car. The periods when the motors are in series and in parallel are plainly shown.

The voltage curve is next plotted, starting at the voltage

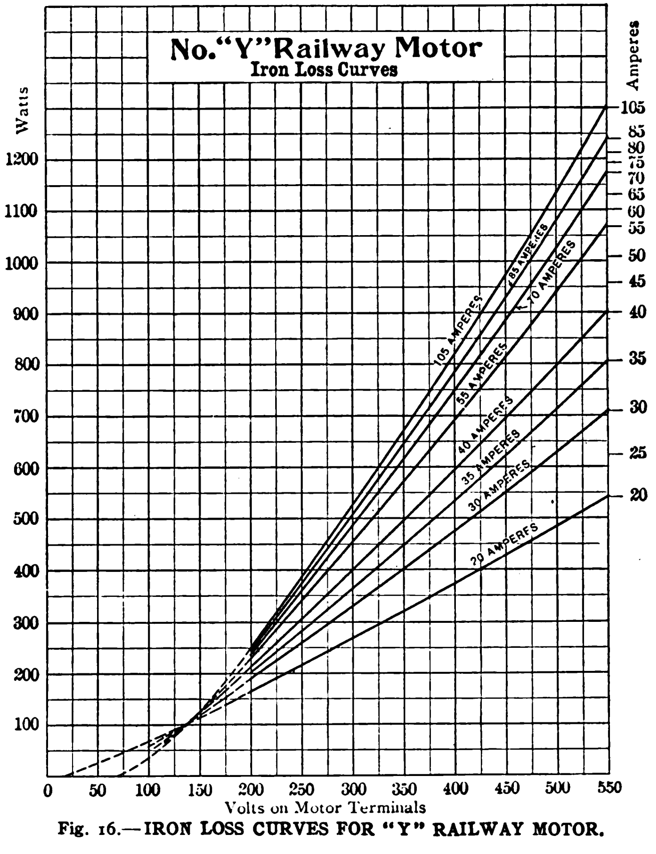


Fig. 16.—IRON LOSS CURVES FOR "Y" RAILWAY MOTOR.

which is required to overcome the ohmic resistance of the motor with 68 amperes flowing. As the resistance is cut out, the voltage rises uniformly till it reaches that of the line, where it remains until the power is cut off.

Fig. 17 thus shows the speed of the car, the current in the motor and the voltage on its terminals, at every instant during the cycle from starting to stopping. The next step is to calculate the average loss, or heating effect.

The electrical losses are divided into two classes, viz.:

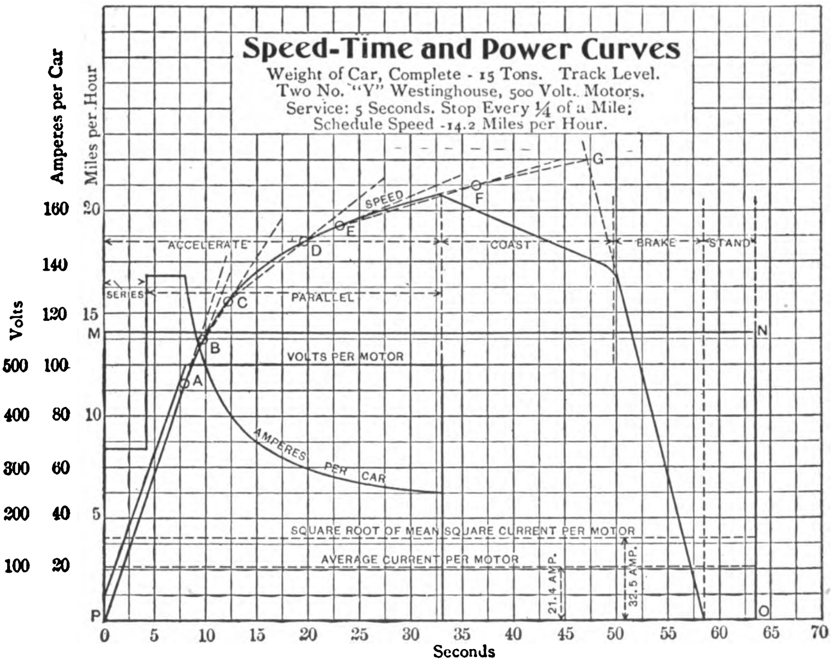


Fig. 17.—SPEED-TIME AND POWER CURVES FOR "Y" MOTOR.

those in the windings, or copper losses, and those in the core, or iron losses. The copper loss, being the product of the square of the current by the resistance of the windings, is proportional at any instant to the square of the current. The average copper loss is, therefore, proportional to the average of the squares of the currents during successive intervals. The current which, when flowing continuously, will give the same average loss, will be the square root of the average of the squares; in other words, the *equivalent* heating current is the square root of the mean square current. This may be found in Fig. 17 by taking the square of 68 amps. for 7.8 seconds, the square of 62 amps. for 1 second, 52 amps. for 1 second, 44 amps. for 2 seconds, and so on until the entire curve is covered; then dividing the sum of these squares by 63.5 — the total number of seconds in the cycle — and extracting the square root of the quotient there results the equivalent heating current of about 33 amps. This current, with a total resistance in the windings of .625 ohms (taken at running temperature), gives an average copper loss of 680 watts.

The iron loss is calculated in a similar manner by reference to Fig. 16. It will be noted (Fig. 17) that the current in each motor is constant at about 68 amps. for the first 8 seconds. This current, with the voltages shown in the curve, gives an average iron loss during the first two seconds of about 40 watts; for the third and fourth seconds, 300 watts; for the fifth and sixth seconds, 580 watts; for the seventh and eighth seconds, 870 watts. After the eighth second the voltage is constant at 500 volts, and the current decreases. For the ninth and tenth seconds, the current averages about 58 amps. per motor, giving an average iron loss of about 150 watts; for the next five seconds, the average loss is 800 watts, and so on. Summing up these losses and dividing the sum by 63.5 gives an average iron loss of 350 watts for the cycle. The total average losses in copper and iron thus amount to 680 + 350, or 1,030 watts.

It follows then that, in order to reproduce the heating conditions of this service in a shop test, all that is necessary is to run the motors at 33 amps., which gives the average copper loss, and at such a voltage as gives, with 33 amps.,

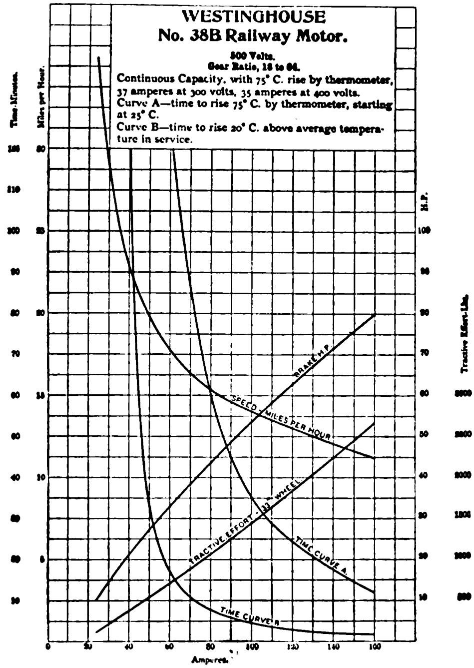


Fig. 18.—CHARACTERISTIC CURVES OF WESTINGHOUSE NO. 38B RAILWAY MOTOR.

an iron loss of 350 watts. This equivalent voltage is found by reference to Fig. 16 to be about 300 volts.

The foregoing analysis might seem to indicate that a large amount of calculation is necessary in order to select a motor for properly meeting given conditions, but this is not the case. The various cycles of work the motor has to do should by all means be laid out and the equivalent heating current and the average voltage on the motor determined. But it is unnecessary to go into the refinements of iron loss to the extent that is done in this analysis. The average voltage on the motor is usually below 250 volts, and for all such work an equivalent voltage of 300 may be taken for the continuous test. For interurban service, where a high average voltage on the motor is maintained by reason of the smaller number of stops, an equivalent voltage of 400 will suffice.

Therefore, if the continuous capacity of railway motors is stated in terms of current at both 300 volts and 400 volts, this information will cover all classes of service with adequate precision.

From the fact that the allowable heating current of the motor in the foregoing example is 35 amps. at 300 volts, and 33 amps. at 400 volts, it will be seen that the exact equivalent voltage is not necessary for the test. The temperature of the armature does not rise in proportion to the total loss in it, as the highest voltage gives higher speed, and, consequently, better ventilation.

The above analysis shows how to find the average heating effect of a single cycle. If the service over the entire line is about the same, the determination of a single cycle will suffice. If, however, there is a difference due to grades, loads, stops or schedule speed, different cycles should be calculated, and the heating effects averaged. This method may be used where the losses are so distributed as not to allow the temperature to increase appreciably during any one cycle. Most roads, however, have heavy grades to surmount, or periods of the day during which the loading of the motors is much heavier than the average. Time curve *B* in Fig. 15 provides for such cases. It shows the allowable time the motor may carry any current above its rated continuous current or during which the square root of mean square current may reach any given value. It is plotted on the basis of an additional rise of 20 degrees C. in windings when the motor is already running at its average temperature, and thus gives a definite idea as to the temperature that may be expected in the worst conditions.

Time curve *A* is the familiar "Load and Time" curve, showing the time the motor will carry any load with a rise of 75 degrees C., starting cold. A reference to this curve will show at the one-hour point, the h.p. rating of the motor according to the old system.

This method of rating is clearly demonstrated in Fig. 18, for the Westinghouse 38 B Railway Motor.

All calculations should be based on complete information which should be furnished by the manufacturer as follows:

(1) Curves of speed, tractive effort and horse-power of the motor within the limits of its commutating capacity and mechanical strength.

(2) A statement of the currents the motor will carry continuously at 300 volts and at 400 volts.

(3) A curve showing the allowable time any load above the continuous current may be carried when the motor is already heated in service.

(4) A curve showing the time the motor will carry any load within its capacity with a rise of 75 degrees C., starting cold.

It is believed that the simplicity, completeness, and accuracy of this method of stating the capacity will commend itself to anyone who has to do with railway motors."

CHAPTER III.

ELECTRICAL FEATURES (Continued).

HUTCHINSON'S METHOD OF DETERMINING MOTOR CAPACITY.

Hutchinson's Method. — "This method affords a means of determining the energy, the power and the losses for any

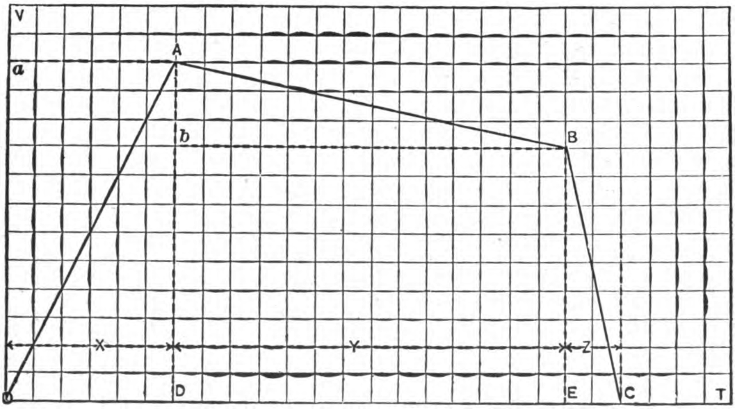


Fig. 19.—TYPE CURVE.

schedule speed, over a course of any length with any initial acceleration, tractive resistance or braking effort, and with any desired use of the "motor curve."

NOTE. — The following description is printed in full from the transactions of the American Institute of Electrical Engineers, before which body this classic paper was presented in January, 1902.

"The solution falls into three stages: (1) The determination of the elements of Fig. 19, to give any schedule speed (this $(v-t)$ curve is referred to as the "type curve"); (2) The determination of a general tramway motor curve sheet and the deduction from this curve sheet of several dependent curves; and (3) The application of the general motor curves to the type curve of Fig. 19, to obtain a general solution of the $(v-t)$ curves of Fig. 20. Each

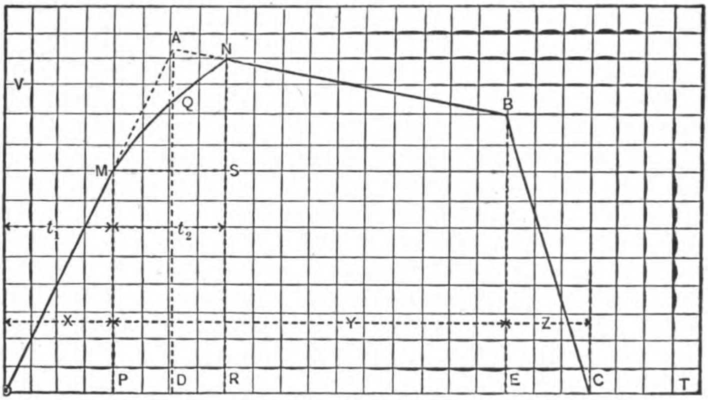


Fig. 20. — ELEMENTARY SPEED-TIME CURVES.

case of Fig. 20 is reduced to a case of Fig. 19 by applying a correction to Fig. 20, represented by the area MAN, by which it is reduced to a corresponding case of Fig. 19. To discuss this method let

a = Acceleration along OA,
b = Retardation along AB,
c = Retardation along BC, and
x, y, and z = Respective Times.
Let T = Total Time = OC.
L = Total Distance = Area $OABC$.
V = Average Velocity = $.682\ L/T$.

Then these three equations hold:

Velocities $ax - by - cz = O,$ (1)

Times $x + y + z = T,$ (2)

Distances $ax^2 - by^2 + cz^2 + 2\,axy = 2 \times .682\,L.$ (3)

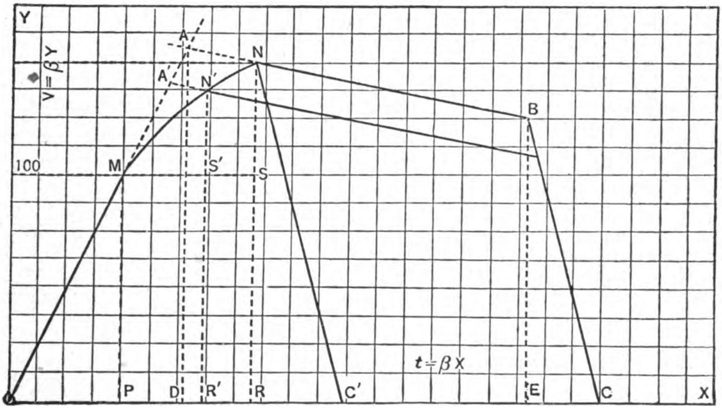


Fig. 21.—CALCULATED SPEED-TIME CURVE.

The work of solving these equations is tedious; the results are therefore given in a simplified form:

Put $A = V/T = .682\,L/T^2 = 1.47\,V^2/L$ (4)

$2\,A_0 = ac/(a + c)$ (5)

$2\,M = (a + b)\,(a + c)\,(c - b)$

$K_1 = (c - b)/M^{\frac{1}{2}}$

$K_2 = (a + c)/M^{\frac{1}{2}}$

$K_3 = (a + b)/M^{\frac{1}{2}}$

where $K_1 + K_2 + K_3 = 0.$

Then will $x/T = 2\,A_0/a - K_1(A_0 - A)^{\frac{1}{2}}$ (6)

$y/T = K_2(A_0 - A)^{\frac{1}{2}}$ (7)

$z/T = 2\,A_0/c - K_3(A_0 - A)^{\frac{1}{2}}.$ (8)

And, $ax/T = 2A_0 - aK_1\,(A_0 - A)^{\frac{1}{2}}$ (9)

$by/T = b\,K_2\,(A - A)^{\frac{1}{2}}$ (10)

$cz/T = 2A_0 - cK_3\,(A_0 - A)^{\frac{1}{2}}.$ (11)

These three equations are the general solution of the problem in kinematics illustrated in Fig. 19.

Through Acceleration. — The only term in equations 9, 10, and 11 containing the average velocity of the length is A; all other terms are functions of the three accelerations. The quantity A determines completely the schedule; all schedules having the same value of A will be accomplished by the same accelerations in the same proportional times, that is, the same fraction of the total time will be occupied in the three phases of the movement. This quantity, A, is termed the ***through acceleration.***

All schedules with the same "through acceleration" but with different V and T are represented by similar figures, the scale only being different.

The curve sheet (Fig. 22) is plotted from equations 6, 7, and 8, and gives the values of x/T, y/T and z/T in terms of A for different values of (a) varying from .25 to 3.0, and for $a = \infty$; for $b = .2$ and $c = 3$.

The values of x/T are the intercepts between the X-axis and the branch of the a-curve lying below the line AB; the values of y/T are included between the two branches of the a-curve, and of z/T are included between the line AD and the upper branch of the a-curve.

For instance, for $A = .4$, $a = 1.5$, $x/T = MN$, $y/T = NP$, $z/T = PQ$. The line $a = \infty$ is the axis of X; the line AB is the locus of $y = 0$ or of "no coasting," and the intersection of the a-curves with this gives the maximum through acceleration for that value of (a). The line AC is the line of no braking, and its intersection with the a-curves gives the minimum values of A.

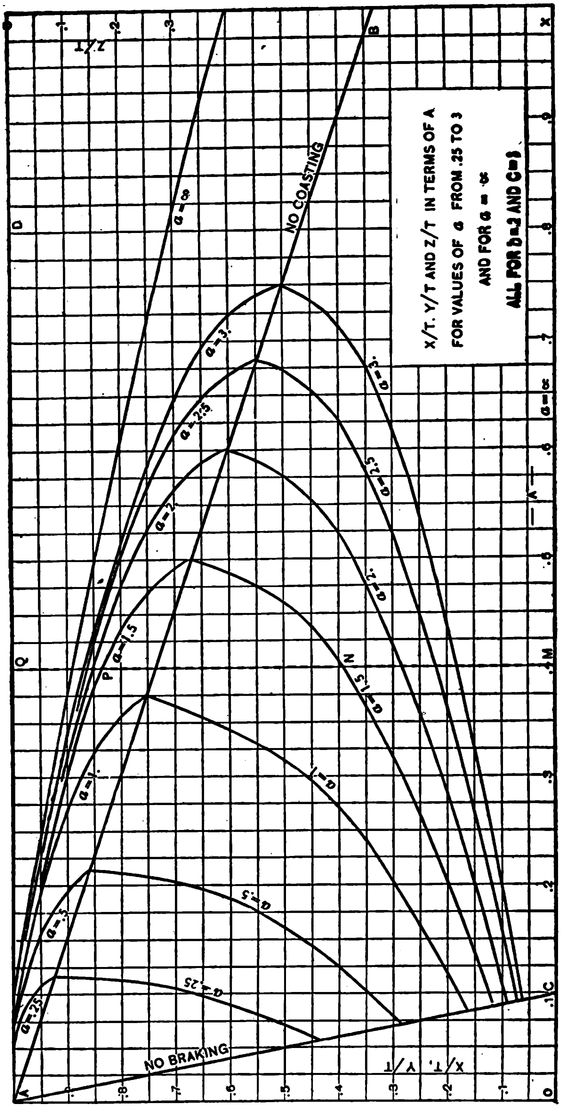


Fig. 22.—INITIAL ACCELERATION, COASTING AND BRAKING IN TERMS OF THROUGH ACCELERATION.

These curves give all possible values of A, and enable Fig. 19 for any particular case to be drawn at once.

These curve sheets give a complete determination of the kinematics of the problem. There remains the determination of energy and power — the kinetics. I limit the discussion to the case in which power is applied along OA only (Fig. 19), and the car is allowed to "coast" with gradually diminishing velocity due to the constant retardation (b) from A to B where a braking force producing a retardation ($c-b$) is applied, making a total retardation equal to (c).

The assumption of (b) constant is necessary to a simple discussion; if it is not so, an average value may be used; considerable variations in the value of (b) make little difference. I use throughout $b = .2$ m.p.h./sec., equal to a force 18.2 lbs. per ton; (b) represents the total tractive resistance on a level at uniform speed, and with electric motors includes motor friction.

The force exerted along OA (Fig. 19) is

$$f = \frac{w}{g}(a + b) \text{ lbs.}$$

and the total energy input at the car axle, per ton, up to the point A is

$$2.50 \times 10^{-2}(1 + b/a)\overline{ax}^2 \text{ wh.} \qquad (12)$$

Of this energy $2.5 \times 10^{-2} \times \overline{ax}^2$ wh.

is represented by the kinetic energy at point A, and

$$2.5 \times 10^{-2}\overline{ax}^2 \times b/a \text{ wh.}$$

is the work done in overcoming tractive resistances up to point A.

The power per ton is

$$P = 0.182\ (a + b)\ ax \text{ kw.} \qquad (13)$$

Schedule Speed. — The relation of schedule speed S to average velocity V is dependent upon the time of stops at the station. If t is the time of stop at station, then

$$T = .682\ L/S - t$$
$$V = .682\ L/T$$
$$A = V/T = 1.47\ V^2/L. \qquad (4)$$

These equations give A in terms of S and L. If t is taken at any constant value, curves can be plotted giving V in terms of S and L; it is, however, simpler to use the equations.

I do not consider the schedule speed further, but assume V and T to be determined from S, (t) and L. Knowing A, curve sheet, Fig. 22, gives x/T and hence (ax) for any values of A. The energy and power are then determined by equations (12) and (13).

These quantities refer to the car axle and do not include losses of any kind in the motor, and hence are of theoretical interest only. If motors had constant efficiency, these values would be proportional to the energy input.

The discussion to this point is applicable to any kind of motive power. The matter of practical interest is the application to electric motors, and the determination of the quantities for the $(v–t)$ curve of Fig. 20; the characteristics of the motor must be taken into account.

General Motor Curves. — In order to make the discussion general, it is not sufficient to consider one or two sizes of motor or one or two gearing ratios. All sizes and all gear ratios must be included, or, what is the same thing, all values of torque at the axle and all values of velocity; in a word, a set of motor curves applicable to all sizes of motors must be prepared.

I have plotted the values of torque and speed in terms of input for some twenty tramway motors of different sizes and makes, expressing all quantities in percentage of their value at rated load, and find that the agreement is close — so close that one set of curves can with sufficient exactness for this purpose be used for almost any modern tramway motor built in the United States. It is immaterial whether

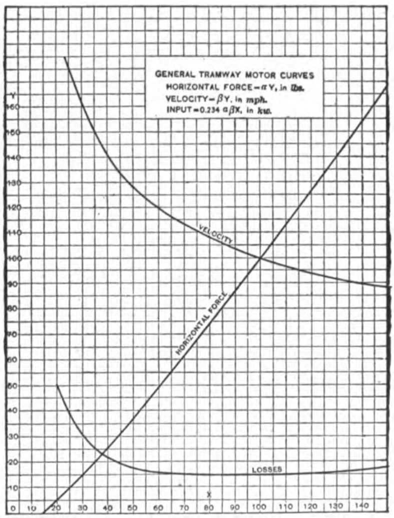


Fig. 23.—GENERAL TRAMWAY MOTOR CURVES.

this general motor curve represents any particular motor. By using this curve, the same characteristics are retained for all initial accelerations, hence the use of such a curve brings out the differences due to the different initial accelerations without complicating them by the differences in individual motor characteristics. Curve sheet, Fig. 23, is this general tramway motor curve; abscissæ are input in kilowatts; ordinates are horizontal force (f) in lbs., and speed (v) in miles per hour; on these curves the rated load is the point (100,100) and is the rating on a one-hour basis, heating to 75° C. — the common tramway motor rating. Losses also are plotted; they differ much more in various motors than do (f) and (v).

Let $\beta Y'$ be the velocity and $\alpha Y''$ the horizontal force, then every variation in conditions can be met by giving suitable values to α and β; this use of horizontal force and linear velocity eliminates the gearing ratio and size of wheel, both of which are determined by considerations outside of this discussion. Then for any value of X,

$$f = \alpha Y'' \text{ lbs.}$$

and $$v = \beta Y' \text{ m.p.h.}$$

The output is $$[\alpha\beta Y' Y'']/503 \text{ kw.}$$

and the input is $$[\alpha\beta Y' Y'']/(e \times 503) \text{ kw.}$$

where e is the efficiency at the point (X, Y', Y'') taken from the motor curve sheet. Choosing the point (100,100,100), the rated load, then $e = .85$, and the input is

$$P = 0.234\, \alpha\beta X \quad \text{kw.} \qquad (14)$$

This determines the constant multiplier for the input in terms of α and β.

Example. — An example will make the use of the previous curves clear. Suppose a motor is to exert a horizontal force of 2,000 lbs. at a speed of 20 m.p.h.; if this is required at the rated load, then

$$\alpha = 20, \quad \beta = .2$$

and $$P = 0.936\ X \quad \text{kw.}$$

At rated load this motor is 93.6 kw.

It is not necessary to choose the point of rated load, for any other point could be taken; for instance, a motor may be assumed to give 2,000 lbs. at 125% torque and 30 m.p.h. at the corresponding value of the velocity, which is 93.8%; the motor is then carrying a load of 119%.

The gear ratio, size of wheel and motor capacity must be mutually adjusted to give the required force and velocity at the chosen point of motor input.

I assume in what follows that α and β are chosen for rated load; this matter is discussed further in connection with motor rating.

Acceleration Curves. — M (Fig. 20) is the point where the external resistance is all out of the circuit, and the motors begin to run on the "motor curve." The force exerted along OM is proportional to $(a + b)$. Assume this force to be the rated force of the motor and represented by the point $Y'' = 100$ on the general motor curve. The velocity at M is the rated velocity; it is represented by $Y' = 100$, and is equal to β 100 m.p.h. The acceleration on the motor curve continues to a point N where the velocity is $\beta\, Y'$, Y' having any desired value greater than 100. The shape of the curve MQN depends on the relative values of (a) and (b). If a/b is large, the curve is steep; if small, flat. This curve is determined as follows:

The force at any point on the curve, as Q, is

$$\text{Force} = \frac{w}{g}[dv/dt + b] = \alpha Y'' \qquad (15)$$

where Y'' is the ordinate of the (f) curve of sheet, Fig. 23. For $Y'' = 100$ at rated load and point M,

$$dv/dt = a;$$

hence $$a = \frac{W}{g} \times \frac{(a + b)}{100} \qquad (16)$$

and $$dv/dt = \frac{(a + b)}{100} Y'' - b.$$

But $$dv/dt = \beta [dY'/dt] = \beta [\Delta Y'/\Delta t]$$

and hence $$\Delta t/\beta = \Delta Y'/[(a + b) Y''/100 - b]. \qquad (17)$$

From this equation, $\Delta t/\beta$ can be calculated for different values of (a) and (b), by taking from the velocity curve of sheet, Fig. 23, $\Delta Y'$, and the corresponding values of Y'', the average force ordinate for the interval, $\Delta Y'$. Other methods may be used to calculate this tangent curve.

The values of $\Delta t/\beta$ are calculated and summed up. Plotting these values as abscissæ in terms of velocity as ordinates, a set of curves is obtained for each value of (a) which I call the acceleration or $(v\text{–}t)$ curve of the motor. The input corresponding to each velocity can be plotted on the same sheet, forming a (kw.-time) curve, and from the last by integration, an energy curve. Moreover, from the $(v\text{–}t)$ curve, by integration, a curve of distance and time can be plotted. This gives a set of curves for each value of the initial acceleration, showing at once the power, energy, velocity, and distance up to any relative velocity on the motor curve.

The deduction of these curves and their constants is as follows: From (14) and (16) and for $w = 2{,}000$ lbs.

Power. — $P = 0.213\,(a + b)\,\beta \times X$ kw./ton (18)

where X is the abscissa, taken from curve sheet, Fig. 23, for any velocity.

Energy. — Similarly,

$$W = \frac{1000}{3600} \int_{v=\beta\,100}^{v=\beta Y} P\,dt \qquad \text{wh./ton;}$$

and substituting from (18)

$$W = 5.92 \times 10^{-2}(a + b) \int_{100}^{Y} Y\,dX \qquad \text{wh./ton.} \quad (19)$$

Y and X are the coördinates of P on the several acceleration sheets.

Distance. —

$$S = 1.467 \int v\,dt = 1.467\,\beta^2 \int_{100}^{Y} Y\,dX \qquad (20)$$

where Y and X are the coördinates of (v) on the several acceleration sheets.

Curve sheet, Fig. 24, is calculated and plotted from equations 17, 18, 19 and 20, for $(a) = 3$. It shows velocity, distance, power and energy per ton in terms of time; the curves all start at $v = \beta\,100$, that is, the energy and distance are for the motor curves, and do not include energy and distance up to velocity $v = \beta\,100$.

Curve sheets, Figs. 25, 26, and 27, give the same quantities for $(a) = 2$, 1, and 0.5, respectively.

The coefficient a has disappeared from these curves; only β the velocity coefficient remains. Power and velocity are proportional to β; energy and distance to β^2.

Example. — As an example of the use of these curves, take $a = 3$, curve sheet, Fig. 24. For a motor to have a rated velocity of 20 m.p.h., $\beta = 0.2$; after a time $X = 70\,\beta = 14$ seconds, the velocity will be $159\,\beta = 31.8$ m.p.h.; the power $21.0 \times \beta = 4.20$ kw.; the energy used on the

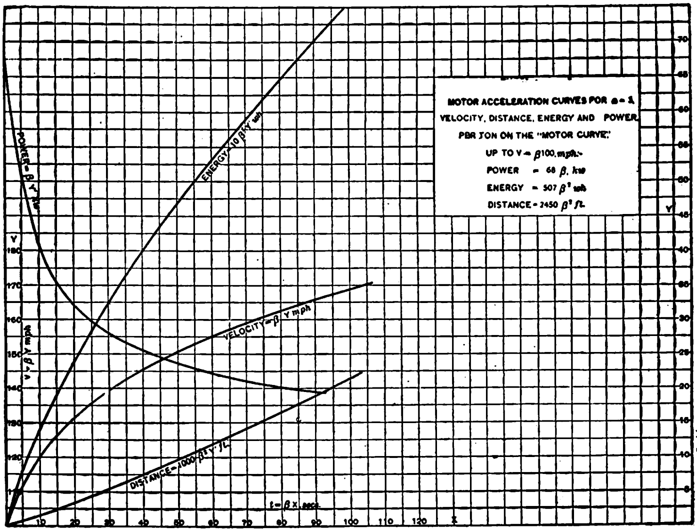


Fig. 24.—MOTOR ACCELERATION CURVES FOR $a = 3$.

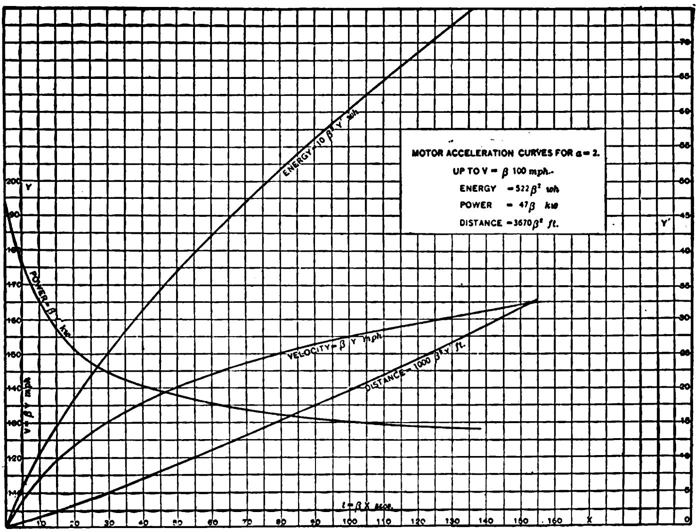


Fig. 25.—MOTOR ACCELERATION CURVES FOR $a = 2$.

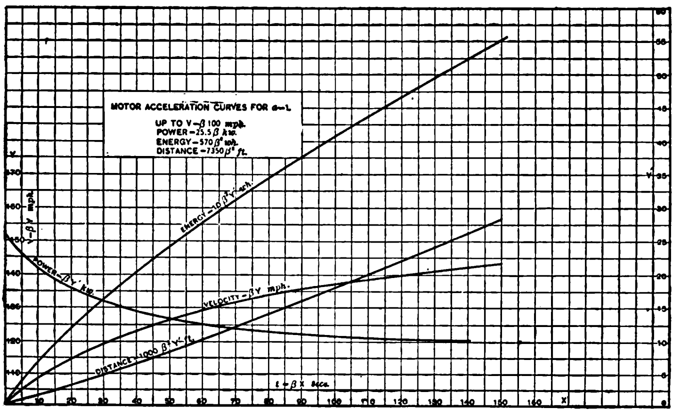


Fig. 26.—MOTOR ACCELERATION CURVES FOR $a=1$.

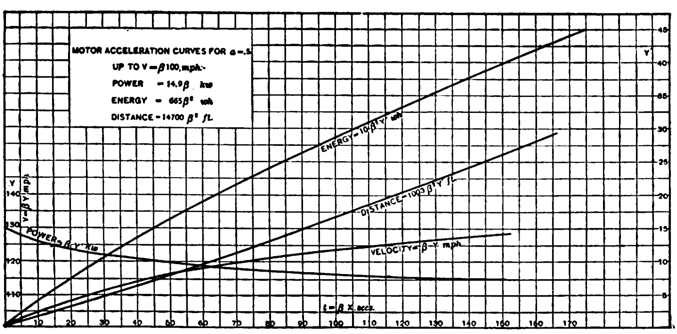


Fig. 27.—MOTOR ACCELERATION CURVES FOR $a=5$.

motor curve, 590 β^2 = 23.6 wh.; and the distance traversed on the motor curve, 14,250 $\times$ β^2 = 570 feet.

From these $(v-t)$ curves, Fig. 21 is drawn, on which the line OM represents the initial acceleration continued to the velocity $v = \beta$ 100, where the acceleration on the motor curve begins and continues to any point N; the velocity RN is made anything within practical conditions; coasting begins at N and continues to B, where brakes are applied.

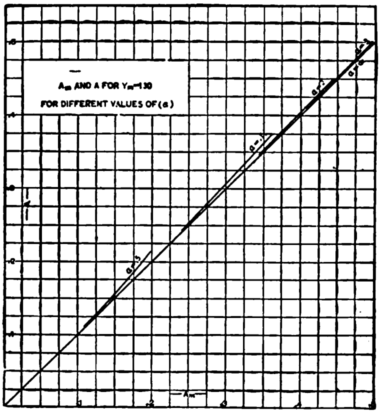


Fig. 28.—CURVE SHEET FOR DIFFERENT VALUES OF INITIAL ACCELERATION.

The ordinates multiplied by β give the velocity, the abscissæ multiplied by β give the time; hence the inclination of any line on this diagram is independent of β.

Correction to Type Curve. — This discussion and the curve sheets deduced from it, determine all the elements of the type curve, $OABC$. This type curve bears a certain relation to the motor curve $OMNBC$. The distance traversed in the first case will be greater than in the second by the equivalent of the area *MAN*. It is then possible to reduce each case for the motor curve to a corresponding case for the type curve, by applying a correction, calculated in the following manner:

Determine the area *MAN* of Fig. 21, for each (a), and for any desired number of points on the motor curve; call this area Δ; then $1.47\ \beta^2 \Delta$ is the distance in feet represented by the area.

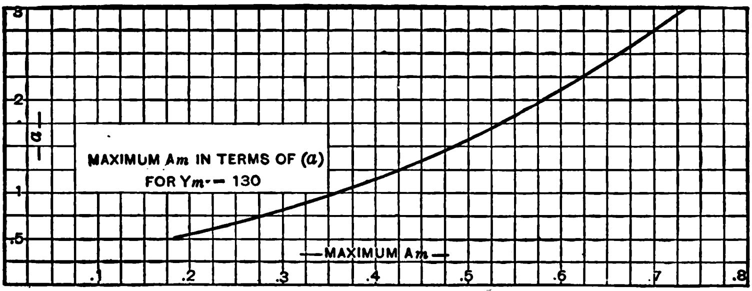


Fig. 29.—MAXIMUM A_m IN TERMS OF (a).

Let Y_t be the maximum velocity *AD* on the type curve;
Y_m be the maximum velocity *RN* on the motor curve;
A be the through acceleration on the type curve;
A_m be the through acceleration on the motor curve;
and X be $\overline{OC}$

Then
$$L = L' - 1.47\ \beta^2 \Delta$$
$$\beta^2 A\ X^2 = \beta^2 A X^2 - \beta^2 \Delta$$
or
$$A_m = A - \Delta / X$$
Put
$$\lambda = ax/T = Y_t/X \qquad (21)$$
then
$$A_m = A - \Delta (\lambda / Y_t)^2. \qquad (22)$$

Y_t is found from curve sheets, Fig. 24 et seq., and λ from curve sheet, Fig. 22, for any values of A, (a) and Y^m; A_m is then calculated, and plotted in terms of A, using the values of Δ previously calculated.

The values of A_m for all values of A, Y_m and (a) have been determined in this way. The corrections for values of Y_m less than 130 are too small to be taken into account. The minimum energy required for all schedules and for all values of (a) is practically at $Y_m = 130$, as I shall show; in some cases greater values of Y_m give slightly less energy, but the difference is so trifling that I have used only this value in discussing the energy relations.

Curve sheet, Fig. 28, shows A_m in terms of A, for $Y_m = 130$, and for the different values of (a).

Maximum A_m. — The maximum A_m is evidently attained when acceleration is continued to the braking point and is represented by $OMNC'$ (Fig. 21). To calculate this maximum, OR is found from curve sheets, Fig. 22 et seq., RC' from the known values of RN and (c); — then $RC'/OC' = z/T$.

Curve sheet, Fig. 22, gives at once the values of A, and curve sheet, Fig. 28, the corresponding A_m. The values so calculated for Y_m = Fig. 130 only, are given on curve sheet, Fig. 29.

Example. — An example best shows the use of these curves:

Suppose Schedule speed = 16.5 m.p.h.
Distance between stops = 2,000 feet.
Time of stop = 15 seconds.

Then, Total time from start to start = 82.4 seconds.
Running time = 67.4 seconds.
Average velocity, V = 20.2 m.p.h.

$$A = V/T = .3$$

Curve sheet, Fig. 29, shows that (a) must be greater than .75; take $a = 1$; then curve sheet, Fig. 26, determines the velocity curve up to the point N (Fig. 21); for $Y^m = 130$, curve sheet, Fig. 28, gives $A = .305$; and from curve sheet, Fig. 22,

$$x/T = .477$$
$$y/T = .130$$
$$z/T = .393.$$

Maximum velocity on type curve = .477 × 67.4 = 32.3 m.p.h. Maximum velocity on motor curve = 32.2 × 130/136 = 30.7 m.p.h. Velocity at braking = 3 × .130 × 67.4 = 26.3 m.p.h.

Energy Input. — The energy at the car axle has already been determined; the electric input depends upon the method of motor control and the efficiency of the motor. I assume that series-parallel control in two steps is used. The power at the axle at rated velocity, point M, is then 0.85 P_o, where P_o is the rated power, and the power at the axle is proportional to the speed. The change from series to parallel is assumed to occur at half speed; the efficiency of the motors will be about 70% when in series and carrying rated current. With these figures the input up to $v = \beta\, 100$ is

$$W_0 = .8\, P_0 t_1 \tag{23}$$

and the output is

$$W' = .425\, P_0 t_1,$$

hence the efficiency up to rated velocity — while resistance is in circuit — is 53%.

Substituting for P_0 its value from equation (18), and $t_1 = 100/\beta$, the input of electric energy per ton up to the point M is

$$W_0 = 475\,(1 + b/a)\beta^2. \tag{24}$$

The values calculated from this equation are included on curve sheets, Figs. 24, 25, 26, and 27, giving the energy up to the point $v = \beta\ 100$. The input from the point M to the point N on the motor curve is taken directly from curve sheets, Fig. 24 et seq., depending upon the initial acceleration.

Velocity Constant, β. — Energy, power, and distance all involve the velocity constant β. The values of β can be expressed in terms of the distance traversed for all values of the through acceleration as follows:

$$.682\ L = AT^2$$

$$T = \beta X$$

and

$$X = Y_t/\lambda;$$

hence

$$\beta = \left(\frac{.682\ L}{A}\right)^{\frac{1}{2}} \times (\lambda/Y_t) = \left(\frac{.682\ L}{A}\right)^{\frac{1}{2}} \frac{a}{Y_t}\frac{x}{T} \qquad (25)$$

The energy used is proportional to the product of β^2 by the ordinates of the energy curves on sheets, Fig. 24 et seq. There will, therefore, be a different multiplier for each value of (a) and of Y_m.

Limiting the discussion to $Y_m = 100$ and $Y_m = 130$, the following table gives the values of the energy per ton in terms of β.

TABLE 10. — *Energy up to $v = \beta$ 100 and $v = \beta$ 130.*

(a)	$v = \beta$ 100	$v = \beta$ 130
.5	665 β^2	1115 β^2
1.	570 "	865 "
1.5	535 "	800 "
2.	522 "	767 "
3.	507 "	7322 "

From equation 25, β can be calculated for all values of A and (a), and for all values of Y_m. The simplest way to calculate these values is, first to assume values of A and (a); then, since $Y_m = 130$, Y_t is fixed; and lastly the value of x/T is taken from curve sheet, Fig. 22.

β is proportional to $L^{\frac{1}{2}}$; β^2 to L; hence the energy used is proportional to the distance for any given value of A. The values of β have been calculated from this equation for all values of Y_m; I give here, however, a curve sheet showing these values only for $Y_m = 130$, for the reason explained below.

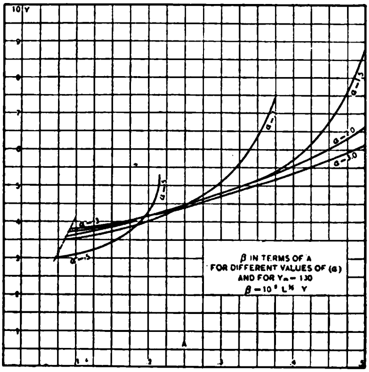


Fig. 30.—β IN TERMS OF A.

This sheet covers the entire range of values of β for $Y_m = 130$, from the minimum to $A = .5$; this value of A is greater than is possible in practice.

The energy for all schedules can now be calculated by multiplying β^2 from curve sheet, Fig. 30, by the constants given in Table 10. The values so calculated for $Y_m = 130$ are plotted on curve sheet, Fig. 31.

I have calculated the energy consumption in this manner for all values of Y_m and for the different values of (a) and of A, up to $Y_m = 160$. To give all these results is of no consequence; suffice it to say that in most practical cases the energy input is substantially a minimum for $Y_m = 130$.

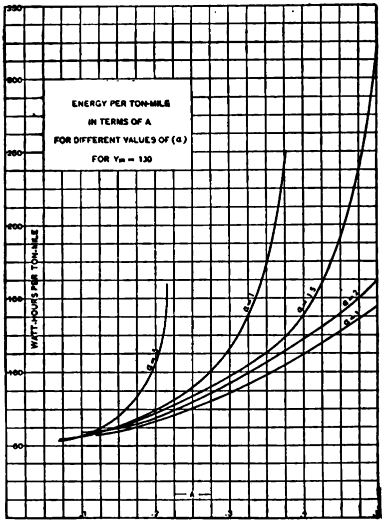


Fig. 31.—ENERGY PER TON-MILE IN TERMS OF A.

Table 11 shows the relative energy for different values of Y_m for $(a) = 2$, in terms of energy for $Y_m = 130$, as 100%, for the various values of A.

TABLE 11. — *Relative Energy for Different Use of Motor Curve for (a) = 2, in Terms of Energy for* $Y_m = 130$, *as 100%.*

Y_m	A				
	.5	.4	.3	.2	.1
160	....	102%	97%	91%	89%
150	104%	101.5	98	93	93
140	100	100	99	95.5	95
130	100	100	100	100	100
120	103.5	106.5	106.5	105.5	105
110	110	112.5	113	112	108
100	119	122	121	128	120

This table is a fair example; it shows that the difference between the energy for 130 and greater values of Y_m is comparatively small. In the rest of this discussion, I use this value of Y_m only, and the values of β are for this reason given only for $Y_m = 130$.

Curve sheet, Fig. 31, gives at once the answer to all questions regarding the energy required for any schedule; it shows clearly how slight is the saving in energy effected by the use of rapid accelerations. For instance, for $A = .25$, the energy for an acceleration of one mile per hour per second is 17.2 wh.; for an acceleration of 3 m.p.h./sec., it is 14.5 wh.; that is, increasing the acceleration in the ratio of three to one diminishes the energy required only 16%.

Motor Capacity. — This discussion has been based throughout on the assumption that the motor operates at the rated capacity on the one-hour basis, when at the point *M* (Fig. 21). On this assumption, the following table gives the capacity of the equipment required:

TABLE 12.

(*a*)	$P_0 = \beta \times$
.5	14.9 kw./ton
1.	25.5 "
1.5	36.3 "
2.	47. "
3.	68. "

These are the starting values of the power curves on sheets, Figs. 24, 25, 26, and 27, and may be considered the rated capacity of motors required, in so far as this rating is determined by commutation.

Heat Losses. — Referring to Fig. 21, the heat losses in the copper up to the point M are directly proportional to the time, since heat is liberated at a constant rate. The magnetic flux density in the motor is constant up to this point; if the core loss were proportional to the speed, the average loss would be one-half of the loss at rated speed; on the other hand, if the core loss were proportional to the square of the speed, the average loss would be one-third of the loss at rated speed; hence the average core loss up to the point OM is between 33 and 50% of this loss at rated speed. The actual variation of the core loss with speed lies between these two values. I assume it to be equal to 41.0% of the loss at rated speed.

I find from an examination of a number of modern tramway motors that at rated output P_o the average core loss is 3.4%, and the average copper loss 8.6%, — a total for the average loss of 12%, excluding friction losses. These losses are the average of a somewhat different group of motors from those used in preparing the general motor curve, hence the small loss left for friction; for this last group the efficiency is 83% instead of 85%. The average loss up to $v = \beta$ 100 is then 10% of the rated capacity, and is independent of initial acceleration.

From M to N on the motor curve, I have determined the losses from curves of separate losses; for the same group of motors the average of the total heat loss from $v = \beta$ 100 to $v = \beta$ 130 is 8.5% of the rated capacity.

Up to $v = \beta$ 100, the average loss is 10% of P_o; for $v = \beta$ 130, the values of t_1 and t_2 are taken from sheets, Figs. 24, 25, 26, and 27, and the average loss over the total time $(t_1 + t_2)$ calculated; it will be found to be constant for all values of (a), as it should be, and equal to 9.4% of rated capacity.

The average rate of heat dissipation will be:

$$.1\ P_0, \quad \text{up to } v = \beta\ 100$$

and

$$.094\ P'_0, \quad \text{up to } v = \beta\ 130.$$

The rates continue for the times t_1 and $(t_1 + t_2)$, respectively; during the rest of the cycle the motors are radiating heat; hence these rates referred to the total time T, are

$$.1\ t_1/T \times P_0, \quad \text{up to } v = \beta\ 100,$$

$$.094\ (t_1 + t_2)/T \times P'_0, \quad \text{up to } v = \beta\ 130,$$

and as percentages of the rated capacities in the two cases, are

$$10\ t_1/T\% \qquad \text{up to } v = \beta\ 100. \qquad (26)$$

$$9.4 \times (t_1 + t_2)/T\% \qquad \text{up to } v = \beta\ 130. \qquad (27)$$

These are the average rates for the entire time from start to stop, and by comparison with the average loss that such a motor will stand continuously without excessive heating, determine whether the motors are running above or below their rated capacity; or conversely, determine what the capacity on a one-hour basis must be, so that when operating in this way they will not overheat.

Equation (27) can be written

$$9.4\ (1 + t_2/t_1)\ t_1/T\%.$$

But (Fig. 21),

$$t_1 = \overline{OP} = OD\ .\ MP/AD$$

$$= x \times 100/Y$$

and

$$t_1/T = x/T\ (100/Y);$$

hence the total heat loss up to the velocity β 130 averaged over the entire time T is

$$9.4\ (1 + t_2/t_1) \times 100/Y \times x/T\% \qquad (28)$$

where x/T is taken from curve sheet, Fig. 22, for the proper values of A and (a). In this deduction it is assumed that $A_m = A$.

Hour Rating. — The one-hour rating of a tramway motor is much in excess of the continuous capacity; approximately such a motor will carry its rated output for 25% of the total time, that is, for one minute out of four; the heat generated at rated capacity for one-quarter of a complete cycle will bring it to its rated temperature. It is assumed that the cycles are repeated at such intervals that a permanent régime is attained. This is only an approximation, but is a fair one, if the percentage be more or less than 25; and the conclusions can be altered to accord.

As the average heat losses at rated load are 12%, it follows that such a môtor can dissipate continuously 3% of its rated capacity; when the average rate is over 3% the motor is overloaded.

Since the average loss that a motor will stand is equal to 3%, it follows that the maximum value of (x/T), or $(x/T)_0$ is

$$(x/T)_0 = 3/[9.4\ (1 + t_2/t_1)] \times Y/100.$$

Curve sheets, Figs. 24, 25, 26, and 27, give then

TABLE 13.

(a)	$(x/T)_0$
.5	0.249
1.	0.260
1.5	0.265
2.	0.270
3.	0.271

For $Y_t = 100$, the limiting value is $(x/T)_0 = .3$ for all values of A and (a).

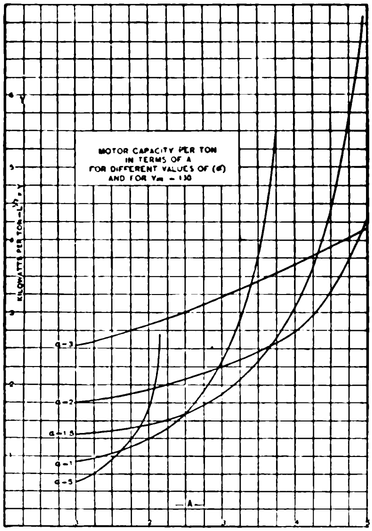


Fig. 32. — MOTOR CAPACITY PER TON IN TERMS OF THROUGH ACCELERATION.

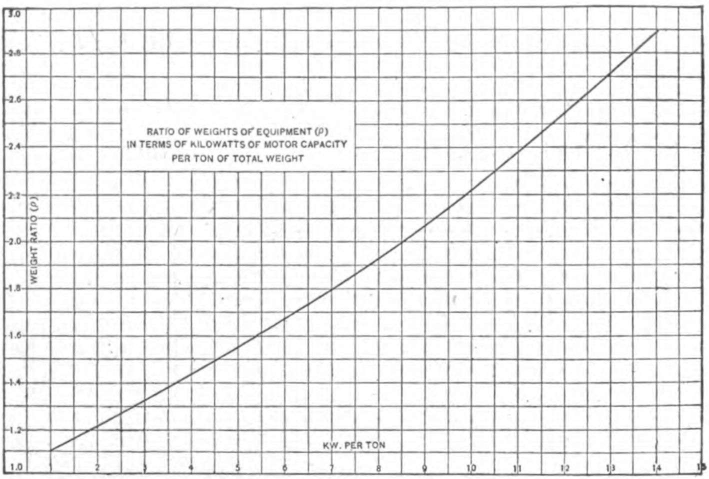


Fig. 33. — RATIO OF WEIGHTS OF EQUIPMENT IN TERMS OF KILOWATTS OF MOTOR CAPACITY PER TON OF WEIGHT.

This means that for schedules in which $x/T > .3$, in one case, and for $x/T > .249$ et seq., in the other, the capacity must be greater than the capacity determined by commutation, that is, greater than the values of Table 12, in the ratio of $(x/T)/(x/T)_0$; for $x/T < .3$, or less than the values of Table 13, commutation determines the capacity.

The motor capacity necessary both to avoid overheating and to keep within commutation limits, can now be calculated from these data. Table 12 gives the capacity required on the assumption that commutation is the only limit to output, and on the further assumption that the hourly rated capacity is the practical limit determined by commutation. These values multiplied by the ratio $(x/T)/(x/T)_0$ give the capacity in all cases, with the limitation that the capacity shall not be less than that of Table 12. Then,

$$\text{Motor capacity} = 14.9\,\beta \times (x/T)/(x/T)_0 \text{ for } a = .5 \quad (29)$$

and, $\text{Motor capacity} > 14.9\,\beta$ for $a = .5$.

The coefficient for other values of the initial acceleration is given by Table 13.

The capacity of the motor, as determined by this equation, has been calculated for all values of A and (a), and curve sheet, Fig. 32, gives the kilowatts per ton, considering both commutation and heating, for $Y_m = 130$.

For the lowest acceleration, $(a) = .5$, heating is the limitation for all values of A; for the higher values of (a), commutation is the limitation for the low, and heating for the high, values of A."

Weight of Equipment. — Curve sheet, Fig. 33, shows the ratio of weights of equipment (ρ) in terms of kilowatts of motor capacity per ton of total weight.

CHAPTER IV.

ELECTRICAL FEATURES (Continued).

SCHEDULES AND LOAD DIAGRAMS.

Discussion of Schedules. — The initial rate of acceleration deserves great attention when selecting a motor equipment for local service. There has been a tendency of late, to use high initial rates of acceleration, with a view to lowering the watt hour consumption per ton mile for a given schedule. A rate of acceleration of 1.5 seems to be the best. This rate of acceleration is the standard for many railways throughout the country; and curve sheet, Fig. 31, of Hutchinson's method, makes the reason plain. For instance, with a through acceleration of .3, the watt hours per ton mile are approximately 115 for an initial rate of acceleration of 1. Where the initial rate of acceleration is 1.5 the watt hours per ton mile become 98, and where a is 2 the watt hours are approximately 92. When we consider that the motor equipment is directly proportional to the rate of acceleration, or, in other words, the current used while accelerating, it is obvious that while it would be advisable to consider a difference in watt hour consumption of 115 compared with 98, it would be hardly justifiable to consider the difference between 92 and 98. The increased motor capacity, namely, in the latter case at 2 m.p.h. / s., would not be economic, unless the motor had a low core loss.

The heating of a railway motor is what determines its capacity. If the motor is overloaded, the armature coils will burn out, causing delay and expense. Furthermore, there should be a reasonable proportion of coasting. Unfortunately, delays at stations due to loading and unloading of passengers, result in the motorman's eliminating the coasting, obtain a higher through acceleration, consume more energy, and overheat the motors. On long grades there is a tendency for a motor to overheat. The temperature curves published by the Westinghouse Mfg. Co., on their characteristic motor sheets showing the time a motor will carry a given overload, are useful when considering this problem.

Energy Consumption at Maximum Speed. — It is interesting to calculate the actual energy used in propelling a car at a given speed from one station to another, neglecting the approximate 65% of energy used in braking the car. This may be done as follows:

When a train is moving at its maximum speed on a level track with no curves, the tractive effort in lbs. per ton, or the propelling force of the motor, is numerically equal to the train resistance forces of friction and windage in lbs. per ton. If at any speed the tractive effort in lbs. per ton is greater than the train resistance in lbs. per ton the train will accelerate, provided no curves or grades exist. The correction for grades would be 20 lbs. per ton per % given and for curves about .6 lb. per ton per degree of curvature. Having from the formulæ determined the train resistance in lbs. per ton at the required maximum speed for the train under consideration, the watt hours per ton mile may be determined as follows: The speed in miles per hour multiplied by 5,280 feet will yield the distance passed over in one hour. This distance multiplied by the train resistance in pounds per ton at this speed will give the foot pounds of work performed in one hour upon each ton of train weight. This quantity divided by 33,000 × 60 will yield the horse-power of work performed per hour. Multiplying this quantity by 746 will convert it into watts, giving the watts per hour consumed. Dividing this quantity by the distance in miles passed over in one hour, which will be equal obviously to the speed in miles per hour, will yield the watt hours per ton mile. This is based on the assumption that the speed is constant, that the track is level, and that no curves exist. Performing this calculation we find that the train resistance in lbs. per ton at a given constant speed multiplied by the factor 1.9893 will give the watt hours per ton mile necessary to perform the service. This transition may be expressed as follows:

$$\text{Watt Hours per Ton Mile} = \frac{S \times 5280 \times r \times 746}{33{,}000 \times 60 \times S}$$

$$\text{Watt Hours per Ton Mile} = 1.9893\, r$$

where S = Speed in miles per hour,
r = Train Resistance in lbs. per ton.

Example. — Given an 8-car train, weighing 45 tons per car, of 110 square feet cross-section, moving at a constant speed of 30 miles per hour, what should be the energy consumption in watt hours per ton mile? The answer is 14.9 ($1.9893 \times 7.5 = 14.9197$). For this condition the train resistance curves obtained by Mr. Armstrong may be used; see page 30. If the conditions were different, the formulæ should be used.

For approximate calculation the Westinghouse Electric Mfg. Co. have compiled a set of curves, Fig. 34, giving the approximate tractive effort and h.p. required to operate cars of different weights under different conditions of grade and speed.

Graphic Time Table. — Having determined, as indicated in Chapter I, the number of miles of track, the frequency of traffic, and the size, type, and seating capacity of cars for a given service, the motor capacity may be determined as indicated in Chapters II, III, and IV. The question of distribution of cars should next be considered.

A proposed time table is prepared, such as will accommodate the possible traffic most economically. A clear con-

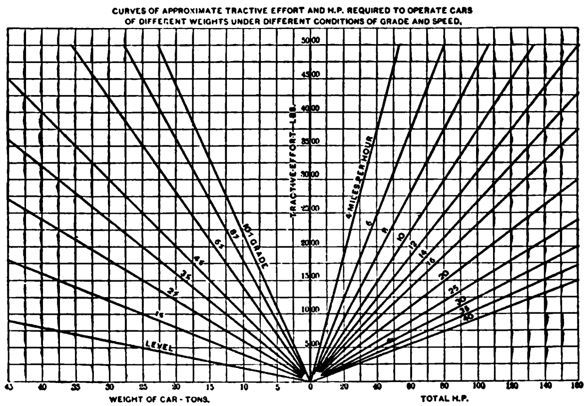


Fig. 34.—CURVES OF APPROXIMATE TRACTIVE EFFORT AND H.P. REQUIRED TO OPERATE CARS.

ception of the distribution of trains during a day may be formed by means of what is termed a *graphic time table.* This table is plotted in terms of station stops or distance and time values representing the various hours of the day. The location of each train during the day at the various time intervals is indicated on this chart. Upon such a chart, Fig. 35, are shown many features such as the passing of trains, location of turnouts on single-track roads, variations of speed of trains, changes in road bed due to curves or grades, and many other features. The following is an abstract of the notes of an excellent lecture pre-

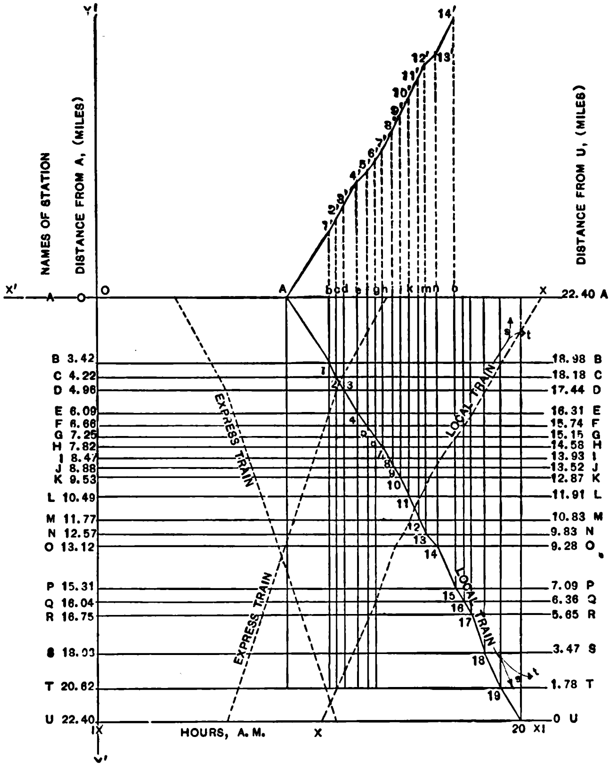


Fig. 35.—GRAPHIC TIME TABLE.

pared on the subject by Mr. C. O. Mailloux, for the students of the Polytechnic Institute of Brooklyn.

"The easiest way to learn to read between the lines of a time table, is by graphical methods (Fig. 35).

The names of stations given in a time table symbolize the distances, which may be plotted as ordinates. The hours given in a time table represent time values, which may be plotted as abscissæ.

On plotting, we have a series of points which, when connected by straight lines, give a form of "distance-time curve." The straight line connecting two points is only a rough, first approximation. The line between two points has, at least, two bends or points of inflection, and assumes a general "S" form.

The location of distance-time curve will be in fourth Cartesian quadrant, when distance values are plotted downward, and in first quadrant, when distance values are plotted upward. In practice both are used, in order to represent train movement in both directions on the same sheet.

In the expressions "distance time," "velocity time," "speed time," etc., all of which are frequently used, the *first* word always denotes the *function* or the *ordinate* of the curve; the *second* word represents the *independent* variable.

Points of intersection for D–T curves on a graphical time table indicate points at which trains pass each other. For a single-track road, these points must occur at stations.

General inclination or slope of D–T curve indicates velocity.

The trigonometrical tangent of a D–T curve is equal numerically to the velocity.

When S = Distance, in miles,
T = Time, in hours,
V = Average speed (m.p.h.),
v = Velocity (m.p.h.),

we have,
$$V = \frac{S}{T} = \frac{\Delta S}{\Delta T},$$
$$v = \frac{ds}{dt}.$$

Changes in schedule speed, or in speed at different points of the run, are generally due to obvious causes.

Difference in schedule time as affected by difference of up-grade in one direction is generally evidenced by a difference between the *D–T* curves for outgoing and returning trains.

The effect of railroad curves on speed is shown usually by some variations in the *D–T* curves for both outgoing and returning trains.

The influence of frequent stops on *D–T* curves is also evidenced by similar effects.

For complete graphical time tables the sheet must be of sufficient size for a distance scale corresponding to the whole length of the line and for a time scale equal to 24 hours. One *D–T* curve is required for every train.

Ordinary railroad time tables are, in reality, only a transcription or tabulated form of graphical time tables.

Graphical time-tables were used as far back as 1850. See preface of "A Graphical Method of Solving Algebraical Problems," by George L. Vose, in Van Nostrand's Science Series, 1875. This book contains a reference to the practical use of graphical time tables on railroad systems.

Comparing the *D–T* curve with the *V–T* curve for return trip of local train, the *V–T* curve in this diagram is plotted from data in Table 15, column 7. See Table 14 for outgoing train. It is impossible, however, for speed to change abruptly in the manner shown by *V–T* curve.

This *V–T* curve therefore affords conclusive proof of imperfection or incompleteness of the *D–T* curves, shown in Figs. 35 and 36.

There is necessity of a larger scale of time values (abscissæ) for a correct representation of *D–T* curve. Since the time unit used in the measure of acceleration is a second, the scale of time values should be sufficiently large to represent differences at least as small as five seconds, and often still smaller. The scale should be large enough to show one

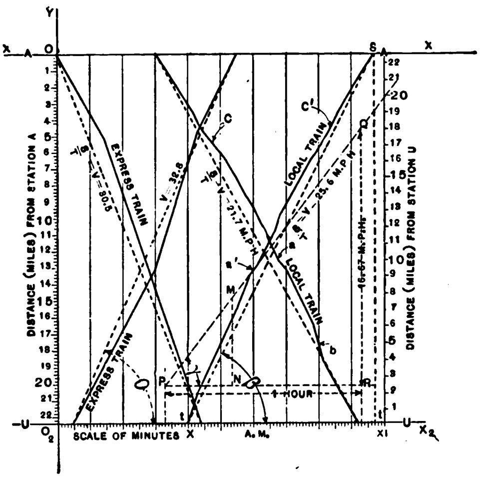


Fig. 36.—GRAPHIC TIME TABLE.

second or even fractions of a second, when accurate work is desired.

The first important correction in the *D–T* curve is the allowance for time of stops at stations. This introduces a short horizontal line between the sloping lines.

The second correction is a gradual change from horizontal to slope form, to take into account acceleration and allow for retardation.

TABLE 14. — *Analysis of Data from Printed Time Table.*

I.	II.	III.	IV.	V.	VI.	VII.
Station.	Distance (Miles). S	ΔS	Time. Hours.	Δt in Minutes.	Δt in Hours.	$\frac{\Delta S}{\Delta T} = v'$ m.p.h.
A	0		9.50			
		3.42		11	0.183	18.69
B	3.42		10.01			
		0.80		2	0.033	24.24
C	4.22		10.03			
		0.74		2	0.033	22.42
D	4.96		10.05			
		1.13		4	0.067	16.87
E	6.09		10.09			
		0.57		2	0.033	17.27
F	6.66		10.11			
		0.59		2	0.033	17.88
G	7.25		10.13			
		0.57		2	0.033	17.27
H	7.82		10.15			
		1.06		3	0.050	21.20
J	8.88		10.18			
		0.65		2	0.033	19.70
K	9.53		10.20			
		0.96		2	0.033	29.09
L	10.49		10.22			
		1.28		3	0.050	25.60
M	11.77		10.25			
		0.80		2	0.033	24.24
N	12.57		10.27			
		0.55		3	0.050	11.00
O	13.12		10.30			
		2.19		5	0.083	26.39
P	15.31		10.35			
		0.73		2	0.033	22.12
Q	16.04		10.37			
		0.71		2	0.033	21.52
R	16.75		10.39			
		2.18		3	0.050	43.60
S	18.93		10.42			
		1.69		5	0.083	20.36
T	20.62		10.47			
		1.78		5	0.083	21.45
U	22.40		10.52			

TABLE 15. — *Analysis of Data from Printed Time Table.*

I.	II.	III.	IV.	V.	VI.	VII.
Station.	Distance (Miles). S	ΔS	Time. Hours.	Δt in Minutes.	Δt in Hours.	$\frac{\Delta S}{\Delta T} = v'$ m.p.h.
U	105.13		10.00			
		1.78		3	0.050	35.60
T	106.91		10.03			
		1.69		4	0.067	25.23
S	108.60		10.07			
		2.89		6	0.100	28.90
Q	111.49		10.13			
		0.73		2	0.033	22.12
P	112.22		10.15			
		2.19		4	0.067	32.69
O	114.41		10.19			
		0.55		2	0.033	16.67
N	114.96		10.21			
		0.80		2	0.033	24.24
M	115.76		10.23			
		1.28		3	0.050	25.60
L	117.04		10.26			
		0.96		2	0.033	29.09
K	118.00		10.28			
		0.65		2	0.033	19.70
J	118.65		10.30			
		1.06		3	0.050	21.20
H	119.71		10.33			
		0.57		2	0.033	17.27
G	120.28		10.35			
		0.59		2	0.033	17.88
F	120.87		10.37			
		0.57		2	0.033	17.27
E	121.44		10.39			
		1.13		4	0.067	16.87
D	122.57		10.43			
		0.74		2	0.033	22.42
C	123.31		10.45			
		0.80		2	0.033	24.24
B	124.11		10.47			
		3.42		10	0.166	20.60
A	127.53		10.57			

Deflections in the *D–T* curve between stopping points represent variations in speed.

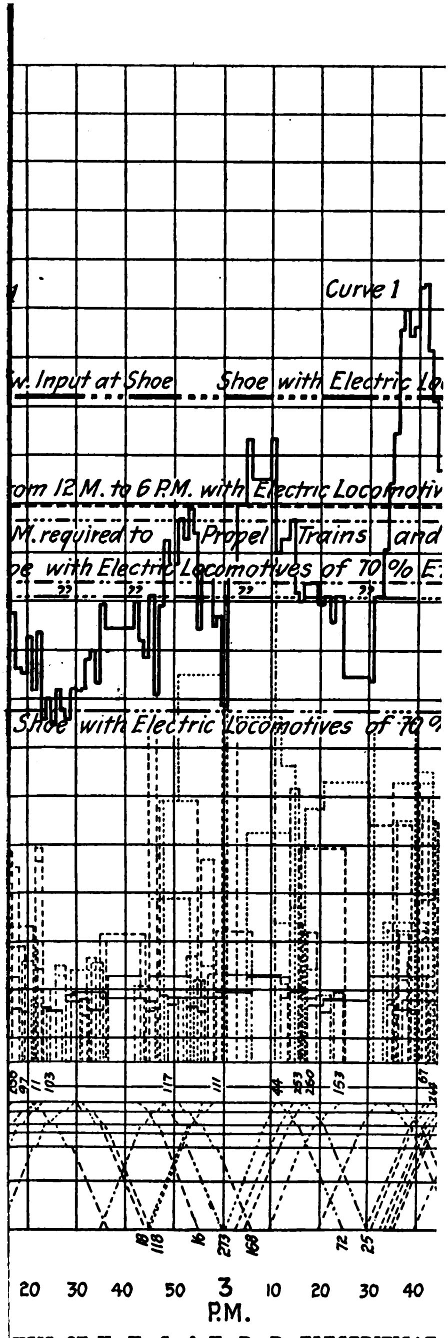
The correct form of the *V–T* curve and the corresponding form of the *D–T* curve should be an irregular and broken line.

Energy Curves, Load Diagrams. — Granting that all preliminary problems relating to schedule, size of cars, control and motor capacity have been considered, the next step is to calculate the amount of electrical energy required by the cars, and to decide upon the most economical method of generating and distributing this energy.

Starting with a single car or train unit, speed-time and energy curves should be plotted for an entire day representing complete service. From sets of these curves corresponding to various cars, may be determined their average watt hour per ton mile energy consumption. This may be determined mathematically as outlined in Hutchinson's "Method of Determining Motor Capacity" for a level tangent track, but in actual practice, where the contour and profile of the proposed road is known, the former method is the most desirable.

Having determined the average energy consumption per ton mile, some idea of the total required energy consumption per day may be gained; knowing the car mileage, facilitates this determination. Furthermore, when the load factor of the proposed service is determined, the installed capacity necessary will at once be apparent.

In order to determine the load factor it is necessary to plot graphically on a chart the energy consumption of each train or single car for a single typical day, the abscissa for this chart being time and the ordinate kw. The kw. values are obtained from the energy curves plotted in



YSIS OF N. Y. C. & H. R. R. ELECTRIFICAT

connection with the speed-time curves for the individual train units as previously referred to. The energy values may be taken at as frequent intervals as the character of the service necessitates. For instance, with trunk-line

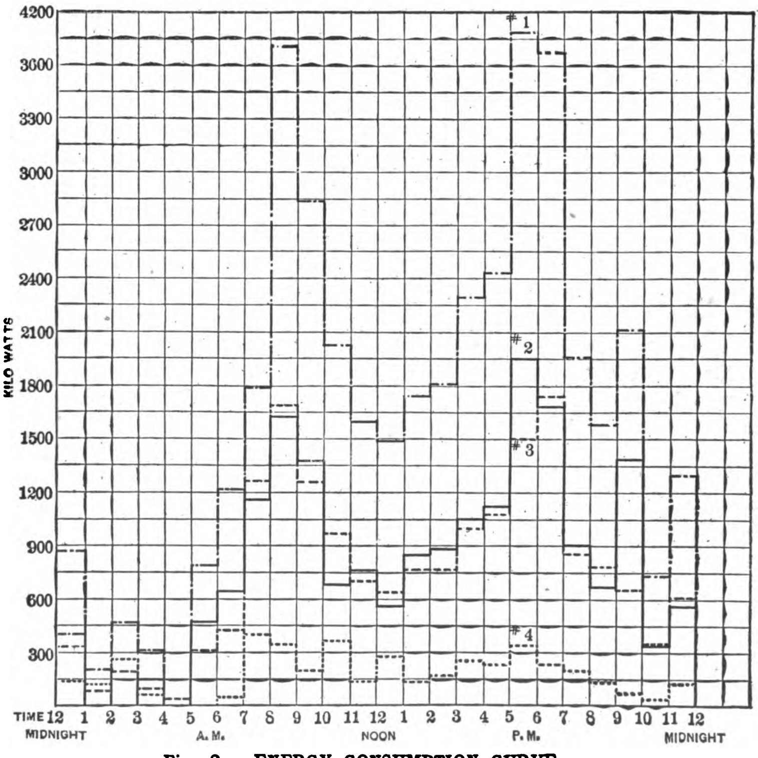


Fig. 38.—ENERGY CONSUMPTION CURVE.

service the power is "on" for a much longer period of time than with an interurban service, and consequently the time intervals plotted may be reasonably long. With trolley service the period in which the power is "on" is quite short.

When the train energy values for an entire day's service have been plotted on this chart, the values should be summed up, and a curve termed "a load diagram" will be the result. Load diagrams are plotted on large propositions for several days so as to obtain a fair average value. Sometimes it is interesting to pass curves through the points representing the energy consumption of the individual trains. From the load diagram the average load values may be quickly determined by means of a planimeter, and with the average value and the maximum value the load factor is at once apparent.

This method was used on a large scale by Mr. Bion J. Arnold when making a preliminary report on the proposed electrification of the N. Y. C. and H. R. R. R. Curve sheet, Fig. 37, represents one of the curves plotted by Mr. Arnold, showing the energy consumption for the proposed electric locomotive service, single-car units being plotted individually. The total approximate energy consumption for the whole service is represented in curve sheet, Fig. 38. Referring to curve sheet, Fig. 38, curve 1 is a condensed load diagram of the entire service. Curves 3 and 4 of curve sheet, Fig. 37, represent the service of the switching, shot train and return engine service. In the problem treated by Mr. Arnold the purpose was to substitute electric locomotives for existing steam service. Dynamometer tests were made upon steam locomotives in use, and the results were compared with proposed electric service. This problem was discussed by Mr. Arnold in a paper presented before the American Institute of Electrical Engineers on June 19, 1902.

CHAPTER V.

POWER HOUSE AND SUB-STATION LOCATION.

COST DATA AND COST FACTOR.

Location of Main Power House. — It is impossible to give any general solution for the location of the main power house of a railway proposition except that it should be as near as possible to the load center of the system. When treating such problems it is customary to consider several sites near the load center with reference to such elements as cost of real estate, use of river water for cooling condensers, transportation of coal and ashes, insurance, and proximity to resident sections. The method of generation and distribution to be used depends upon the distance over which the system extends. It is the purpose of the author to treat of this phase of the subject in a detailed manner in a subsequent volume.

Location of Sub-Stations. — The location of sub-stations for a railway proposition is usually determined by certain fixed centers of load, which develop with almost every proposition. As an example, assume that we have an elevated railway consisting of a few branches. If the traffic is heavy, it is generally desirable to locate sub-stations near the junctions of the two structures, and to use the elevated structure for the return circuit. This results in great economy of copper, for if a 12% loss in the feeders is allowable, 9% of this can be in the positive feeders and 3% in the negative feeders. It is found in practice that the carrying capacity of an elevated structure, when well bonded, is very great. If the voltage at the consuming point is low, it seems that no matter how much additional copper is added to the positive feeders the voltage rises only slightly. Where tunnels, sheathed in metal, are used, it is customary to employ the sheathing of the tunnel for the negative circuit.

Where the traffic on a road is light and the system is not complicated, Kelvin's law may be used to advantage in the location of sub-stations as shown by Mr. C. W. Ricker in a paper presented before the American Institute of Electrical Engineers, Dec. 15, 1905. This paper is an excellent treatment of the subject and is given here in detail.

C. W. Ricker's Method of Sub-Station Location.—"No attempt will be made in this paper to define the conditions under which indirect distribution, through the medium of transformer sub-stations, is more economical than direct distribution from one or more generating stations containing prime movers. It is assumed that because of the size of the railways to be considered, and the local conditions determining the cost of generating power, the indirect method of distribution has been selected as offering the best economy in commercial operation, and an attempt will be made to outline a general method for determining the number and location of sub-stations.

In many and perhaps the majority of cases, a general solution of this problem is quite impossible. Most of the large electric railway systems now in existence are the result of development not foreseen by their original projectors, and there is little reason to believe that future systems will differ in this respect. They will probably grow by extensions and consolidations depending upon the distribution and development of local centers of industry and population.

For convenience of discussion, electric railways large enough to require indirect distribution may be classified as follows:

1. Large simple networks, serving a single community.

2. Long single lines or groups of such lines, connecting separate communities or different parts of a very large one.

3. Complex networks, with connecting lines, serving a city and its suburbs.

4. Several networks with long connecting lines, serving separated communities.

Railways of the last-named class are often consolidations of the local systems of neighboring cities or towns, and interurban lines which frequently furnish power for lighting and general uses in the towns served. There are usually well-marked centers of load which, together with local business conditions, determine the position and equipment of sub-stations.

Railways of class 3, those serving a large city and its suburbs, are also most often the result of the consolidation of separate lines and networks, and while the large central network belongs in class 1, the outlying districts present a difficult problem to the engineer, for he must anticipate the direction, character, and sequence of growth so as to provide against it. This requires an intimate knowledge of local conditions, both industrial and social, and in addition he has need to be something of a prophet to foresee the changes which the building of new lines and the starting up of new works may produce. The problem is a local and particular one, and must depend mainly upon individual judgment for its solution.

Classes 1 and 2 can be treated more generally. Take first the case in which a large network, or long line or group of lines, is contained wholly within a large city, so that a fairly uniform schedule can be operated over the whole, and the mean load upon each mile of road is approximately uniform throughout the system, at any given time. It is required to adjust the cost of losses in the primary distribution, the secondary distribution, including the track, and the sub-stations, the fixed charges upon each of these three divisions, and the cost of sub-station attendance, so that their sum shall be a minimum, with due regard to the conditions of regulation and continuity of service.

As the density of the load in such a system is very great, the unit of sub-station equipment may be made so large that at the time of least load, one unit per sub-station may be operated at or near its best efficiency. Hence the sub-station losses per kilowatt hour may be considered constant.

The aggregate capacity of the sub-stations will equal the capacity of the generating station plus the sub-station reserve capacity, if any is necessary, which will not exceed one unit per sub-station. The greater the distance between sub-stations, the larger the sub-station unit will be; hence the cost of sub-station apparatus will increase as the number of sub-stations increases, until the largest practicable unit is reached. The same is true of sub-station land and buildings.

The cost of sub-station attendance will depend only upon the number of sub-stations, as the same number of attendants is required in a small as in a large sub-station. If, however, the cost of land makes it necessary to double-deck the sub-stations, a sharp rise in the cost of attendance will follow, since the number of units becomes greater than can be placed on one floor.

When direct-current motors are used, the secondary voltage is fixed by conditions of standard practice. The secondary conductors may be proportioned by Kelvin's law, subject to the limiting condition that the lowest potential shall be enough to allow the required acceleration. As the number of sub-stations increases, the cost of the conductors will rapidly decrease. The energy losses in the conductors may be constant or decreasing. The primary distribution in this case must be by underground cables. The primary voltage will be determined by the relative cost of copper and insulation, and should be as high as is consistent with safety. Hence the losses per mean kilowatt in the primary distribution may be considered constant. The total weight of primary conductors will be practically independent of the number of sub-stations, depending upon the total energy and the mean distance of distribution, and may be determined by Kelvin's law.

To obtain the greatest reliability of service, each sub-station should be fed directly from the generating station by at least three cables; and in the case of a wide difference in the number of sub-stations considered, the total cost of cables and conduits would be somewhat greater with the larger number of sub-stations, as more and smaller cables would be required. Otherwise the cost of the high-tension distribution, and the losses in it, may be considered constant.

Neglecting those quantities which are constant, the fixed charges on sub-station land, buildings, and apparatus, and the cost of sub-station attendance increase as the number of sub-stations increases; the fixed charges on the secondary distributions decrease and the losses in the secondary distribution decrease or remain constant.

The various losses and charges upon which the solution of the problem depends may then be considered as constants or variables directly dependent upon the number of sub-stations and inversely dependent upon the distance between sub-stations. These quantities may be reduced to a common base of annual kilowatt hours. Curves representing them may be drawn with respect to the number of sub-stations as one coördinate, and a summational curve may be drawn which, if the premises are rightly chosen, will indicate the number of sub-stations at which the sum of the various charges is a minimum.

In a far greater number of railways the load is not uniform throughout the system. This is true especially of the long interurban railways using a comparatively small number of heavy train units. The load at any given time is concentrated upon parts of the system, or travels from end to end of the long lines. In such a system, the aggregate capacity of the sub-station apparatus in operation at any given time, is greater than that of the generators; hence the load factor of the sub-stations is unfavorable, and in most cases the power factor of the system is low.

In a solution by the method outlined in this paper, several new curves must be drawn in addition to those named: the first showing the all-day losses in the sub-station apparatus, which will increase with the number of sub-stations; the second showing the losses in the primary transmission lines, which will also increase with the number of sub-stations, due to the greater length of lines and to the lower power factor; the third showing the fixed charges on the primary transmission lines.

The last two curves are relatively much less important. It is possible, by compounding or automatic adjustment of fields, to keep the power factor of the synchronous converters very near unity, making the transmission losses more nearly constant, and independent of the number of sub-stations. In such systems it is neither usual, nor often practicable, to use separate feeders from the generating station to each sub-station; and the primary distribution is generally by overhead lines, supported on poles which are used for other conductors as well. But with all the sub-stations along a single line of railway, or a group of such lines connected to one transmission line, the additional cost of extending the same for a greater number of sub-stations will usually be but a small part of the whole expense. So, for a preliminary consideration of the problem, the last two curves may be omitted and the same quantities may be used as are considered in the solution for a road having a uniform distribution of load, with the addition of one containing the all-day losses of the sub-station apparatus.

In systems consisting of long lines with infrequent train service, the cost of attendance and all-day losses in converter sub-stations often becomes so great that the regulation in secondary conductors economically proportioned for standard direct-current voltage will not permit the operation of the required schedule. A common remedy is to set the sub-stations nearer together, though at the cost of operating economy.

If other conditions still make the use of standard direct-current equipment desirable, it would seem that lengthening the sub-station sections and using boosters would be economic. This has been found profitable in the supply of lines of less length from direct-current generating stations. The fixed charges on, and losses in the boosters should then be included in the curves of sub-station apparatus.

In method of sub-station location herein suggested, the usual type of converter sub-station, with direct-current, secondary distribution has been kept in mind, but the method is no less applicable to a complete alternating-current system with static sub-stations, in which case the curves of sub-station losses, attendance and fixed charges, all become flatter, while the higher trolley voltage available, permits a wider spacing of sub-stations, without exceeding the limiting conditions of regulation, all of which indicate a better efficiency of sub-station apparatus and secondary distribution in roads of low and non-uniform load density.

Example. — To show this method of treatment more clearly, a simple problem will be discussed by means of it. A typical interurban railway consisting of one long line has been selected, because it suffices to exhibit the method without excessive labor. No attempt has been made to determine exactly the quantities used, as in any problem they must be determined for the particular conditions encountered.

Assuming the following data, there is required the number of sub-stations to obtain the best operating economy.

Distribution . . . . Alternating-current — direct current.
Length cf line . . . . 60 miles.
Service . . . . . . Hourly in both directions, 20 hours per day.
Schedule speed . . . . 30 miles per hour.

Stops per single trip	10.
Cars on the line	4 for 18 hours, 2 for 2 hours.
Car hours per day	76.
Weight per car (approximate)	30 tons.
Mean amperes per car	135.
Mean square amperes per car	35,000.
Running current, multiple, per car	200 amperes.
Starting current, multiple, per car	200 amperes.
Track	Single, 80 rails.
Track resistance per mile	0.0313 ohm.
Sub-station power factor	1.
Resistance of copper per mil mile	54,750 ohms.
Weight of copper per mil mile	0.016 lb.
Price of copper per lb.	$.15.
Rate of interest	5%.
Annual fixed charges on sub-station buildings and land	7%.
Annual fixed charges on sub-station equipment	15%.
Cost of energy at sub-station alternating-current bus-bar	$.0125.

The secondary copper is assumed to be continuous and of uniform section from end to end of the line.

The sub-stations are arranged so that the drop in the secondary copper and track is the same at points midway between sub-stations and at the ends of the line, the end sections being three-fourths the length of the intermediate sections.

Assuming this line to be fed through different numbers of sub-stations, it is desired to draw the following curves, with the number of sub-stations as abscissas, and the total annual cost in dollars, as ordinates.

Annual charges on sub-station buildings and land.
Annual charges on sub-station equipments.

Annual charges on secondary conductors.
Annual cost of sub-station attendance.
Annual cost of sub-station losses.
Annual cost of losses in secondary conductors and track.

The cost of and loss in the primary distribution are assumed to be nearly enough constant, so that they may be neglected in a preliminary discussion; but if desired, curves representing them may be added to those enumerated. These quantities have been computed and the curves drawn, for the number and arrangement of sub-stations shown in Table 16.

Sub-Station Capacity. — With the service outlined, the maximum load of any sub-station will be that due to the starting of two cars at once, 800 amperes, lasting for a few seconds. With the largest number of sub-stations, the capacity of each has been made equal to one-half of this, allowing a momentary overload of 100% in case the whole load falls upon one sub-station. With the smallest number of sub-stations, the capacity of each has been made equal to the maximum load. In the intermediate arrangements, the capacity of each sub-station is graded between these limits in the proportion of the combined line and track resistance between adjacent sub-stations; this is very nearly proportional to the distance between the sub-stations.

Sub-Station Losses and Secondary Copper. — The mean all-day efficiency of the sub-stations of each arrangement was obtained by dividing the total output of the sub-stations by the total input. The total output was assumed constant at 6,669 kw. hr. The efficiency of each sub-station at the mean load of one car and at the mean load of two cars was computed from typical efficiency curves of synchronous converters and transformers, allowing 6% for losses when running idle. From these the mean rates of input and the total input were computed. From the all-day efficiency the cost of energy at the direct-current bus-bar was computed, for use in proportioning the secondary conductors by Kelvin's law.

The exact computation of the losses in the secondary conductors is very laborious; to approximate these losses the load was assumed to be fixed at its mean distance from the sub-station, one-quarter section, and the resistance of the secondary copper multiplied by the car hours per section, and the mean square current per car. The annual cost of the secondary copper was taken at 6% to cover interest and cost of reclaiming. The secondary copper was proportioned by Kelvin's law, for each arrangement of sub-stations as follows:

$$\frac{35{,}000 \times \text{car hr. per year} \times \text{res. per mile copper} \times \text{length section} \times \text{cost kw. hr.}}{4{,}000}$$

$$= \frac{\text{wgt. mil mile} \times \text{res. mil mile} \times \text{length section} \times 15 \times 6}{\text{Res. per mile copper} \times 10{,}000}$$

$$\text{Res. per mile copper} = \frac{0.95}{\sqrt{\text{car hr. per year} \times \text{cost kw. hr.}}}$$

The annual loss in the secondary conductors and tracks was computed in the same way. The annual loss in the sub-station apparatus is the difference between the total input and output. In computing the cost of these losses the cost of power at the sub-station alternating-current bus-bar should be used.

Secondary Copper calculated by Kelvin's Law.

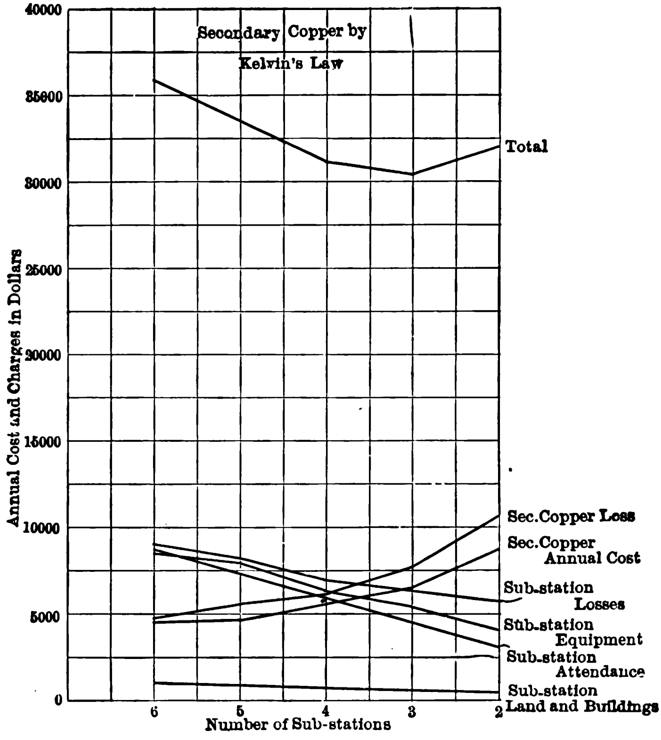


Fig. 39.—SUB-STATION LOSS CURVES.

Secondary Copper calculated by Limiting Drop.

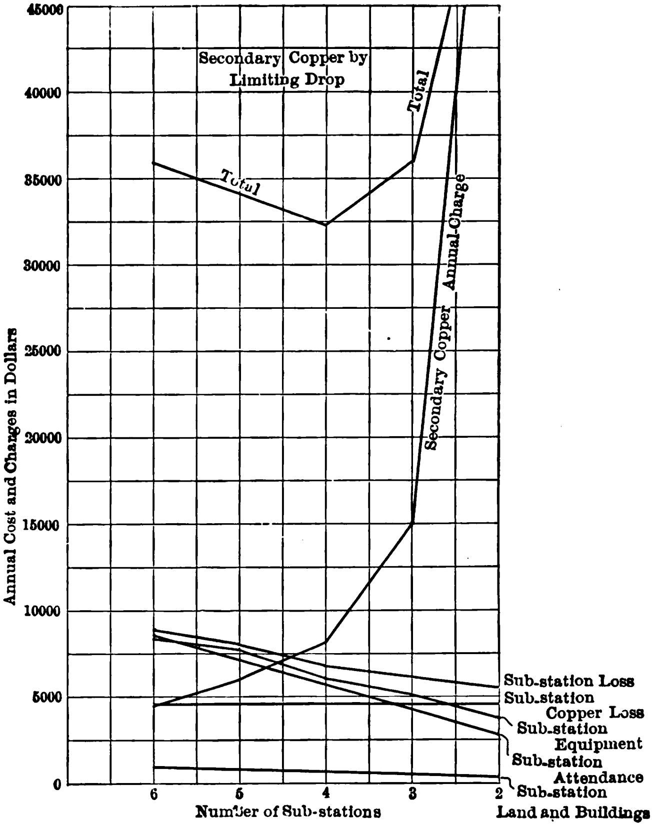


Fig. 40.—SUB-STATION LOSS CURVES.

TABLE 16. — SECONDARY COPPER BY KELVIN'S LAW.

Sub-Stations.					Daily Total Input Kw. hr.	All-Day Eff.	Cost Kw. hr. Direct-Current Bus-bar.	Annual Charges on			Annual Cost of			Totals.
No.	Dist.	Cap.	Com. Cap.	Total Cap.				Real Estate	Sub-Sta. Equip'ts.	Second'y Copper.	Sub-Sta. Attend.	Sub-Sta. Losses.	Second'y Copper Loss.	
6	10.9	260	250	1 560	8 500	77.6	1.61	840	8 550	4 480	8 640	8 730	4 530	35 770
5	13.3	281	300	1 400	8 410	79.3	1.58	700	7 780	4 550	7 200	7 960	5 450	33 640
4	17.1	315	300	1 260	8 185	81.7	1.53	560	6 225	5 480	5 760	6 920	6 110	31 055
3	24	377	400	1 131	8 070	82.7	1.51	420	5 220	6 450	4 320	6 400	7 625	30 435
2	40	520	500	1 040	7 926	84.3	1.48	280	3 900	8 690	2 880	5 750	10 420	31 920

TABLE 17. — SECONDARY COPPER BY LIMITING DROP.

No. of Sub-Station.	Annual Charges Secondary Copper.	Annual Cost of Secondary Copper Loss.	Totals.
6	4 460	4 560	35 780
5	5 850	4 560	34 050
4	8 380	4 560	32 405
3	15 120	4 560	36 040
2	76 400	4 560	93 770

Cost of Sub-Stations. — The cost of sub-station buildings and land was taken at $2,000 each. Switchboards and wiring were estimated at $2,500 per sub-station. The nearest commercial sizes of synchronous converters and transformers were used in estimating the cost of sub-station equipments, at prices varying from $21 per kw. for 500 kw. to $38 per kw. for 250 kw.

Table 16 and Fig. 39 show the results of this computation, with a minimum operating expense at three sub-stations, spaced 24 miles apart, and with secondary copper, of 746,000 cir. mils, which is evidently impossible to operate without the use of boosters in the sub-stations.

Table 17 and Fig. 40 show the results of recomputing the same problem with the secondary copper proportioned to permit a maximum drop of 300 volts in line and track, about the worst condition in which operation is practicable.

It is apparent then that economy of operation is usually sacrificed to regulation."

The Relation of Variable Load to Cost of Transmission. — The cost of transmitting electrical energy is an important consideration in nearly all electrical problems. On a given circuit the power lost in transmitting a given current is equal in watts to the line resistance in ohms multiplied by the square of the current in amperes. In the case of circuits carrying variable load, the line loss also varies. The following shows how it may be found from the load diagram.

The relation of actual line loss to ideal line loss may be called "cost factor." Ideal line loss is here taken to be the line loss which would occur with steady load in place of the variable load. Since for a given daily load the ideal line loss is easily computed, it is necessary only to determine the cost factor under given conditions of varying load. The cost factor is obviously greater than unity.

The line current is represented graphically in a station load diagram, Fig. 41. The heating effect or line loss at any moment will be proportionate to the square of the

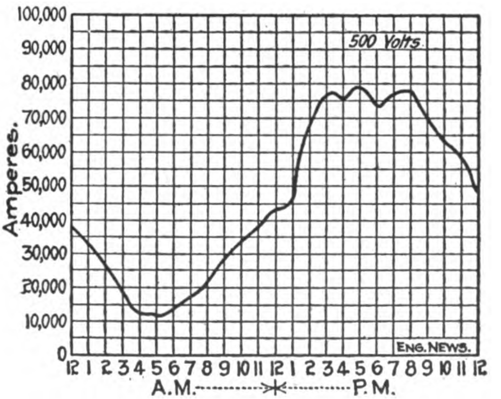


Fig. 41.—LOAD DIAGRAM BROOKLYN RAPID TRANSIT CO., SUNDAY, MAY 8, 1904

current, and the total heating effect throughout the diagram is therefore proportionate to the mean square current value. The latter may be obtained from the diagram by either of two methods: (1) Squaring the successive current values, at short time intervals, and plotting the resulting values on the same abscissas as the load diagram; the area of the curve can be found with a planimeter; dividing this area by the length of diagram gives the mean square ordinate, and multiplying the latter by line resistance gives the average line loss in watts. (2) By means of an instrument called the integraph, the area of the current-squared curve may be found directly, and the line loss then computed as before.

. The ideal line loss is easily found by averaging the original ampere or load diagram (either by planimeter or by arithmetical averaging), squaring the average current and multiplying by the line resistance.

Letting

I_1 = average current,

I = square root of mean square current,

r = line resistance;

then,

$$\text{Cost Factor} = \frac{\text{Actual Line Loss}}{\text{Ideal Line Loss}} = \frac{I^2 r}{I_1^2 r} = \frac{I^2}{I_1^2}.$$

Example 1. — The curve in Fig. 41 is the load diagram for the Brooklyn Rapid Transit System for Sunday, May 8, 1904 (extracted from the Transactions of the Brooklyn Engineers' Club). To find the cost factor for the line loss, by averaging the hourly ordinates the average current is found to be 47,000 amperes. By squaring the hourly ordinates and averaging, the mean square current is found to be 2,850,000,000 amperes. For work with the planimeter, the values of current squared would be plotted on the diagram to an arbitrary scale as shown in Fig. 42.

Then two operations with the planimeter give the areas of the ampere curve and the amperes-squared curve, which divided by the length of the diagram give the same values as found arithmetically.

$$I_1 = 47{,}000,$$
$$I^2 = 2{,}850{,}000{,}000.$$

The cost factor for this case is, then,

$$\frac{I^2}{I_1^{\,2}} = \frac{2{,}850{,}000{,}000}{47{,}000 \times 47{,}000} = 1.29.$$

Thus the line loss on the system on May 8, 1904, was 29% greater than if the load had been constant.

The installed capacity of this system is 50,000 kw. The

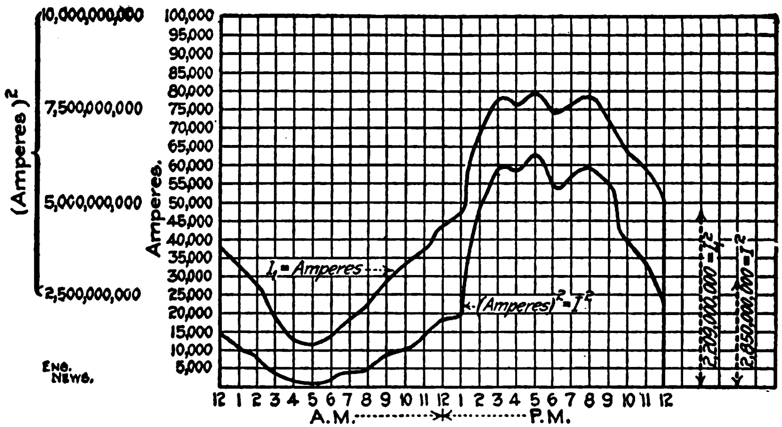


Fig. 42.—CURRENT-SQUARED CURVES.

average load during the day mentioned, the pressure being 500 volts, was 47,000 × 0.500 = 23,500 kw. The line loss of the system is stated to be about 15%, or on this day 23,500 × 0.15 = 3,525 kw. Since the line loss on varying load = I^2r, and the value I^2 has already been found, we can find the line resistance, thus,

$$r = \frac{3{,}525{,}000 \text{ watts}}{2{,}850{,}000{,}000} = 0.00122 \text{ ohms.}$$

Example 2. — What was the line-loss cost factor of the same system on Friday, May 6, 1904, the load diagram being given in Fig. 43? It will be observed that this curve is for a week day and differs materially from that of

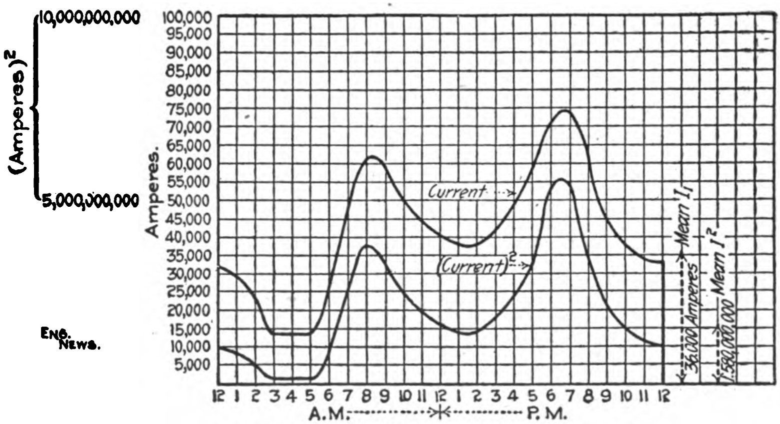


Fig. 43.—LOAD DIAGRAM AND CURRENT-SQUARED CURVES OF BROOKLYN RAPID TRANSIT CO., FRIDAY, MAY 6, 1904.

Fig. 41, showing two peaks instead of one. The average current here is 36,000 amperes, the mean square current is 1,580,000,000, and the cost factor is

$$\frac{1{,}580{,}000{,}000}{36{,}000 \times 36{,}000} = 1.22.$$

The "effective" current = $\sqrt{1{,}580{,}000{,}000}$ = 39,700 amperes; this current would produce the same line loss as the actual load diagram of Fig. 43. In Fig. 43 is also drawn the curve of current squared.

Cost Data. — The cost of materials for construction varies so much in different parts of the world that tables of cost data, as a rule, are quite variable. The writer, therefore, has refrained from inserting many such tables. The few that follow are presented in the text for the benefit of students who may be given problems in design and who desire an approximate cost of materials. Since these tables were originally prepared by the author, the price of copper has changed considerably, and this fact should be borne in mind when using them.

TABLE 18. — POWER PLANT COST.

(H. G. Stott.)

	Per Kw.	
	Minimum	Maximum
1. Real estate	$3.00	$7.00
2. Excavation	.75	1.25
3. Foundations, reciprocating engines	2.00	3.00
4. Foundations, turbines	.50	.75
5. Iron and steel structure	8.00	10.00
6. Building	8.00	10.00
7. Floors, galleries and platforms	1.50	3.50
8. Tunnels, intake and discharge	1.40	2.80
9. Ash-storage pocket, etc	.70	1.50
10. Coal-hoisting tower	1.20	3.00
11. Cranes	.40	.60
12. Coal and ash conveyers	2.00	2.75
13. Ash cars, locomotives and tracks	.15	.30
14. Coal and ash chutes, etc	.40	1.00
15. Water, meters, storage tanks and mains	.50	1.00
16. Stocks	1.25	2.00
17. Boilers	9.50	11.50
18. Boiler setting	1.25	1.75
19. Stokers	1.80	2.20
20. Economizers	1.30	2.25
21. Flues, dampers and regulators	.60	.90
22. Forced-draught blowers and air	1.25	1.65
23. Boiler hand and other pumps	.40	.75
24. Feed-water heaters, etc	.20	.35
25. Steam and water piping, traps, separators, high and low pressure	3.00	5.00

TABLE 18. — POWER PLANT COST (*Continued*).

	Per Kw. Minimum	Per Kw. Maximum
26. Pipe covering	$.60	$1.00
27. Valves	.60	1.00
28. Main engines, reciprocating	22.00	30.00
29. Exciter engines, reciprocating	.40	.70
30. Condensers, barometric or jet	1.00	2.50
31. Condensers, surface	6.00	7.50
32. Electric generators	16.00	22.00
33. Exciters	.60	.80
34. Steam turbine units complete	22.00	32.00
35. Rotaries, transformers, blowers, etc.	.60	1.00
36. Switchboards complete	3.00	3.90
37. Wiring for lights, motors, etc.	.20	.30
38. Oiling system complete	.15	.35
39. Compressed-air system and other small auxiliaries	0.20	0.30
40. Painting, labor, etc.	1.25	1.75
41. Extras	2.00	2.00
42. Engineering expenses and inspection	4.00	6.00

EXCAVATION.

Earth	$2.44 cubic yard
Rock	6.00 cubic yard
Brickwork	11.30 cubic yard

TABLE 19. — COMPARATIVE COSTS OF THIRD-RAIL AND OVERHEAD TROLLEY CONSTRUCTION.

(Thomas Conway, Jr.)

THIRD-RAIL LINE.

Ties — 2,640 per mile at 75c. delivered	$1,980.00
Ballast — 2,200 cu. yds. per mile at 80c. delivered	1,760.00
Rail — 70 lbs. per yd. at $31 per ton delivered	3,819.20
Joints, spikes and bolts per mile	500.00
Labor on track — per mile	600.00
Farm and highway crossings per mile	150.00
Wire fence — 640 rods at 75c. in place	467.20
Switches, special work, etc.	300.00
Bonding, per mile	400.00
Third rail, 70 lbs. per yd. at $36 per ton delivered	2,199.60
Insulators, spikes and bolts at 62c. in place	109.12
Joint plates, bolts and labor laying rail	175.00

TABLE 19. — COMPARATIVE COSTS OF THIRD-RAIL AND OVERHEAD TROLLEY CONSTRUCTION (*Continued*).

Power station — per mile	$3,000.00
Power station building — per mile	275.00
Transmission line — 500 pr. triple-braided strand 7,000 lbs. per mile at 20.05	1,403.50
Pole brackets and insulators for transmission line — per mile	450.00
Sub-station freight and depot buildings	2,000.00
Sub-station railway apparatus	1,000.00
Telephone line	150.00
Block-signal systems	500.00
Platforms	100.00
Switch and platform lighting circuit	70.00
General office building — per mile estimated	125.00
Cars — per mile	5,500.00
Accidents, contingencies and insurance 5 %	1,500.00
Administration, superintendence, office expenses, engineering, etc., 5 %	1,500.00
	$30,033.62

OVERHEAD TROLLEY LINE.

Ties — 2,640 per mile at 85c. delivered	$2,006.40
Stone ballast — 2,315 tons per mi. at $1 delivered	2,315.00
Rail — 70 lbs. per yd. at $31 per ton delivered	3,819.20
Joints, spikes and bolts per mile	1,000.00
Bonds — 352 per mile at 75c. in place	264.00
Constructing track per mile	600.00
Farm and highway crossings	250.00
Wire fence, 640 rods at 73c. in place	467.20
Switches, especial work, etc.	300.00
Poles — 52 per mile at $7.50 delivered	390.00
Brackets — 52 per mile at $1.50 each	78.00
Trolley wire — 4/0 — 3,382 lbs. per mile at 19.80	669.63
Feed wire — 500 triple-braided strand 700 lbs. per mi. at 20.05,	1,403.50
Constructing overhead work — per mi.	600.00
Power station — per mile	3,000.00
Power station building — per mile	275.00
Sub-station, freights and depot buildings	2,000.00
Telephone line	150.00
Block-signal system	500.00
Platforms	100.00
Switch and platform lighting circuit	70.00
General office building	125.00
Cars per mile	5,500.00
Accidents, contingencies and insurance 5 %	1,500.00
Administration, superintendence, office expenses, engineering, etc., 5 %	1,500.03
	$28,782.90

From *Street Railway Journal*, April 4, 1903.

(Mr. Ernest Gozenbach.)

TABLE 20. — COST OF INTERURBAN ELECTRIC RAILWAY, 62.5 MILES LONG.

Excavation and embankment	$96,000.00
Bridges, abutments, and culverts	91,050.00
Two overhead railroad crossings, at $32,000	64,000.00
Ties, 2,640 per mile, at 55c.	96,250.00
Ballast, 2,200 cubic yds. per mile, at 80c.	116,000.00
Rail, 70 pounds per yard, at $31 per ton delivered	225,000.00
Joints, spikes and bolts for 60-ft. rails	29,500.00
Labor on track, 56 miles, at $600 per mile	33,600.00
Labor on street track, 6.5 miles, at $1,800 per mile	11,700.00
Farm and highway crossings	9,500.00
Wire fences, 24,000 rods, at 75c. in place	17,500.00
Switches, special work, etc.	21,000.00
Bonds, 24,000, at 61c. in place	14,650.00
Cross-bonds and special bonding at switches, etc.	2,000.00
Third rail, 70 lbs. per yd., 56 miles at $36 per ton delivered,	131,000.00
Insulators, spikes, and bolts, at 62c. in place	18,000.00
Joint plates, bolts, and labor laying rail	9,800.00
Bonds, 15,000, at 73c. in place	10,950.00
Crossings and crossing cables	13,500.00
Trolley in streets, single-track span construction	24,000.00
Power station, 1,500 kw. at $120 per kw.	180,000.00
Power station building, $11 per kw.	16,500.00
Transmission line, 55 miles, at $1,400	77,000.00
Sub-station freight and depot buildings	24,500.00
Sub-station railway apparatus	65,000.00
Batteries	80,000.00
Telephone line	9,000.00
Block-signal system	35,000.00
Stations and platforms	5,250.00
Switch and platform-lighting circuit	4,000.00
General office building	8,000.00
Car shops, shop tools, etc.	24,000.00
Car bodies and locomotive body	49,000.00
Trucks and air brakes	27,500.00
Electrical car equipment	76,000.00
Lighting and power apparatus and supply systems	70,000.00
Accidents, contingencies, and insurance at 5%	89,000.00
Administration, superintendence, office expenses, engineering, etc., 5%	89,000.00
	$1,963,750.00

TABLE 21.— OPERATING COSTS FOR ELEVATED ROAD.

Car Mile Basis.

(GOTSHALL.)

Train crews, telegraphers, couplers, and yard men	$.0237
Station men, agents, porters, and laborers	.0072
Maintenance, inspection, and up-keep of cars, trucks, and motive power	.0125
Repairs of structure and roadway	.0065
Cost of power for transportation, lighting, and braking	.0123
Miscellaneous expenses, supplies, etc.	.0021
General expenses, salaries, etc.	.0084
City tax on cars and other taxes	.00648
Legal expenses and injuries	.00532
Total	$ .0845

Testing Rolling Stock. — In the operation of every electric railway, there are times when tests on the equipment seem necessary. These tests should indicate the ability of the motorman in manipulating the brakes, and whether the rate of acceleration is reasonably constant on a level track without curves. The energy consumption in watt hours per ton mile should also be determined. Sometimes the limit switches are not properly set, the proportionate cutting out of resistance is not properly calculated, and the rate of acceleration is too low. In order to determine these values with reasonable accuracy and at a small outlay, the writer designed a simple train-testing set modeled on lines somewhat similar to the Keiley recorder described in Vol. I. A complete description of this instrument may be found in the "Street Railway Journal" of Sept. 8, 1906. Speed values are obtained directly with this recorder by means of a Weston Speed Tachometer which is mounted upon rubber cushions on the cross-beam of the truck and belted directly to the axle of the car wheel. A low-range voltmeter connected to this instrument indicates voltage values directly proportional to the car speed. The calibration curve for this instrument is shown in Fig. 44. With a knowledge of the diameter of the car wheel, the diameter of the car axle, and the running circumference of the magneto pulley, the voltage values indicated may be readily converted to speed in miles per hour.

The instrument records in ink, upon transparent paper,

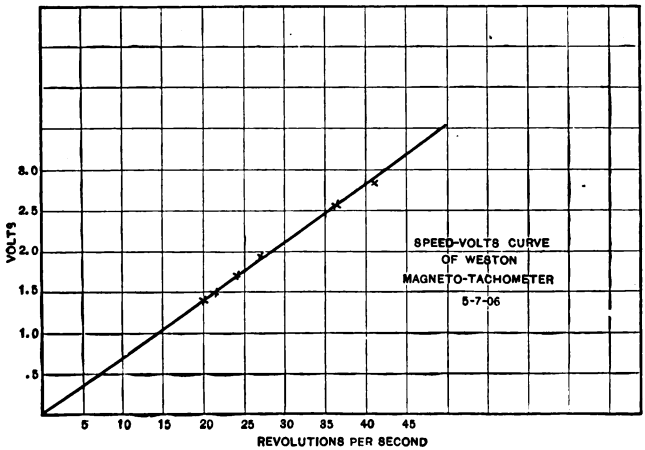


Fig. 44.—CALIBRATION CURVE OF WESTON SPEED TACHOMETER.

and from this blue prints may be made directly. A record includes revolutions of car wheel, motor or line current, line voltage, time in half seconds, and instantaneous speed (see Fig. 45).

With this instrument, which was constructed by Messrs. Hewlett and McCarty of the Polytechnic Institute of Brooklyn, the writer made an elaborate series of tests over the Brooklyn Rapid Transit Company's Lines.

Fig. 46 illustrates a partial profile of the section of the road over which the tests were made, and Fig. 47 illustrates

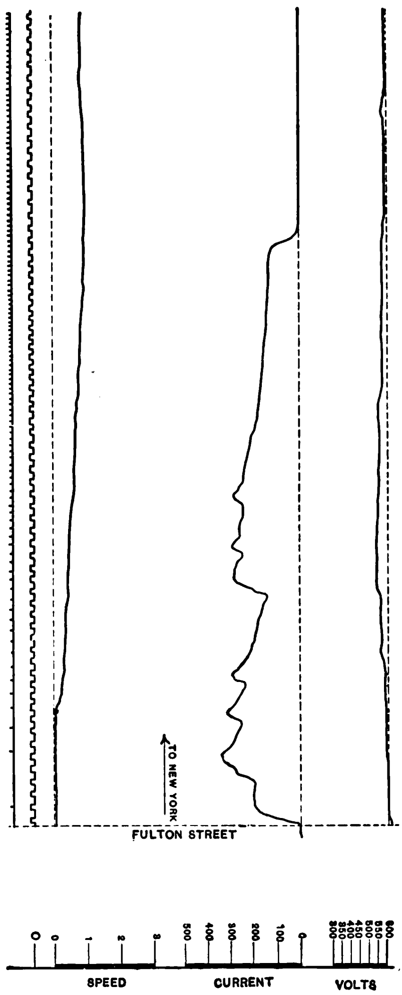


Fig. 45.—TRAIN TEST SHEET.

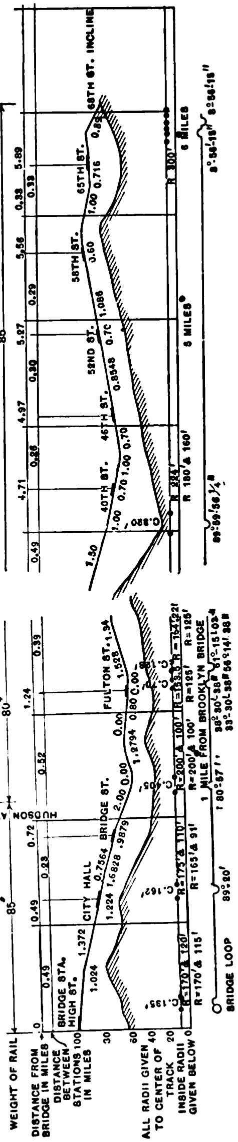


Fig. 46.—PROFILE MAP OF FIFTH AVENUE LINE, B. R. T. CO.

a curve sheet replotted for a run between Bridge St. and Fulton St., on the same lines. Tests were also made

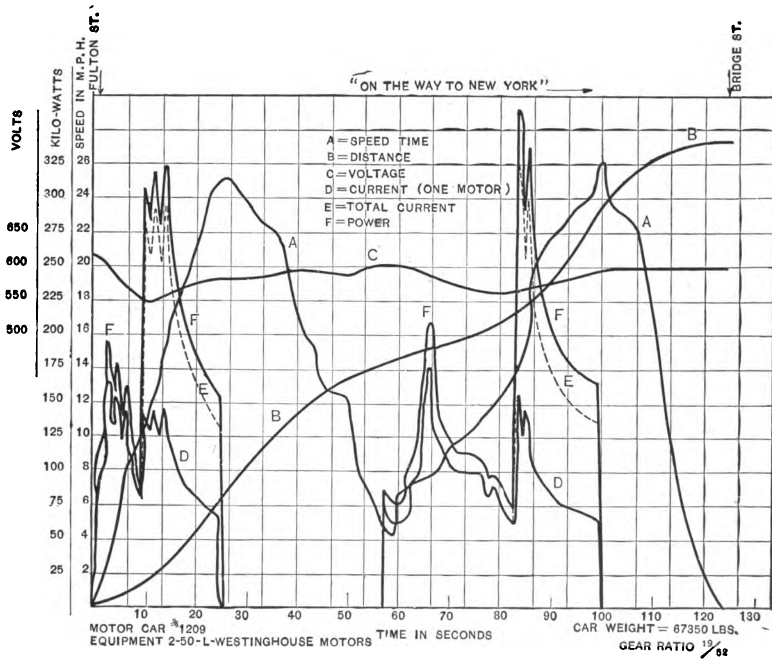


Fig. 47.—TRAIN CURVES OBTAINED FROM TEST SHEET.

on the Coney Island Express and the B. R. T. Instruction Car. (See frontispiece.)

CHAPTER VI.

ROTARY CONVERTER SUB-STATIONS.

ROTARY converter sub-station practice has, at the present day, been fairly well standardized. The general dimensions of a sub-station building vary with the amount of apparatus to be accommodated. This apparatus usually consists of converters, oil switches, transformers, operating switchboard, high-tension bus, general distributing board, control board, cranes, protective devices, instruments, transformer blowers with motors, local storage batteries for the operation of switches, relays, signal lamps, etc., motor-generator sets, and starting sets where employed. These pieces of apparatus bear a definite relation to one another, as will be shown later under the head of circuits.

In order to reduce the expense of wiring to a minimum, and also to economize space and produce a symmetrical station, the converters are arranged in rows, near which are placed the transformers. Where the station load is heavy, two rows of converters facing each other are employed. The switch gear in some cases is located in galleries, while in other cases it is located on the main floor. The advantages and disadvantages of both methods will be discussed later.

Structural Features. — When a site is proposed for a sub-station, soundings should be made to determine the presence of water, rock, and the general character of the soil. Oftentimes this important point is overlooked with sad results. The use of concrete for foundation beds seems to be the approved practice at present. While the foundations are being constructed, concrete pedestals for the converters and for the general support of the framing should be built. A cross section of a typical sub-station, such as is used by the Long Island Railroad Company, is given in Fig. 48. With this sub-station a white granite ashlar footing course extends nearly up to the floor level. With

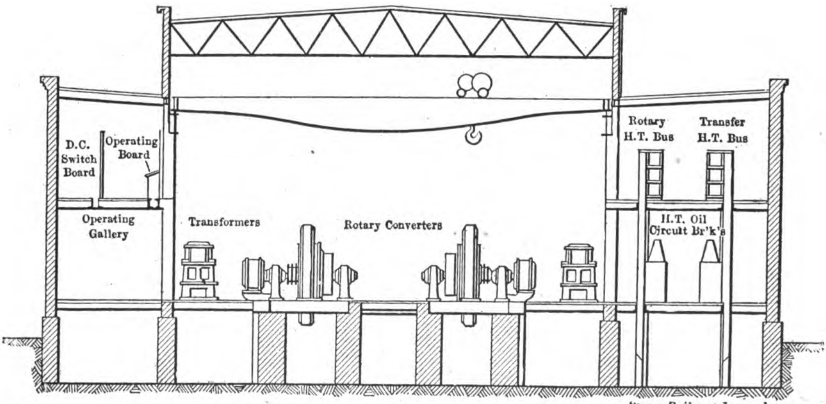


Fig. 48.—TYPICAL SUB-STATION, LONG ISLAND RAILROAD.

the New York Central & Hudson River Railroad concrete was used, resulting in very rapid construction.

Sub-station buildings should be built preferably of fireproof materials, such as brick or terra cotta, with firm girder construction. This form of construction is expensive, but it pays in the end. The floors should be of concrete or stone slabs, and the window frames and doors should be of copper sheet properly strengthened and soldered.

Where space is limited and galleries are employed for switchboards, the galleries are built at the rear of the station. This is the practice of the Interborough Rapid Transit Company of New York. On the other hand, the Long Island Railroad Company build their sub-stations with galleries on the sides.

Care should be taken to see that there is ample ventilation in the sub-station. The writer has operated switchboards where the temperature was 106° F. Such a condition is unwarranted. It is also a good plan to have a clear space under the converters, so that air can circulate through the windings. It is advisable to see that the sewer connection is not too low, so that there will be no possibility of the cellar of the sub-station becoming flooded and the water passing into the air chambers of the transformers. When this happens, there is likelihood of the air from the blowers sending the moisture up into the transformers. The windows of the station should be arranged so that they can be shut quickly in case of a rain storm, to prevent moisture coming in on the converters.

It is quite common to see converters mounted with their bed-plates flush with the floor. The metallic surface of the bed-plate exposed is covered with rubber mats. It is undesirable to have converters set low in the floor, as it creates a tendency on the part of the rotary tender to shirk cleaning the lower brushes. Furthermore, when in this position, the converters draw dirt from the floor into the machines. On the other hand, it is inconvenient to have converters projecting too far out of the floor. With some sub-stations, it is necessary for the rotary tender to climb a few steps to reach the upper brushes of the converter. This is not warranted unless the machines are of such large capacity as to make it necessary. For instance, in the new sub-stations of the New York Edison Company, this system is used with their 2,000-kilowatt converters. Where the frame of the converters projects about 18″ out of the floor, the operating results seem to be most satisfactory. Although this arrangement is less artistic than that of a converter whose frame is flush with the floor, it is more satisfactory.

It is not desirable in the limited space at hand to enter into a discussion of the architectural features of the construction of sub-station buildings, except in so far as they affect operation. Many excellent treatises have been published, giving all the essential details on strength of materials, framed structures, foundations, and bearing surfaces of soils, and to these the reader is referred. Many of the structural features are obvious, however, from a consideration of existing sub-stations. For instance, Fig. 49 is an elevation of the Woodhaven Junction sub-station of the Long Island Railroad. From this figure the general arrangement of the foundations is apparent, and the pedestal support to the walls, partitions, and rotary converters is shown. The large windows allow for excellent ventilation and lighting. The wiring circuits as they enter the building from the pole line to the lightning arresters, high-tension bus, etc., are evident. This arrangement of sub-station interior consists of three parts — the main room containing the converters with starting motors and transformers, the high-tension galleries containing lightning arresters, high-tension bus and oil switches, and the galleries for the instrument board and direct-current distributing panels. This arrangement separates as much as possible the direct-current side of the system from the alternating-

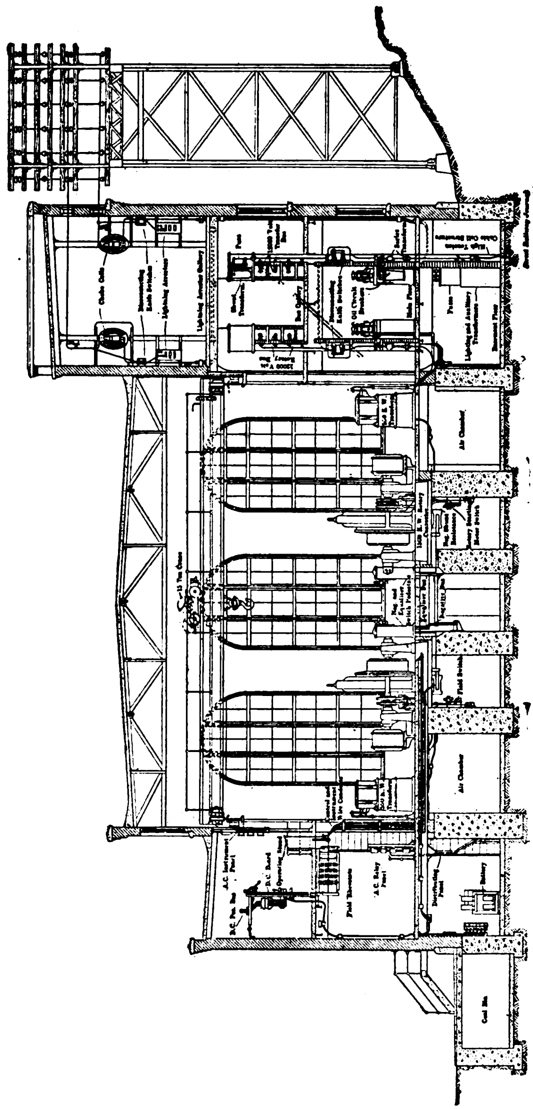


Fig. 49. — SIDE ELEVATION — SUB-STATION, LONG ISLAND RAILROAD.

current side. The direct-current positive bus with feeder switches is located in the direct-current operating gallery, and the negative bus is located in the cellar near the converters and the negative feeder ducts.

Before discussing the advantages and disadvantages of various arrangements of sub-station equipment, it is perhaps desirable to trace out the electrical circuits and show the relation which the various pieces of apparatus bear to one another. As an example, the case of a sub-station fed with high-tension current at 11,000 volts, three-phase, 25 cycles through underground cables, is cited. The converters in this sub-station are started from the direct-current side by means of a starting set. As the system is underground, lightning arresters are dispensed with.

Circuits. — There are usually three distinct circuits to be considered in a sub-station layout — the incoming high-tension feeders conveying alternating current, the outgoing feeders carrying low-tension direct current, and the local storage-battery circuit previously mentioned. There are also auxiliary circuits in the station for the operation of lights, cranes, motors, etc.

Fig. 50 is a wiring diagram, in elementary form, of a model sub-station layout. This represents General Electric practice.

Owing to simplicity, ease of handling, and other economic conditions three-phase transmission is rapidly becoming the standard for interurban practice. This description therefore, will confine itself to that sphere.

With underground systems, current usually enters the sub-station through high-tension, three-phase, lead-sheathed cables terminating in a bell, in which are connected the house feeders. This bell is filled with an insulating compound to keep all moisture from entering between the end of the lead sheathing and the cables proper. Where overhead cables are used for transmission, it is necessary to bring the high-tension feeders in through the upper

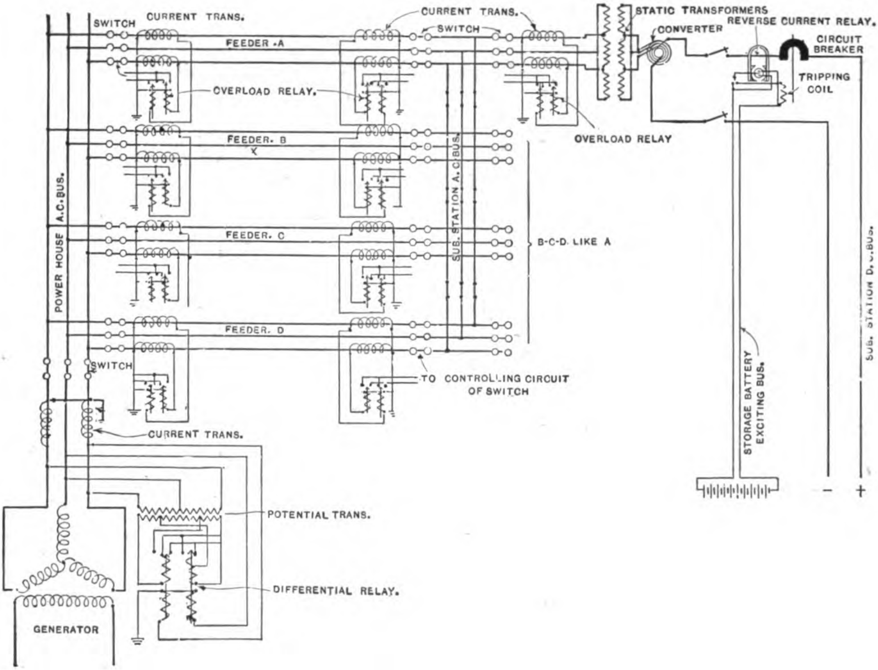


Fig. 50. — CIRCUITS OF TYPICAL SUB-STATION LAYOUT.

side walls and connect in lightning arresters. (See Fig. 49.) The house feeders go direct to oil switches (Figs. 51 and 52), passing through these to a high-tension bus (Figs. 49, 50, 53 and 54). Several high-tension feeders may thus be connected in multiple to the same bus, each feeder being protected by an oil switch.

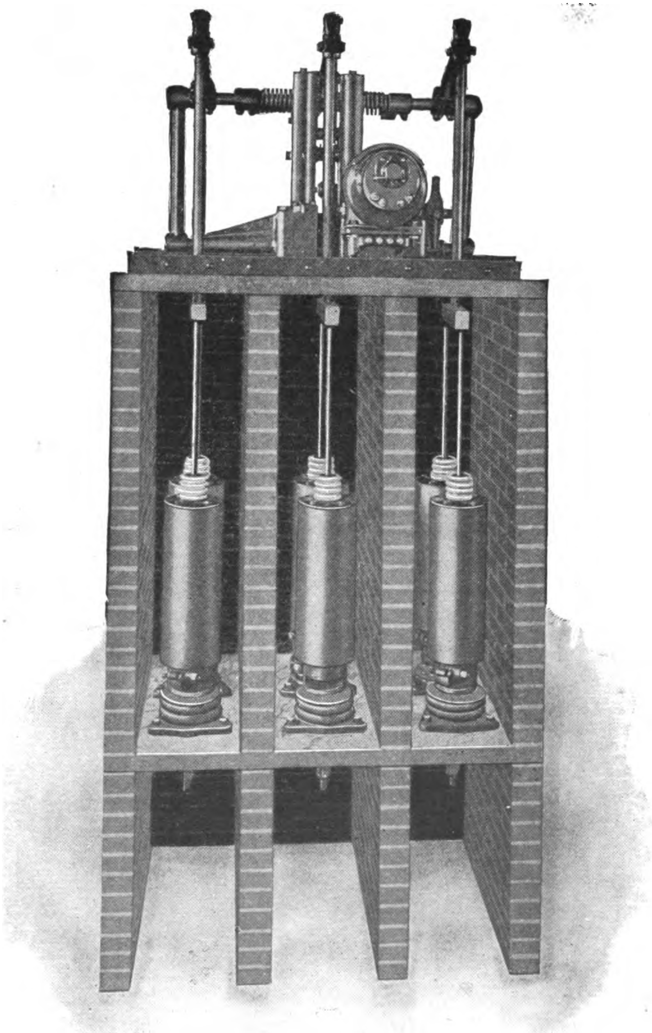


Fig. 51. — G. E. ELECTRICALLY OPERATED OIL SWITCH.

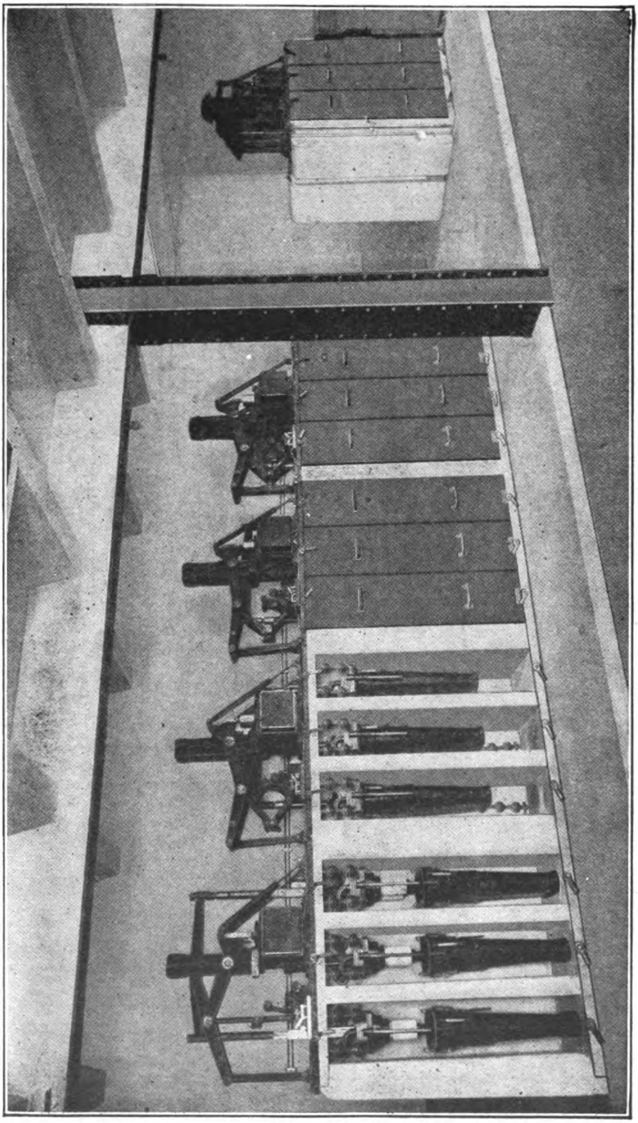


Fig. 52.—STATION OIL SWITCHES.

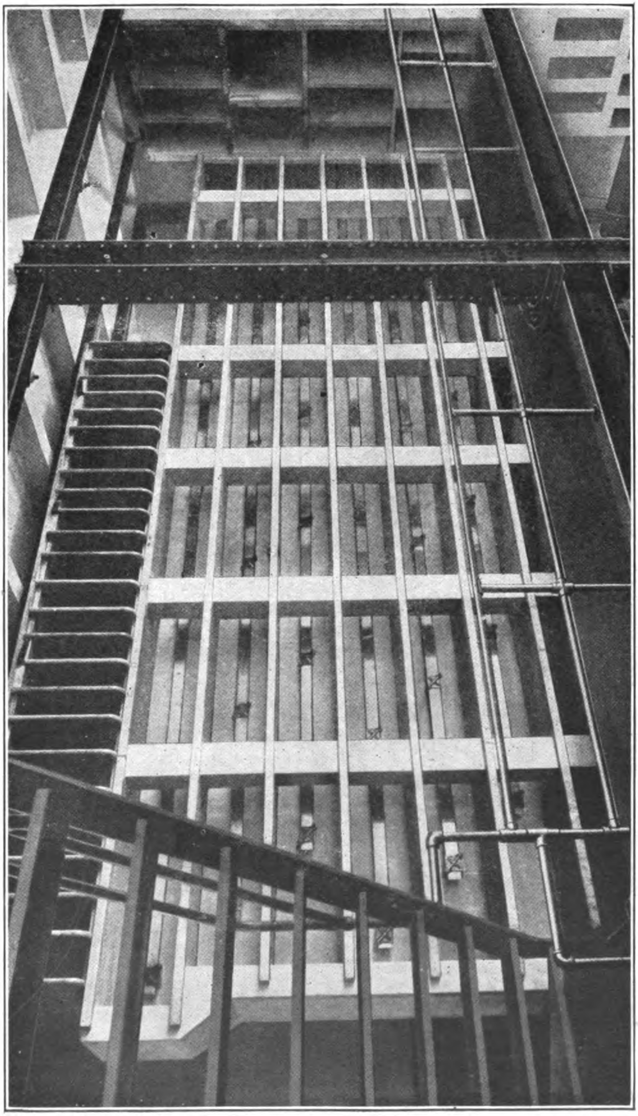


Fig. 53. — HIGH TENSION BUS.

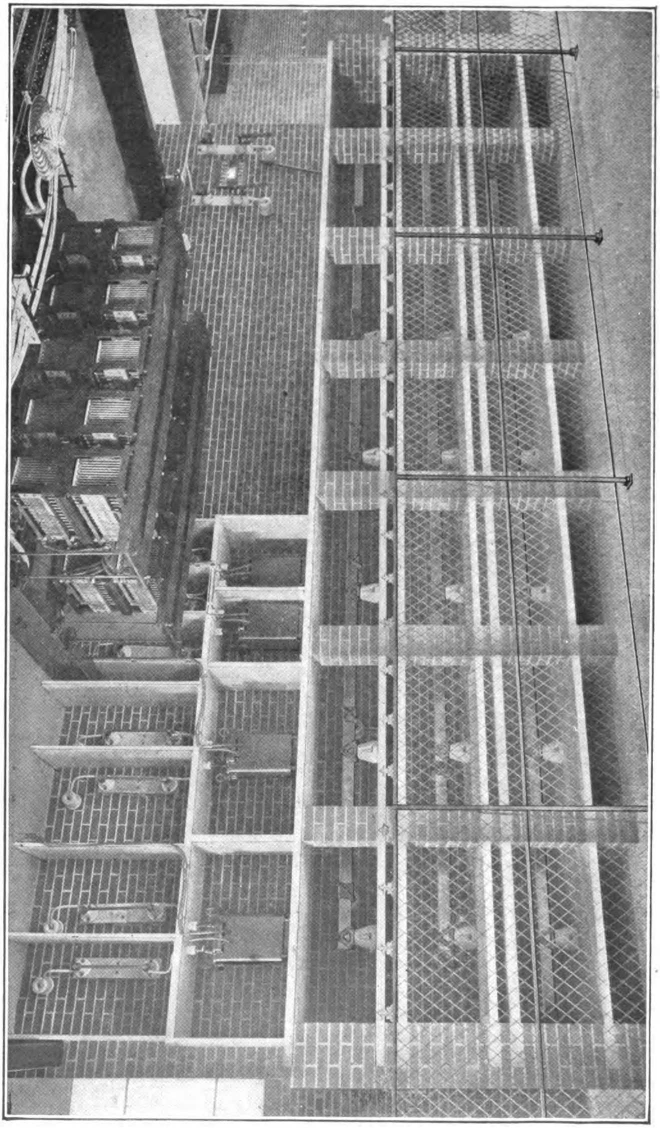


Fig. 54.—HIGH TENSION BUS.

These switches are equipped with time-limit overload relays which open the switches when a severe overload has been upon the feeders for a predetermined number of seconds. From the high-tension bus, feeders pass to single-pole switches and then to the transformer oil switches. These switches are likewise protected with time-limit overload relays. From the oil switches the feeders pass to the high-tension side of step-down transformers, the low-tension side of the transformers being connected direct to the rotary alternating-current brush-holders. In case of accident to the synchronizing apparatus, it is sometimes desirable to insert single-pole switches in the circuit at this point, one in each phase. The converters may then be synchronized by means of a bank of lamps.

By means of the transformer oil switches it is possible to control independently each converter circuit. When machines are synchronized from the high-tension side, these switches are closed at the instant of synchronism. Considering the low-tension side of a converter, the negative armature terminal and the negative field terminal are tied together and grounded to the ground bus through a single-pole switch. Where converters are compounded, an additional switch is provided for connecting the compound coils of the converter in multiple with the coils of the other converters, an equalizer bus being provided for the purpose. The positive armature and field terminals of the converter are carried to the operating board (Fig. 55 and Fig. 56).

Here it is possible to connect the positive feeder to the positive bus through the medium of a circuit breaker and a single-pole switch. The circuit breaker is provided with an overload relay and a reverse-current relay. The overload relay should be blocked where an oil switch is used

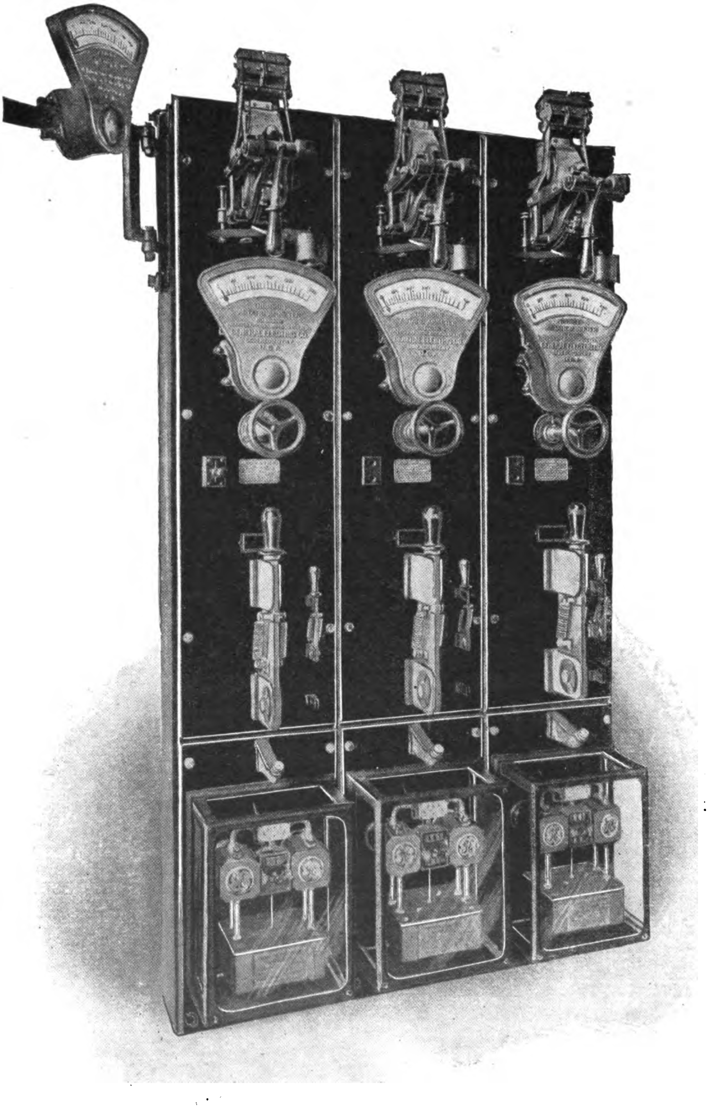


Fig. 55.—(Front View) DIRECT-CURRENT PANELS OF G. E. SWITCHBOARD.

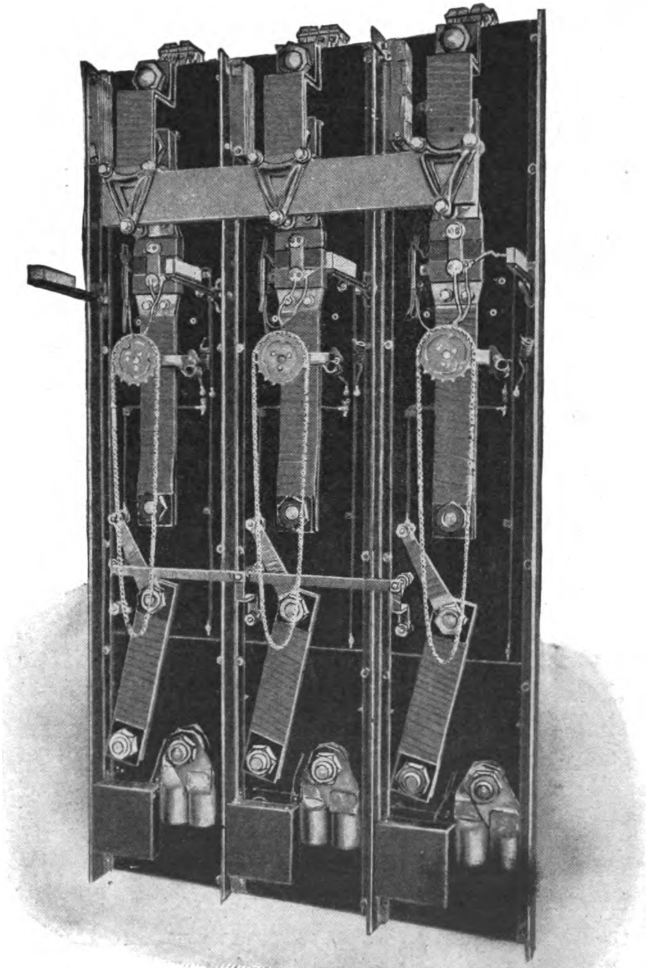


Fig. 56.—(Rear View) DIRECT-CURRENT PANELS OF G. E. SWITCHBOARD.

on the alternating-current side of the rotary, provided the oil switch is equipped with a time-limit overload coil. The function of the reverse-current relay is to trip the breaker if the voltage of the rotary should become slightly lower than the bus, a sudden rush of current tending to motorize the rotary. These relays trip at about 15 per cent, supposedly, of the normal full-load reverse current of the rotary. In practice they are usually set, however, about 25 per cent of full load, as they would otherwise be too sensitive.

From the direct-current bus the current passes through a circuit breaker and a single-pole switch to the rail feeder, passing out of the station to the individual third-rail sections. The feeder circuit breakers are protected with a straight overload relay. With this arrangement it is possible for an excessive overload or a short circuit to occur on an individual rail section, opening the feeder breaker, taking the power off that section without interfering with the operation of the rotaries. Sometimes, however, the short circuit or overload is so great as to open the oil switches on the rotary, throwing the machine out of step.

The positive field switch of the rotary is arranged on the switchboard panel (Figs. 55 and 56) so that when the field has been properly built up and the rotary is operating at about normal speed, the field, if separately excited, may be made self-exciting by throwing this two-way switch over to the positive-rotary armature-switch circuit. The stud of the two-way switch is usually connected to the stud of the positive switch. (See small single-pole switch, Fig. 55 and Fig. 56).

All of the controlling relays may be operated from a common bench-board (see Fig. 57 for the main instrument bench-board installed in the Interborough Rapid Transit Company's power house), but usually the negative switches are separated from the positive switches and have aux-

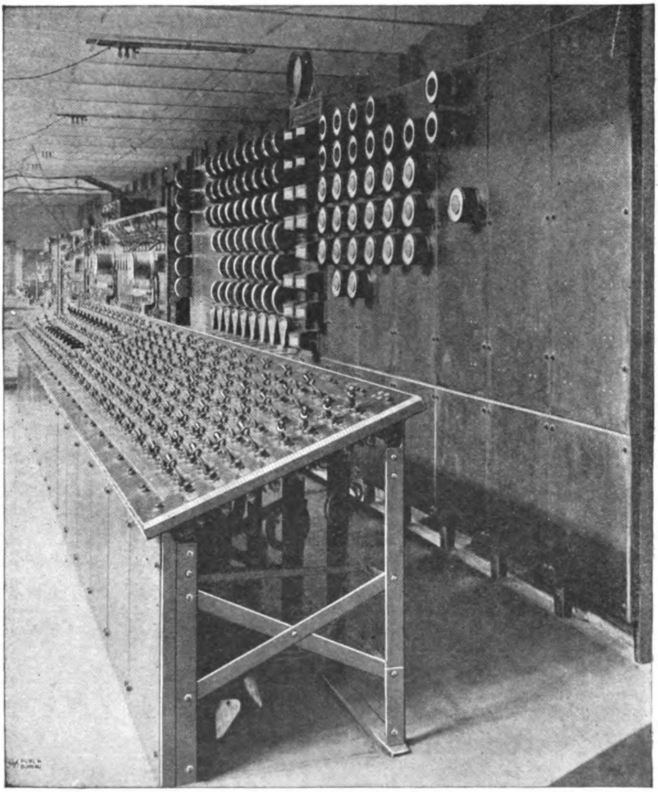


Fig. 57.—BENCH-BOARD OF INTERBOROUGH RAPID TRANSIT COMPANY.

iliary apparatus such as starting sets separate, so as to be operated by the rotary tender. Indicating instruments and synchronizing mechanisms are also provided. Local battery circuits are arranged for the tripping of oil switches, circuit breakers, etc., as already noted. Fig. 55 is a front view of a direct-current panel showing the recording wattmeter, the positive rotary armature switch, the rotary field switch, the field rheostat, the circuit breaker, with overload release and tripping coil. The switchboard instruments are also shown. Fig. 55 is a rear view of the same board, showing the positive bus with special V-shaped clamp, ammeter shunts and chains connecting to spindle of field rheostat. Rheostats are seldom mounted on the board, since they are cumbersome, heavy, and generate heat.

Fig. 58 shows the front view of the switchboard installed by the Westinghouse Manufacturing Company in the stations of the Long Island Railroad. Fig. 59 is a rear view of the same board, showing the heavy ammeter shunts and the clamps for the positive bus. A very compact board combining the alternating-current panels with the direct-current panels in addition to the bench-board is shown in Fig. 60. This board was designed by the General Electric Company for Necaxa, Mexico. It is for 50-cycle transmission. Fig. 61 is a view of an improved form of bench-board developed by the Westinghouse Manufacturing Company in which relay switches, controlling the oil switches, mounted on the top of the board, have a lateral motion instead of the vertical motion used in the old type of switch. With this new arrangement there is no possibility of the switch closing because of gravity or by accidental contact.

Arrangement of Switch Gear. — The most suitable arrangement of switch gear is obviously that which best facilitates the manipulation of sub-station apparatus with a minimum outlay.

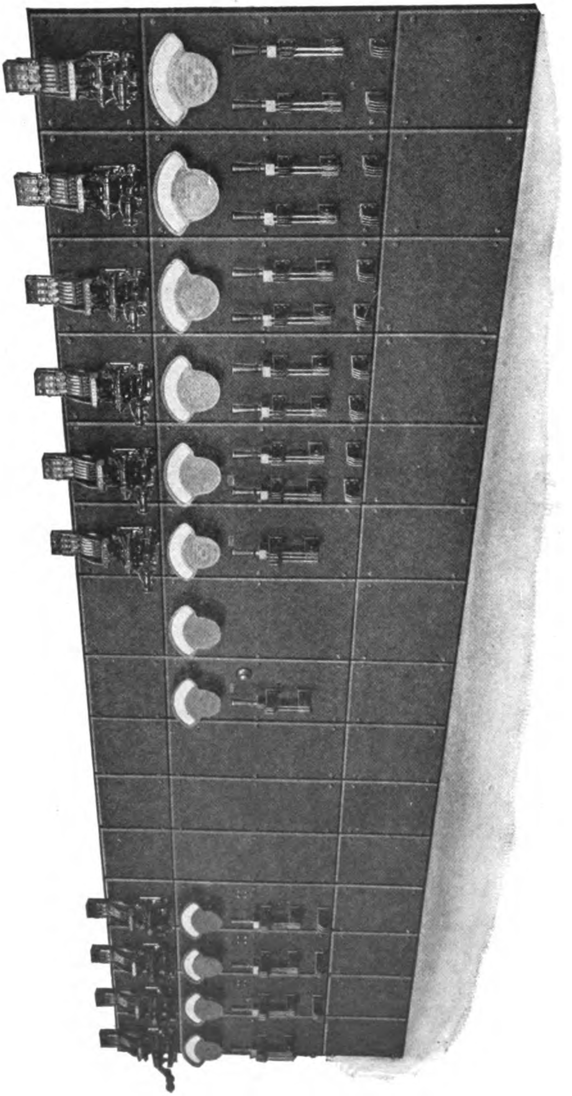


Fig. 58.—(Front View) SWITCHBOARD INSTALLED IN LONG ISLAND R R CO SUB-STATIONS.

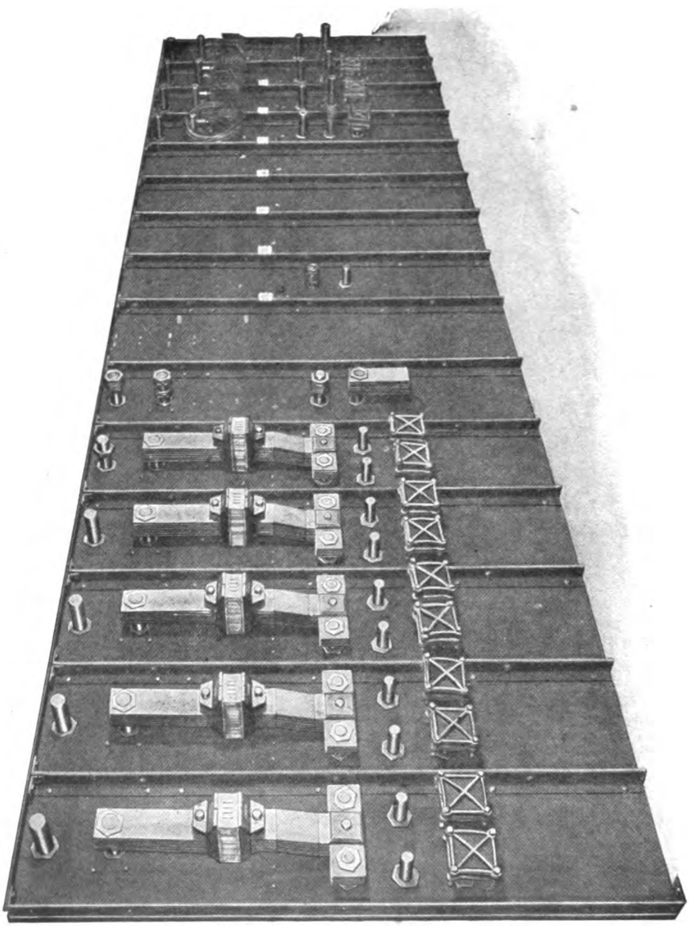


Fig. 59. —(Rear View) SWITCHBOARD INSTALLED IN LONG ISLAND R. R. CO. SUB-STATIONS.

There are two distinct arrangements of switch gear, their adoption depending upon the capacity of the sub-station. With one arrangement, which is especially applicable to small sub-stations, all of the switch gear is located on the main floor with the converters and with the trans-

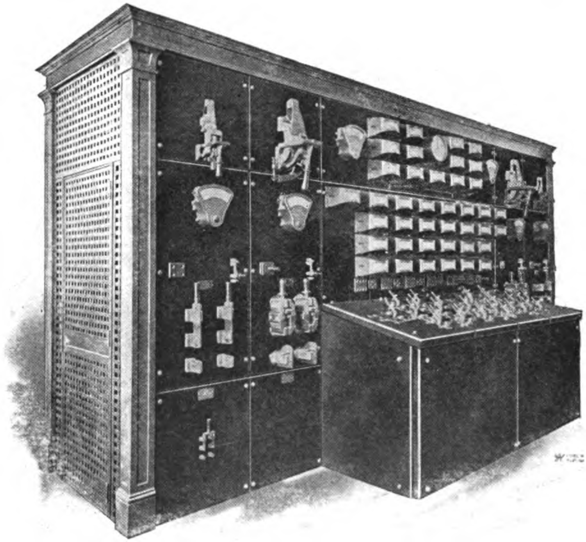


Fig. 60.—COMPACT SWITCHBOARD FOR NECAXA, MEXICO.

formers. (See Fig. 62 for N. Y. C. & H. R. R. sub-station. See also Fig. 63 and 64.) The other method, which is usually employed in stations of large capacity, consists in locating all the manually operated switches, except the negative switches, in a switchboard gallery.

It is worth noting that in the first case, where all the switching apparatus is located on the same floor with the transforming apparatus, as in Figs. 62, 63, 64, the station attendance is minimized; for the operator may also per-

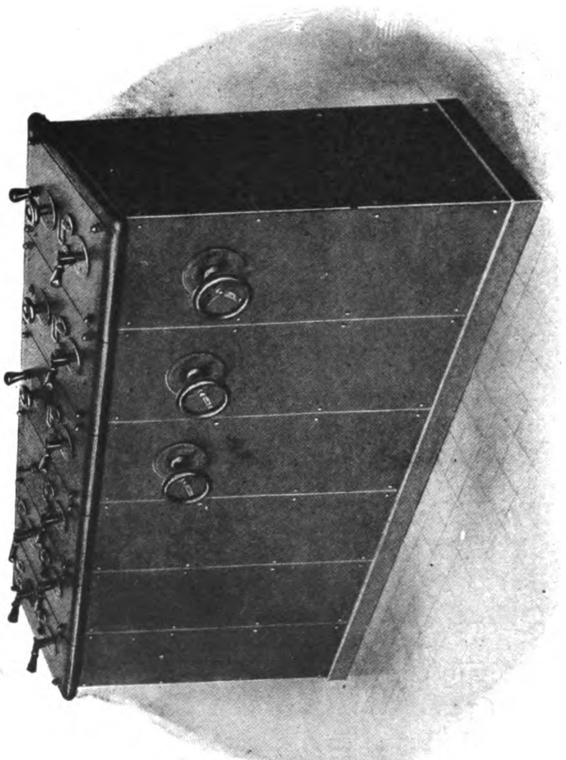


Fig. 51. — WESTINGHOUSE IMPROVED BENCH-BOARD.

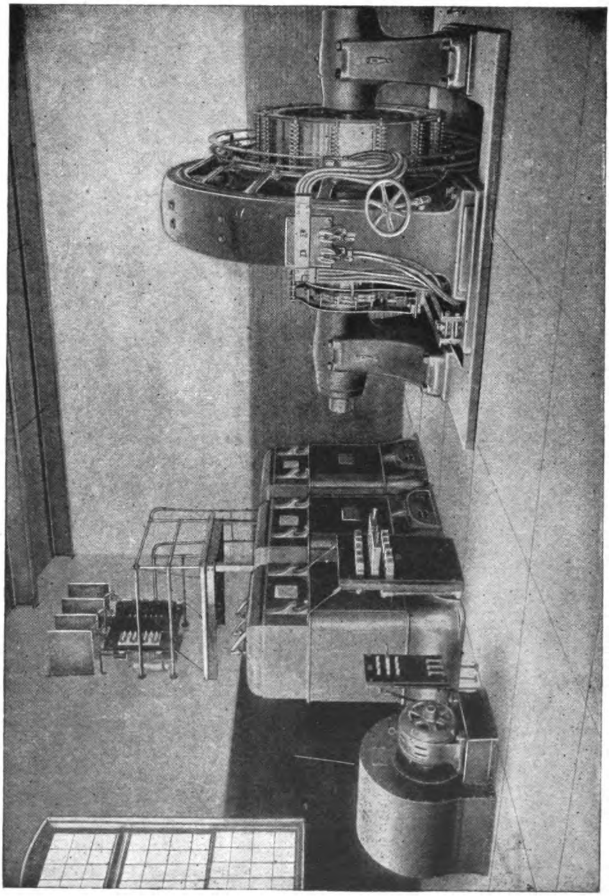


Fig. 62. — SUB-STATION FOR TEST TRACK OF N. Y. C. & H. R. R. R. CO.

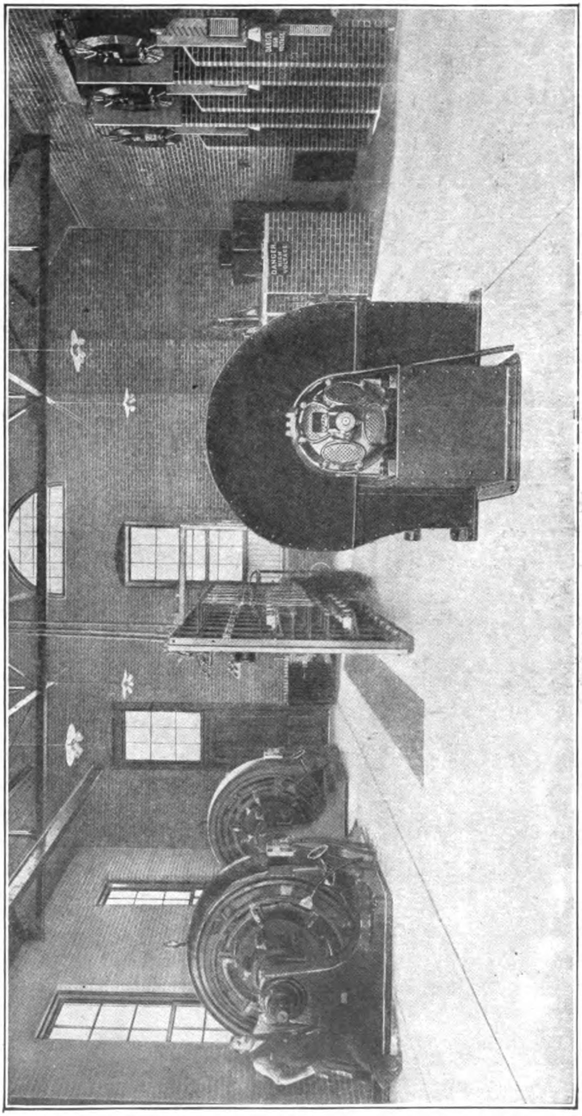


Fig. 63.—SUB-STATION APPARATUS MOUNTED ON ONE FLOOR (WESTINGHOUSE).

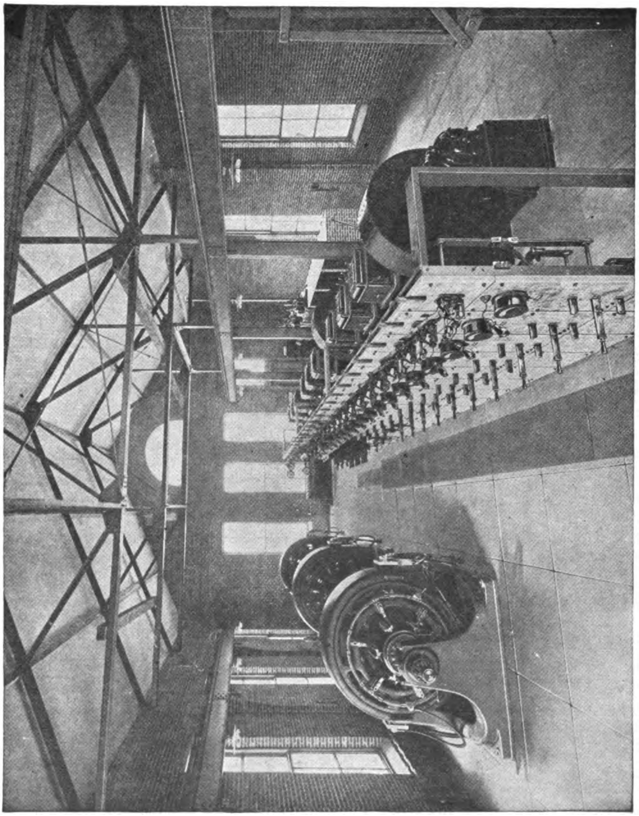


Fig. 64. — WESTINGHOUSE SUB-STATION APPARATUS ARRANGED ON ONE FLOOR.

form part of the duties of station foreman, and the rotary tender may also perform the duties of janitor, thus dispensing with two men. But this system is not wholly advantageous. In the first place it is difficult to keep the switch gear clean; and in case of trouble the operator is too near the converters to act with unconcern. On the

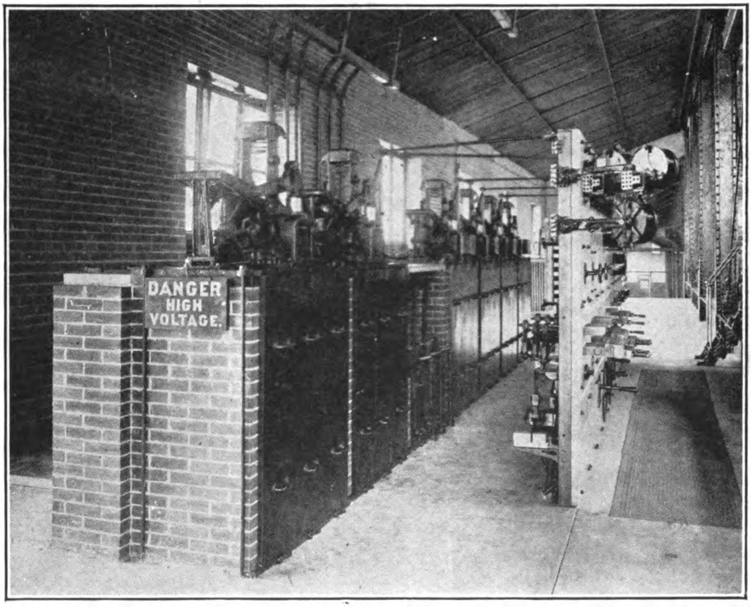


Fig. 65. — SWITCHBOARD GALLERY, LOUISVILLE RAILWAY COMPANY.

other hand, this system reduces the expense of wiring to a minimum, allows excellent ventilation, and results in a very compact station.

Where a switchboard gallery is employed, as in Fig. 65, the operator is able at a glance to scan the whole station, a great advantage in case of trouble. He is relieved of the fear of personal injury, he is less hampered and more comfortable, and can better perform his duties. But the expense of wiring is greater and the ventilation inferior. Fig. 66 is an interior view of the Quincy sub-station of Boston, Mass. This station is very compactly arranged. This represents G. E. practice.

It is becoming the standard practice to construct the

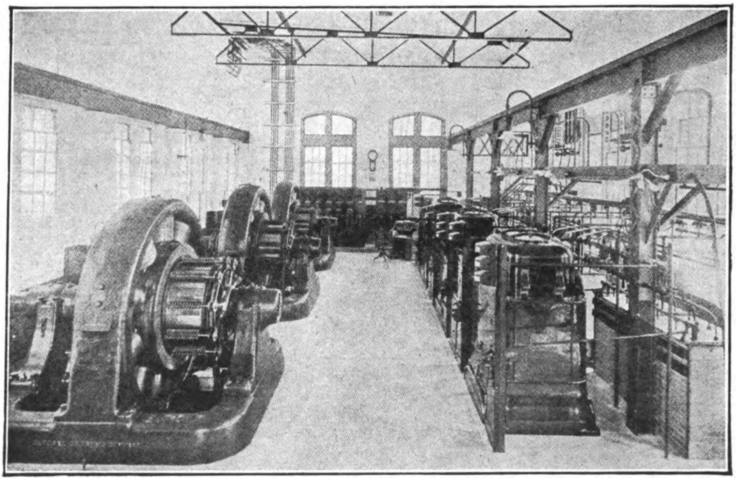


Fig. 66.—QUINCY SUB-STATION, BOSTON, MASS.

switchboard in three distinct sections; namely, a controller board from which the oil switches are operated, a set of machine panels, and a set of distributing panels. The positive direct-current bus-bar forms a connecting link between the machine panels and the distributing panels. This system is sometimes modified in small stations.

Various arrangements of circuit breakers are employed;

in some cases they are mounted upon the switch-board panels; in others distinct compartments are used. The latter arrangement is preferable if the expense be justified, for it disconcerts an operator to see the flash of an opening circuit breaker. For obvious reasons it has become quite common to separate the negative switches from the positive switches.

A feature worth mentioning is the arrangement of a circuit of lamps on the switchboard, and their feeding from the local battery circuit, so that in cases of failure of power at the power house there may be sufficient illumination in the evenings for the operator to manipulate the board. Upon the same circuit a complete set of signal lamps should be installed to indicate whether switches and circuit breakers are open or closed.

Switchboards should be built of fireproof materials, preferably of slate free from metallic grains. They should be mounted in place with angle iron framework, and should be built rigidly a sufficient distance away from the wall to permit of passage. An example of excellent construction is shown in Fig. 67. This represents General Electric practice. The cables should approach the board through conduits, and should terminate in lugs and there be soldered. Where cables carry heavy currents, the cable connections are liable to heat up if the connections are not properly made, owing to their increased resistance. It should also be borne in mind when running the positive feeders through metallic conduits that when grounded the conduits are equivalent to the negative feeders, so defects in the cables should be carefully avoided.

The National Board of Fire Underwriters' Rules should be closely followed when wiring and erecting switchboards.

Local Storage Battery for Station Use. — Many large sub-stations are equipped with a set of small storage batteries for the operation of oil switches, reverse-current relays, signal lamps, and for energizing the field coils of switchboard instruments. These batteries have an ampere-hour capacity of about 30 ampere hours and a rated vol-

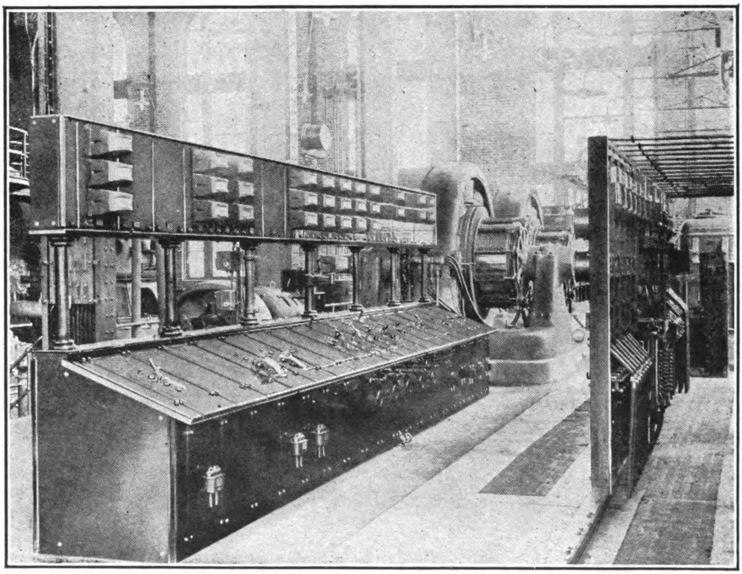


Fig. 67.—AN EXAMPLE OF EXCELLENT CONSTRUCTION (G. E. PRACTICE.)

tage when charged of 125 volts. The reason a local battery is employed for such a purpose in preference to the low-tension railway circuits is that in case the central station should go out of service it would be possible to operate the oil switches from the sub-station. It is true that oil switches could be tripped mechanically, but it would not be desirable, as it would take too much time; and, furthermore, to trip the switch the operator would have to leave the operating board. Another reason why storage batteries are used is that the operation of relays and oil switches is affected very materially by a change of voltage. For instance, if the voltage falls, the switches fail to operate. This is exceedingly inconvenient when synchronizing, for if the battery switch does not operate, it means that the operation of synchronizing must be tried again with another machine. Usually each converter is provided with its individual oil switch. Where railway circuits fluctuate 50 volts or more, the service is not reliable enough to be used for switch operation. If the voltage were somewhat low, for instance, the oil switch might close a fraction of a second late, causing the converter to close the circuit out of synchronism, which would produce severe sparking. Where converters are started from the alternating-current side, many of these objectionable features disappear, as the converters build up directly into synchronism.

The signal lamps previously referred to require a constant battery discharge of about five amperes in a large station; the closing of an oil switch takes about twenty-five amperes. These values change slightly, owing to different operating conditions.

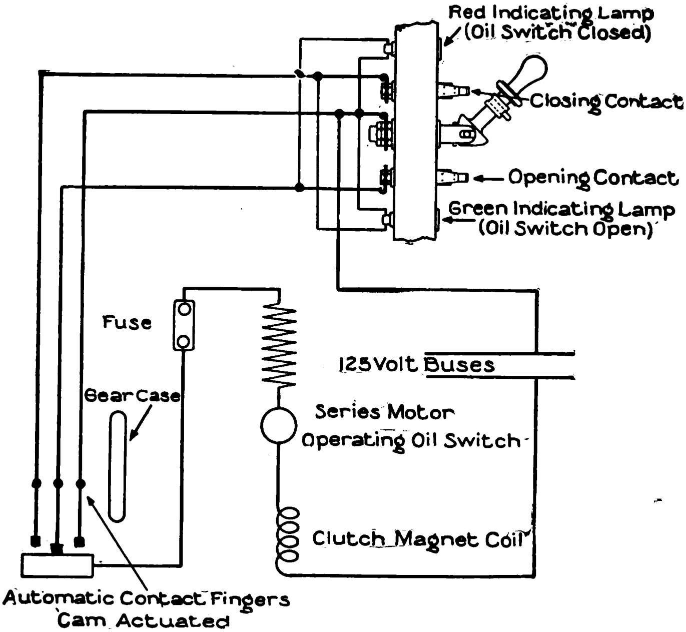
The local storage batteries are charged from small generator sets, duplicates of which are installed. When there is any possibility of an oil switch failing to close in time, the operator starts the motor generator set, and charges the batteries. If the oil-switch mechanism, which may consist of magnets or a motor, is connected to the battery circuit while charging, the switch closes properly, as the voltage of the batteries is high. The batteries in this event act as a balancer to the motor-generator set.

When the central station goes out of service, the operating mechanisms in the sub-station can be taken care of easily by the station batteries for about two days; but the length of time varies with the number of applications of power.

Associated with all circuit breakers and oil switches are signal lamps which are illuminated the instant a switch opens. It is thus possible for the operator to tell immediately by the illumination what circuit has been opened. With the General Electric switchboard colored crystals are arranged to indicate whether an oil switch is opened or closed, a green crystal mounted in the switch-board being illuminated when the switch is open, and a red crystal similarly lighting up when a switch is closed. This arrangement of switch gear is illustrated in Fig. 68 for a General Electric oil switch, motor operated. This method is also employed by the Westinghouse Manufacturing Company, except that the oil switches are solenoid operating. Referring to Fig. 68, when the operating battery switch on the bench-board is shut, current passes from the local battery circuit through a small series motor and the clutch magnet coil, operating the switch. By means of contact fingers on the switch, the battery circuit is also closed through signal lamps. The circuits are plainly shown in the figure. The operating mechanism for these switches is evident in Fig. 51, page 119.

The arrangement of signal lamps to indicate whether switches are open or closed is very convenient, as feeder circuit breakers are usually placed in enclosures of brick or concrete and cased in on three sides. It would otherwise be impossible to tell from the middle of the board what circuit breaker had opened. A row of five or ten incandescent lamps of 16 c. p. are usually lighted from this battery also. These lamps are placed over the switchboard so that in case of failure of power at night, the illumination will be sufficient to enable the operator to clear his board.

There is only one slight objection to the use of lamps



Oil Switch in Closed Position.

Fig. 68.—G. E. OPERATING OIL SWITCH CIRCUITS.

for illuminating the switchboard crystals just referred to. These lamps heat up the slate board and cause the lamp sockets to expand. This requires that the lamps be tightened frequently in their sockets, as they would otherwise go out. This, however, is a small matter.

Methods of Starting Rotary Converters. — There are several ways in which rotary converters may be started. Among these are: starting from the direct-current side from either the direct-current bus or a separate starting set; starting by means of an induction motor; starting from low potential taps on the transformers connected to the alternating-current side of the machine; starting by means of a compensated single-phase motor; and starting first from the direct-current side and then from the alternating-current side, suitable throw-over switches being provided. These methods may be modified, resulting in still other ways of starting. In order to ensure maximum reliability some converters are arranged to be started in two ways; for instance, the new converters installed in the New York Central and Hudson River Railroad sub-stations may be started either from the direct-current bus or from low-potential taps on the transformers connected to the alternating-current side. Under ordinary circumstances these converters will be started from the direct-current side, whereas in emergency cases they will be started from the alternating-current side. The methods in general use are restricted to three, each of which possesses advantages and disadvantages. A description of these methods, as presented by the writer in a paper before the American Institute of Electrical Engineers on Dec. 15, 1905, follows. The principal points brought out in the discussion of this paper are included as well.

"In considering the various methods of starting converters, it should be noted that the prime requisite of every method is ability to start and synchronize a converter in the shortest possible time without affecting the system generally. The first rule that a sub-station operator must learn is to be in readiness at all times to carry upon the converters whatever load may come upon the sub-station, this load being limited only by the maximum carrying capacity of the feeder oil-switches. Occasionally, as a result of congestion of traffic, excessive overloads come upon a station. In this case another converter must be started immediately, synchronized, and placed on the bus-bar. This calls for a convenient arrangement of switch-gear, a rapid, reliable method for starting and synchronizing converters, and a quick and steady operator."

Three methods are usually employed for starting converters, namely:

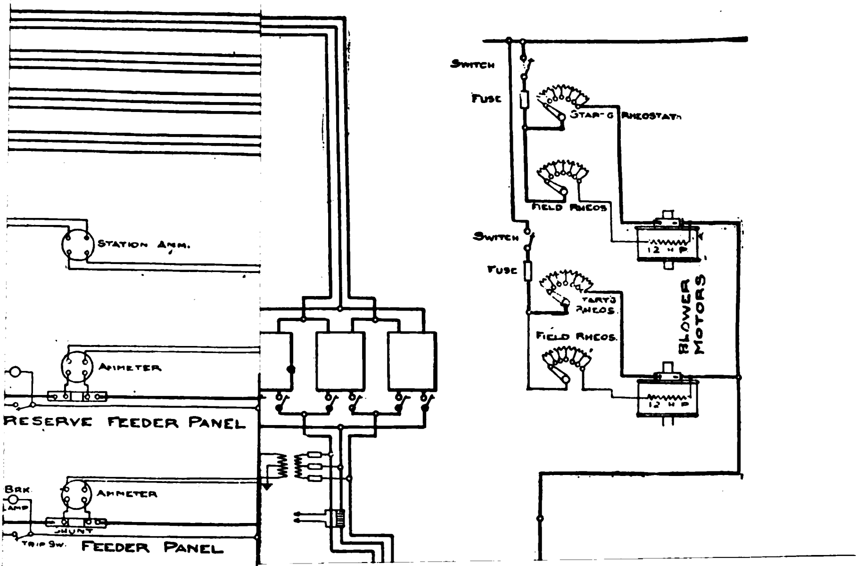
A. Starting from the direct-current side.

B. Starting by means of a small direct-connected induction motor.

C. Starting from the alternating-current side.

Method A. The converter in this case is started as an ordinary shunt motor, receiving its current either from a shunt-wound generator or from the direct-current bus-bar. A double-throw switch is usually provided so that the converter may receive current from either source. Ordinarily, when started by current from a shunt-wound generator about two minutes are required to start, to synchronize, and to connect to the bus-bar a 1500-kw. converter. In emergency cases the machine is started by current from the direct-current bus-bar, and only a minute and a half is required to place it in service. The advantages of method *A* are the rapidity of starting, the smallness of first cost, since it requires but one starting set for all the converters, and the slight expense of maintenance.

The disadvantages of the method consist in a small



Station Amm.
Ammeter
Reserve Feeder Panel
Brk. Lamp
Ammeter
Shunt
Trip Sw.
Feeder Panel
Switch
Fuse
Field Rheos
Switch
Fuse
Field Rheos.
12 HP
12 HP
Blower Motors

factor of reliability and the possibility of a heavy surging of current during the process of synchronizing. The latter disadvantage, however, may be obviated by the use of a simple modification of the switch-gear, devised by Mr. H. G. Stott. This device is now used in connection with the Interborough Rapid Transit Company's equipments. It consists in closing a local storage-battery through the tripping coil of the circuit-breaker of the starting bus-bar a fraction of a second before the converter oil-switch closes. The converter then runs practically free from the direct-current side, self-excited, at the instant the oil-switch closes. The oil-switch motor and the tripping-coil of the circuit-breaker are in multiple with the battery when the control-switch on the bench-board has been closed. The oil-switch requires only 0.4 of a second for complete connection, whereas the circuit-breaker operates almost instantly.

When the converter is rotating slightly under or above its synchronous speed, and the pointer of the synchronism indicator is moving slowly round the dial, if the local storage-battery switch be closed just as the pointer is approaching zero it is possible to connect the converter through the transformer to the alternating-current bus-bar without the operator being conscious of the fact except from the noise made when the oil-switch closes. A complete wiring diagram of a sub-station in which this method of starting converters is employed is shown in Fig. 69.

Method B. With this method, by means of a small induction motor mounted upon the main shaft of the converter, the converter is brought up to synchronous speed (see Fig. 70 for Westinghouse Converter). The starting motor has fewer poles than the converter and therefore a higher normal speed. A variation in speed may be obtained by placing a slight load upon the converter through the medium of a resistance shunted across the brushes, the converter being self-excited. Varying the resistance in series with the converter field-coils will also cause a

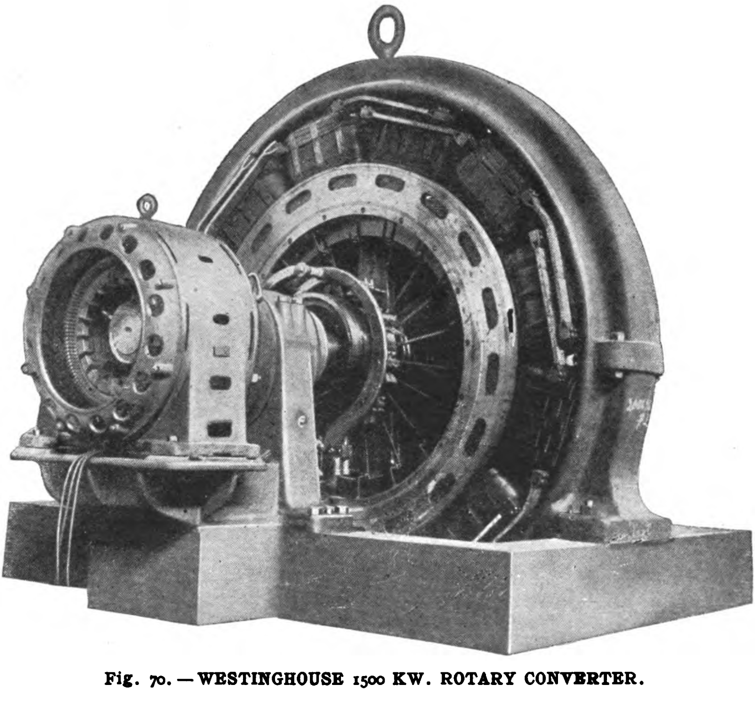


Fig. 70.—WESTINGHOUSE 1500 KW. ROTARY CONVERTER.

slight variation of load upon the induction motor. This is the means usually employed, the electrical connections for which are shown in Fig. 71.

The main advantage of this method is the increased factor of reliability, since each converter has its individual starting motor. For mechanically starting the converter armature it is common practice to install a motor somewhat smaller than the motor used for driving the exciter genera-

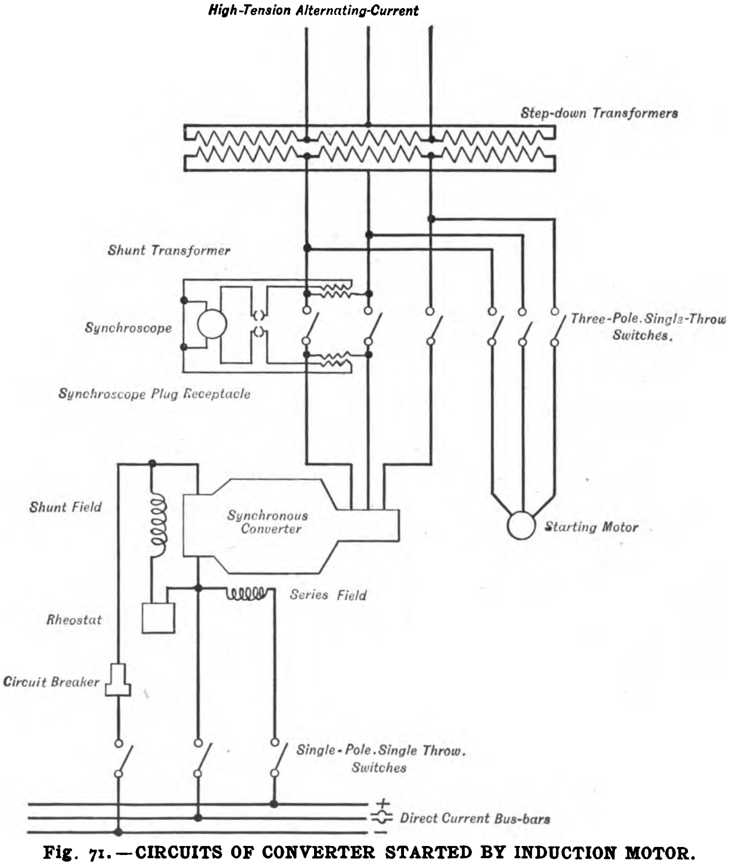


Fig. 71.—CIRCUITS OF CONVERTER STARTED BY INDUCTION MOTOR.

tor in method *A*. As a result the converter does not accelerate so quickly with this method as when started from the direct-current bus-bar. One of the disadvantages of this method is the fact that owing to the torque of the induction motor varying with the square of the impressed voltage, a very small drop of voltage will keep the motor from starting at all. For instance, if only 80 per cent voltage were received, as is sometimes the case after a bad shutdown at the power house, or on the system, due to a variety of causes, it is highly improbable that the converter will start. Another bad feature is that in case of a burn-out on a starting motor, the converter will be crippled. Other disadvantages are the greater first cost and increased cost of maintenance.

Method C. In this method, the ordinary connections for which are shown in Fig. 72, two sets of taps on the low-tension side of the step-down transformers are commonly used. These taps are connected to a two-way switch, the middle terminals of which are connected to the converter slip-rings. To prevent an excessive starting current, reactance is inserted between the converter slip-rings and the low-tension windings of the transformer. During the discussion of this paper before the American Institute of Electrical Engineers, the following statement was made by Mr. Taylor of the General Electric Company in connection with this reactance: "There seems to be a general impression that the purpose of the reactive coils is to permit of starting from the alternating-current side. As a matter of fact the reactive coils are used for several reasons. to permit of automatic compounding, to compensate partly or wholly for drop in the transmission line, transformer, and in the converter itself; to allow the converter to run under variable load with comparatively slight changes in power-factor; to make it almost unnecessary for a station attendant to change the adjustment of field rheo-

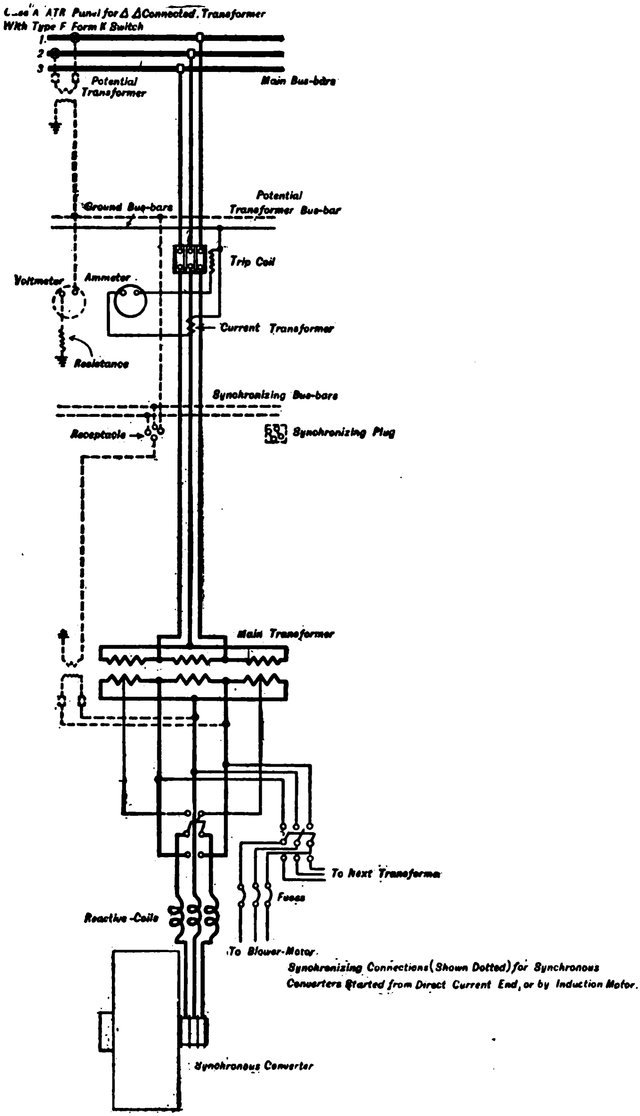


Fig. 72.—CIRCUITS OF CONVERTER STARTED FROM ALTERNATING CURRENT SIDE.

stat; to permit the desired division of load between converters.

"All such factors as brush resistance and field resistance become of small importance when reactive coils are used, as there is no more difficulty in securing adjustment of load between converters than with any class of direct-current machinery.

"Reactive coils permit the running in parallel of machines of different manufacture, or of different rating of the same manufacture. For example, I call to mind a case where the secondary voltage on one bank of transformers in a substation is 370 volts, and on another bank in the same substation the pressure is 380 volts, and there is no difficulty in dividing the load between two converters connected respectively to each of the two banks of transformers."

The converter is started as an induction motor by throwing the two-way switch so that the low-potential taps are connected. The field switch is left open while starting. When the current has fallen sufficiently low — the converter speed increasing — the field-switch is closed. If the converter is in step at this point the voltmeter connected across the direct-current brushes will indicate the direct-current voltage corresponding to the first set of alternating-current voltage taps. If the voltmeter tends to indicate the wrong way, the field switch is opened and reversed, causing the converter to slip a pole and build up correctly. The two-way starting switch is then thrown in the opposite direction, connecting the converter directly to the normal voltage taps. As the converter is in step, the speed will not change with increase of voltage.

It is usual with this method to start converters of 300 kw. or less, from starting taps giving one half normal voltage.

Converters varying from 300 kw. to 1,500 kw. are started by voltages of one third and two thirds the normal voltage. Referring to Fig. 73, two triple-pole, double-throw, starting switches are employed. The operation consists of first closing upward the switch at the left in the figure, followed by closing upward the switch at the right. This connects the converter to the first set of voltage taps. The field switch is then closed, or reversed, and closed again until the machine is in step. The switch at the right in the figure is then closed downward, connecting the converter to the second set of voltage taps. The switch at the left is then closed downward, connecting the converter directly to the normal transformer taps. On the one-third voltage taps, with 25-cycle converters, the current at starting is generally a little less than that at full load.

Owing to the large ratio of the field turns to those of the armature, high electromotive forces are likely to be induced in the field windings when making use of this method of starting. It is common practice to provide a field switch which disconnects the windings at several points, as represented by Fig. 74.

With this method no time is lost in adjusting the speed as the converter builds up into synchronism, but an objection to the method is the large current drawn at starting. This, however, is generally at a power factor that yields a correspondingly increased starting torque, and brings the converter up to synchronous speed in a shorter space of time. Another important advantage is the large factor of safety due to the entire absence of starting sets and starting motors. The additional field switches, however, consume additional time for their manipulation.

The starting switches used with this method may be

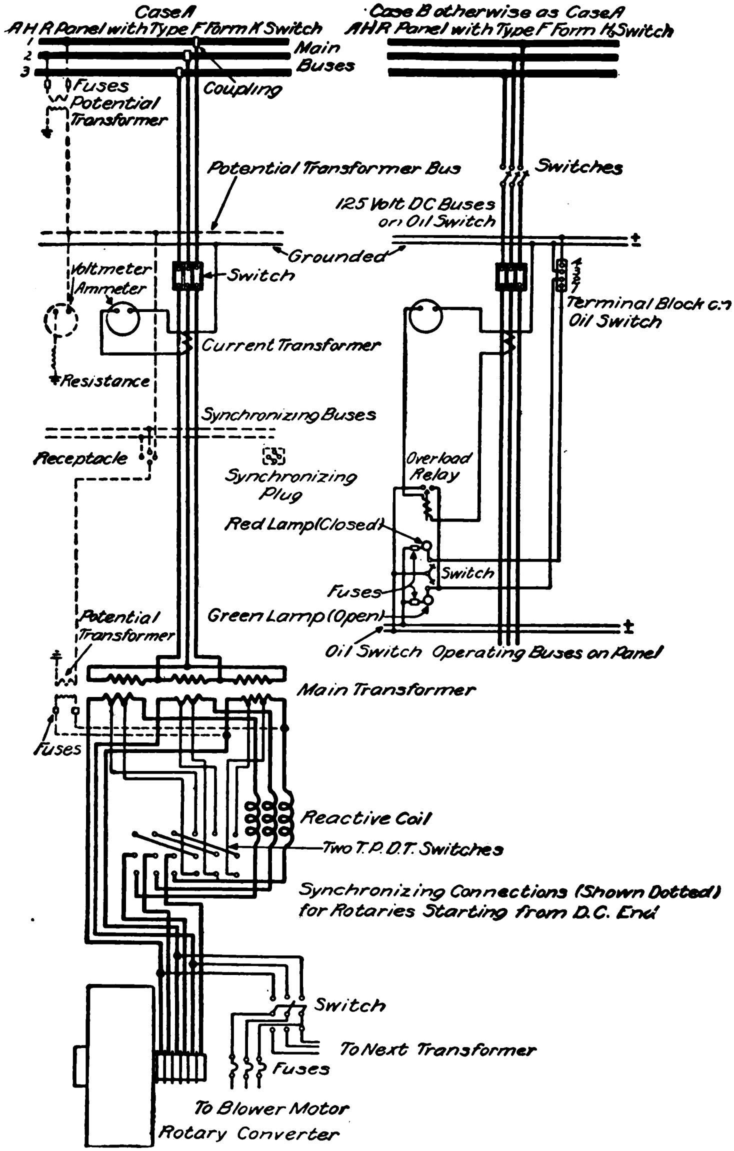


Fig. 73.—CONVERTER CIRCUITS WITH MULTIPLE VOLTAGE TAPS FOR A.C. STARTING.

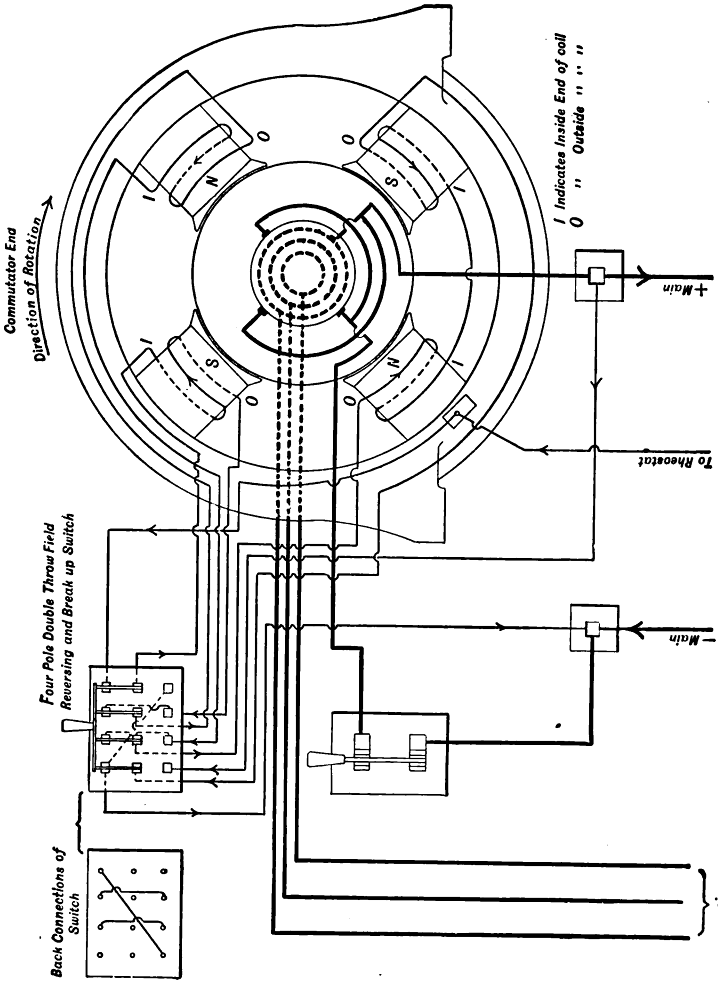


Fig. 74.—BREAK UP FIELD SWITCH.

observed by referring to the illustration of the New York Central and Hudson River Railroad sub-stations, Fig. 62, page 133. They are two double-throw, three-pole switches mounted near the first transformer.

The time ordinarily required to put converters in service when using this method is approximately as follows:

300 kw.	45 seconds;
1,000 kw.	75 seconds;
1,500 kw.	120 seconds.

It is possible to start these converters more quickly. The following times have been recorded, though they do not represent the minimum:

300 kw.	16 seconds;
1,000 kw.	40 seconds;
1,500 kw.	65 seconds.

This includes the time necessary to close the high-tension alternating-current switch of the converter transformer, the time of starting by means of air-brake lever switches, and the time included in closing the field switches, the direct-current circuit-breakers, and the line switch.

Curve shown in Fig. 75 illustrates one of a series of tests made by the writer upon converters started upon the alternating-current side. The converter reached synchronism in 32 seconds on the first set of voltage taps. It was a 1000-kw. machine. The minimum time value ever reached by the writer for the whole operation of starting for a 1000-kw. machine was 28 seconds.

The chief disadvantages of the method are the high potential generated in the field windings at starting, the large starting current which may affect the regulation of the system, and the necessity for a modification in design. The two former disadvantages are minimized by the arrangements previously mentioned. The latter disadvantage, however, necessitates the modification or perhaps the elimination of the circular dampers embracing the entire pole-piece. It should not be inferred, however, that converters cannot be started from the alternating-current side when equipped with pole dampers, but the starting current in such cases

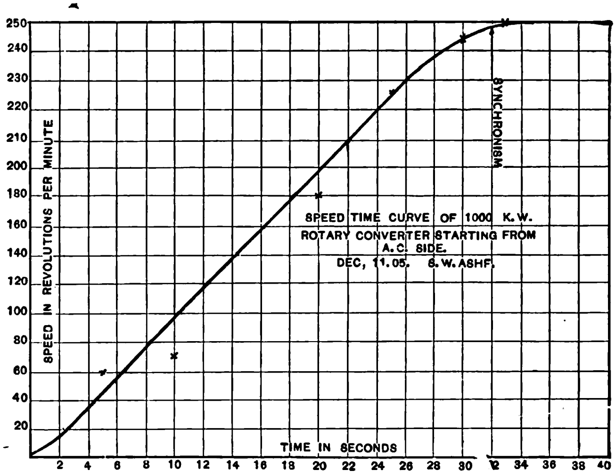


Fig. 75. — SPEED LINES STARTING CURVE FOR CONVERTER STARTED FROM A. C. SIDE.

is excessive, owing to the fact that the dampers neutralize the self-induction of the armature. The writer has in mind an instance when a 1,500-kw. rotary converter was so started, and the starting current was three times full load value or twelve times that when started from the direct-current side from a starting set. A converter constructed without pole dampers will "hunt" on the slightest provocation, and ultimately trip itself out of the circuit.

For instance, a short circuit on some other part of the system, throwing a lagging current on the line, or some slight trouble in the governor of one of the engines supplying it, or anything which may happen to vary the angular velocity of the prime mover, is sufficient to start hunting in a synchronous converter. The starting current is approximately four times that used with methods *A* or *B* for the same capacity machine.

It should be noted when considering the time necessary to start converters that this time depends to a great extent upon the personal peculiarities of the operator. Moreover, the interval of starting for all methods has been so far reduced as to be adequate to the demands of railway operation. When an excessive and steady overload comes upon a station, the operator may easily trip a few of the section breakers, while an additional machine is accelerating. The cars on the rail sections fed by this sub-station will receive slight power from adjoining rail sections as the *I R* drop will be excessive. The cars will consequently slow down. When the power has been off the circuit for about 20 seconds and the speed of the converter is approaching synchronism, the circuit breakers formerly opened may be closed, and the other section breakers and switches may be opened. In this way trains may be kept moving during the time required to start, synchronize, and place on the bus-bars this additional machine. Passengers in the cars will hardly be conscious of what has occurred.

Details of the Starting of a 1500-kw. Converter from a Motor Generator Set. — This method is employed by the Interborough Rapid Transit Co. of New York. The starting set consists of a three-phase induction motor of

150-kw. directly connected to a 120-kw. direct-current shunt motor. The induction motor is fed from the low-tension side of three 50-kw. transformers. The motor-generator oil switch is controlled from the operating board, but an oil switch operated manually is located on the motor generator panel near the starting set. When the motor generator oil switch has been closed by the operator a signal lamp is illuminated on the motor generator panel for the benefit of the rotary tender. A double-throw starting switch is also located on the starting panel in addition to an ammeter and a recording wattmeter. The negative switch, Fig. 76, and the equalizer switch of the rotary are located on the main floor near the individual converters.

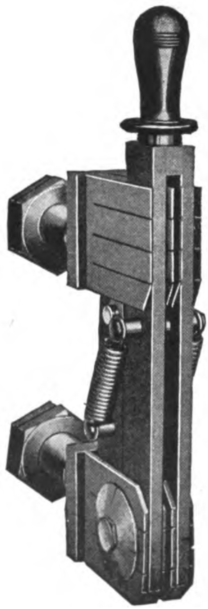


Fig. 76.—G. E. NEGATIVE CONVERTER SWITCH.

Operation. — The negative rotary switch and the equalizer switch are first closed by the rotary tender. The oil switch is then closed by the switchboard operator from the operating board, the signal lamp on the motor generator panel lighting. The rotary tender then closes the starting switch in the first position, and immediately closes the oil switch on the same board. The motor generator then begins to operate, the switchboard ammeter indicating the amount of current being taken by the induction motor. When the current falls to practically a minimum value the starting switch is thrown over to the running position. Meanwhile the switchboard operator proceeds to perform the following manipulations in the order given, first closing switches connecting machine oil switches to high-tension bus-bars.

1. Place voltmeter plug in receptacle on panel corresponding to converter about to be started.

2. Throw field switch of converter to the right, which connects the positive field terminal of the converter to the positive armature terminal of the motor generator. Since the negatives of both machines are grounded, this arrangement permits of converter fields coils being excited from motor generator.

3. Close five-point switch, Fig. 77, on first point. This

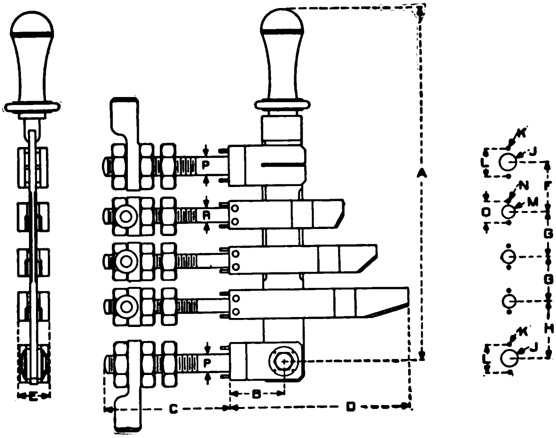


Fig. 77.—STARTING SWITCH.

switch is wired to the various points of the starting resistance of the converter, and is in circuit between the circuit breaker of the starting set and the converter starting switch.

4. See that field rheostat of the converter is adjusted to

position of all resistance out. This is so that the converter field will have maximum excitation.

The field rheostat of the starting set should then be adjusted so that about two thirds of its resistance will be in circuit. Where the operator is uncertain as to the proper location of this switch handle it is preferable to have all resistance in circuit and gradually reduce it step by step when the remaining starting switches on the starting set have been closed, building up the field gradually until proper voltage has been obtained. The latter method saves the converter field the shock caused by connecting it directly to the circuit. This is not severe, however, owing to the choking effect of the inductance of the field coils.

5. The direct current circuit breaker of the starting set should then be closed.

6. The two-way single pole motor generator switch is to be thrown up. If thrown down, the starting circuit of the converter will be fed from the bus.

7. The voltmeter of the starting set should then indicate about 700 volts. If it does not the field rheostat should be adjusted. The starting switch of the converter is then closed "up" and the converter should begin to operate. The sudden rush of current into the converter will approximate 450 amperes. The five-point switch should not be moved until the current passing through the armature of the converter falls to 100 amperes.

8. The five-point switch should then be closed notch by notch, waiting each time until the current falls to 100 amperes. This operation should continue until all the starting resistance has been cut out, the rotary operating as a shunt motor being fed directly from the starting set.

9. The field switch of the converter should then be thrown over to the left, making it self-exciting.

10. Adjusting the field rheostat of the converter and lowering the voltage of the starting set to about 50 volts above the bus, arrangements should be made to synchronize.

With the General Electric Co.'s switchboard two plugs are arranged to connect the synchronism indicator in the circuit. This arrangement where the secondaries of the potential transformers are grounded is illustrated in Fig. 78.

One plug should be placed in a receptacle on the panel corresponding to any machine which is operating, and the other plug should be similarly placed in a receptacle corresponding to the machine starting. Two other receptacles are used, one in case a machine is being started from the bus, and one when the station is without power. In this case the starting set furnishes the extra circuit for the receptacle.

11. The pointer of the synchronism indicator, Fig. 79, will now start to move over the dial. The field rheostat of the converter should then be adjusted until the speed of the rotary is synchronous. When the pointer of the indicator is moving slowly over the dial and approaching zero the converter oil switch should close at the instant of synchronism. As this switch is operated by a motor which takes about .4 of a second to close the switch it is evident that to close the switch at the instant of synchronism the local battery switch controlling the motor must be closed .4 of a second before the pointer, of the dial indicates perfect synchronism. This time interval corresponds to a motion of about one inch on the circumference of the dial when

the pointer is moving slowly. It depends, however, entirely upon the speed with which the pointer is moving. If the operator waits until the pointer indicates exact phase rela-

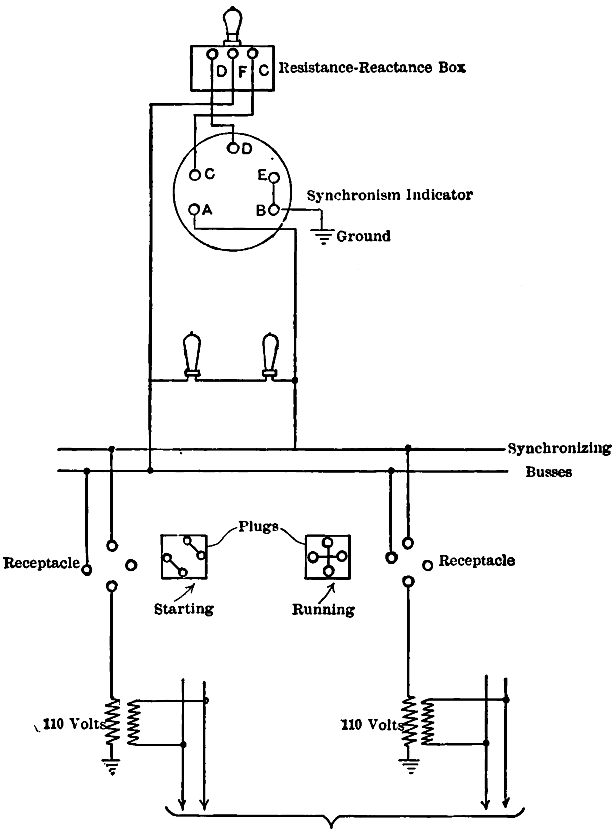


Fig. 78. — G. E. SYNCHRONIZING CIRCUITS.

tion and then closes the auxiliary switch, the converter may be 15° or more out of step before the oil switch closes. In this case the converter will spark viciously. If the converter is much out of step, a ball of fire and smoke will come from the machine accompanied by a dull roar. The damage in such cases is usually quite severe.

The converter is then ready to be placed on the direct current bus, and all the auxiliary starting switches except

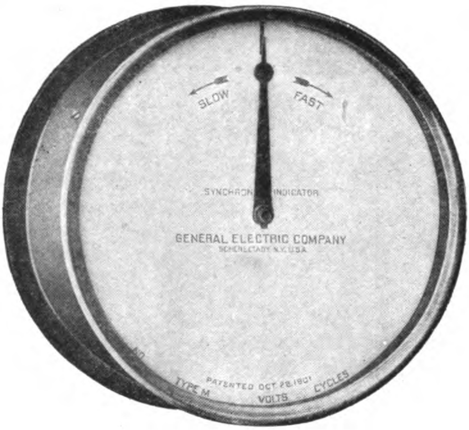


Fig. 79.—SYNCHRONOUS INDICATOR (G. E. CO.).

the field switch and the armature starting switch should be opened. Tne armature starting switch should be thrown down. The positive direct current circuit breaker, Fig. 80, and the positive switch should then be closed.

Precautions to be Observed when Connecting a Rotary in Synchronism to the Direct-Current Bus. — When a rotary has been synchronized and is about to receive its load, the following precautions should be taken: The polarity and voltage of the direct-current brushes should be tested with a voltmeter to see that the machine voltage corresponds to the direct-current voltage of the bus, as well as to see that the polarity has not become reversed. The field rheostat should then be adjusted so that when the rotary is connected to the direct-current bus it will take a minimum load. This is readily accomplished by having most of the field resistance in the circuit. If the proper field resistance is not in the circuit, the voltage of the rotary will be slightly lower than the bus, and when the positive rotary switch is closed, connecting the machine to the bus, a sudden rush of current will enter the machine from the direct-current side, and the reverse-current relay will trip the direct-current circuit breaker.

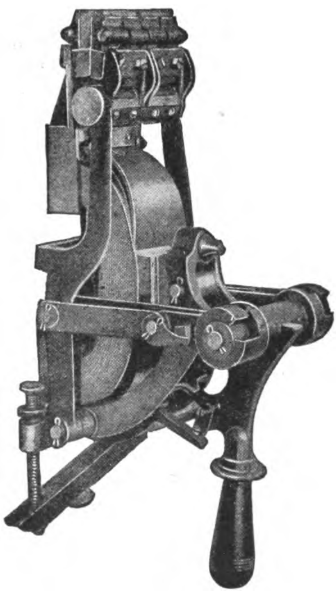


Fig. 80. — POSITIVE CIRCUIT BREAKER (G. E. CO.).

With a 1,500-kilowatt machine the proper time to throw the load upon the machine is when the individual load on the rotaries operating in the same station is about two thirds full load. If the individual load is greater than this, the rotary being placed upon the circuit is liable to take such a heavy share of the load as to trip its oil switch, throwing the machine out of step. When a rotary has been stationary for some time its field resistance changes quite perceptibly. This is quite noticeable when the machine has been operating a few hours and has had time to warm up.

Load Adjustment. — Each rotary is usually provided with its individual set of instruments, consisting of a direct-current ammeter, a recording wattmeter, an indicating wattmeter, a power-factor meter, and an alternating-current ammeter. The last-named instrument is seldom used by the station operator.

The power-factor meter is of primary importance to the operator. With this instrument in view, the individual load on the rotary may be adjusted by the field rheostat, so that the rotary may have a lagging or a leading current. The machine should have unity power factor at full load. If the rotary be not in proper condition, and it is desirable to shift some of the load to the other rotaries, the field of the rotary is weakened by cutting in more resistance. This is not considered good practice, as the rotaries now built by the large companies are fully capable of standing temporary overloads, provided their maintenance is good. They should, therefore, always be in the best possible condition when operating.

When a rotary is to be disconnected from the direct-current bus it is good practice each time to try the reverse-current relay. The field rheostat of the rotary should be cut in entirely, the rotary dropping its load, and when there is sufficient difference in the machine and bus voltage, the reverse-current relay should trip the direct-current circuit breaker controlling the machine. The reverse-current relays are usually mounted on the rear of the circuit breaker panel. They consist of a soft-iron shell almost surrounding the positive feeder. This shell terminates in two poles, between which moves an armature whose motion is limited. This armature is energized by the local storage battery circuit previously mentioned. When the current in the feeder reverses, it magnetizes the iron core in the opposite direction, turning the armature. This through, a slender arm attached, closes the battery circuit through the tripping coil of the circuit breaker, which opens instantly. It is a very easy matter to break the flexible connections of a reverse-current relay when the relay is exposed. Operators while dusting behind the operating board may strike the terminals with the duster, rupturing the contact wires. This has happened several times to the writer's knowledge.

It is desirable to use plenty of time when disconnecting a rotary from the bus. When the field rheostat has been cut in and the reverse-current relay has tripped the direct-current machine bus circuit breaker, it is wise to allow the rotary to operate on the alternating-current side as a synchronous motor for about five minutes. Where railway circuits are operating heavy interurban trains the fluctuations of power consumption are sometimes quite heavy. If these fluctuations should occur while a machine is being "cut out" the load might be too heavy for the remaining machines, and, as a result, trip all the circuit breakers, putting out the station.

When the rotary about to be disconnected from the alternating-current mains is operating as a synchronous motor it is an easy matter to close the direct-current circuit breaker and switch, allowing it to carry the overload in the above-mentioned case, whereas if the machine were out of synchronism, resulting from tripping the oil switch, it would take at least a minute and a half to get the machine on the bus again. As a result the time-limit overload relays set only for a few seconds would trip the other machines out, shutting down the station. Caution: Never close a circuit breaker with its switch closed, and never open a switch without first tripping the breaker.

There is another possibility of trouble worth mentioning. Assume three rotaries feeding the direct-current bus, and also imagine the load to have fallen to such a point that the operator feels confident that two machines will carry the load. He decides which machine to take off the bus, and cuts in all of its field resistance, expecting the reverse-current relay to trip the machine circuit breaker. But suppose the conditions to be such that the relay does not trip the breaker and that in his excitement the operator trips out the circuit breaker on one of the remaining machines in preference to that on the machine whose field resistance is "cut in." This would throw the entire load on the remaining machine, which would be carrying anywhere from 100 to 125 per cent overload. Probably with a small fluctuation happening at this time, the station would be put out.

There are many such slight mistakes likely to throw out a station, and it requires a cool head and quick action on the part of the operator to know what to do on these occasions. Only after the operator has had considerable experience in watching other operators' troubles and in studying what to do in an emergency, can he guard against difficulties of this kind.

A good method is to ask yourself questions. For example, "What will happen if I open this five-point switch when I have made the first contact and the rotary is just beginning to rotate?" Answer: "The current interrupted will be from 400 to 500 amperes, and probably little will remain of the operator's switch."

Similar questions are, "What will happen if the wrong oil switch is tripped? if the field circuit is opened when the rotary is connected to the alternating-current mains?

if the rotary is compounded feeding the direct-current bus, and the alternating-current oil switch is tripped? if the rotary is operating alone and the field switch is thrown over to the starting set operating in preference to the switch of a rotary just starting?

It is unwise, however, in solving such problems to try the experiment, for sometimes protective devices refuse to protect, as the operator will find to his cost.

The Adjustment of Load between Sub-stations that Feed the Same Circuit. — Where all sub-stations are equipped with converters of the same capacity, it is desirable to have a definite rule governing the adjustment of power factor of converters, in order that the rail load may automatically distribute itself to the proper sub-stations. Such a rule requires the adjustment of the power factor of all converters so as to be unity at full load; but it fails where applied broadly, owing to the practical impossibility of finding any two converters of the same capacity, with identical characteristics and equal brush contact resistances, even though manufactured by the same company. This rule is usually observed, however, with discretion by sub-station operators, and its observance yields good results. But if the rule be adhered to rigidly, the results are not altogether satisfactory.

For instance, assume two converters operating in multiple between a common alternating-current bus-bar and a common direct-current bus-bar. Assume also that the field resistances of the converters are adjusted for unity power factor at full load. When the load upon both machines is greater than the combined full load capacity of each machine, one converter may draw more than half the load. Further, when the total load is less than the combined normal load of both machines, the other converter may absorb the greater proportion of the load. This condition is aggravated by the resistance of the converter field coils changing with the temperature, and also by the maintenance of the converter direct-current brushes.

When an individual converter in a sub-station is disconnected from the direct-current bus-bar, it does not follow that the original station load will distribute itself over the remaining converters operating in multiple. Moreover, when an additional machine is connected to the circuit, the sub-station will draw more of the load from the adjoining sub-stations. The energy in this way surges back and forth with each operation. It is obvious, therefore, that it is impossible to frame a rule of this character which may be adhered to rigidly. If storage batteries are employed as a method of regulation, keeping the individual load upon the converters practically constant, this rule would apply more generally: but where the energy fluctuation upon the converters varies from quarter load to 50 per cent overload and sometimes 100 per cent overload, it is obvious that the previous rule will not apply. The same reasoning holds good in the case of sub-stations equipped with machines of different capacities.

The Regulation of Load. — Railway operation does not call for as close a voltage regulation as is requisite for electric lighting circuits. Economic operation, however, demands that converters be run on as constant a load as possible. The general use of storage batteries for load regulating in railway work seems to have been retarded owing to their objectionable features; for instance, their acid fumes, the necessity for special wiring, and their heavy depreciation. In addition, their enormous first cost has placed them actually out of competition with synchronous converters and generating apparatus. The usefulness of storage batteries, however, in railway work is being more and more appreciated, as is evidenced by their recent applications. An interesting development in connection with storage batteries is a carbon regulator put to use during the last few years by the Electric Storage Battery Co.

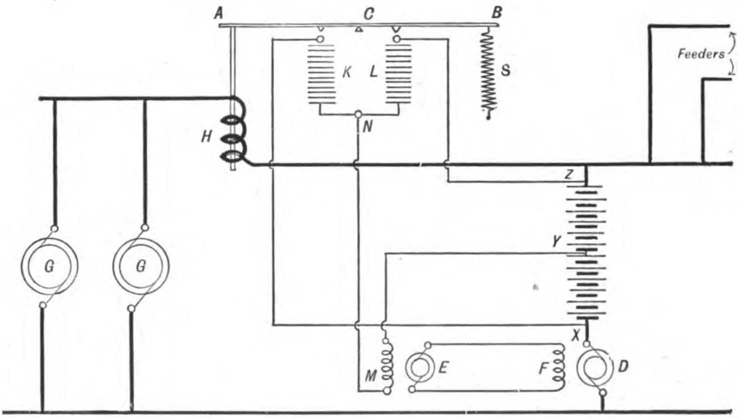


Fig. 81.—CIRCUITS OF CARBON REGULATOR.

It consists of a variable carbon resistance which is used in connection with pilot cells and an exciter, to vary the excitation of the field coils of a booster.

Referring to Fig. 81, *H* is a solenoid carrying the total generator load, which acts on a soft-iron plunger suspended from the lever *A-B* of the carbon regulator. At the other end of the lever is a spring *S*, whose tension is adjustable. *K* and *L* are piles of carbon discs on the opposite sides of the fulcrum *C* of the lever. The resistance of these piles is altered by slight variation in mechanical pressure, produced by slight fluctuations of current in the coil *H*. The details of the electrical connections are self-explanatory. The battery booster is represented by *D*, *F* being its field coils. *E* is a small exciter, whose

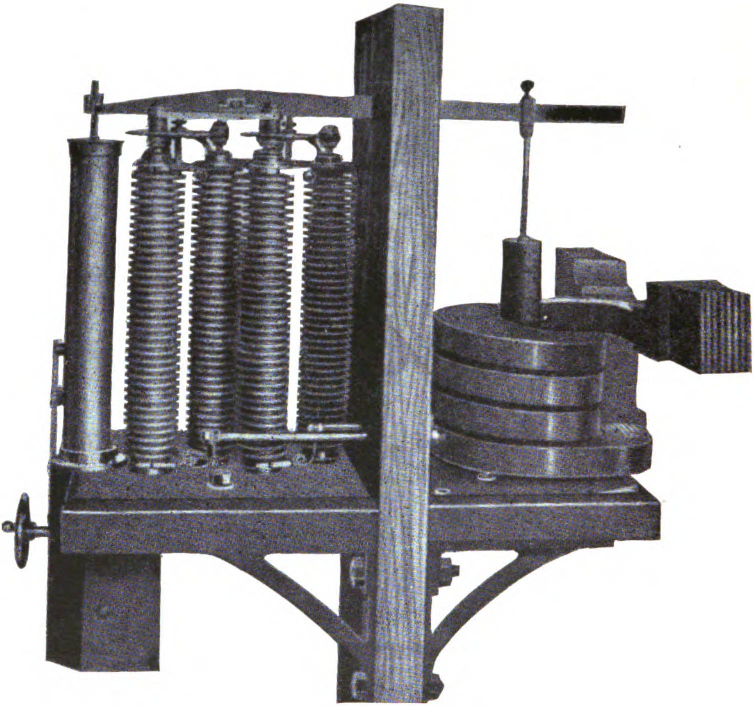


Fig. 82.—CARBON REGULATOR.

field coils, *M*, are connected to the carbon regulator as shown.

Consider the operation of this regulator, a perspective view of which is shown in Fig. 82. As the lever arm is raised or lowered, the resistance increases in one arm and decreases in the other, causing wide variations in voltage across the exciter field coils, the direction and intensity of the current in the coils varying accordingly. The action is somewhat analogous to that of Wheatstone's bridge.

With the polarity of the booster changing and its field excitation varying in intensity, it is possible automatically to charge the main battery or to raise the battery voltage so as to carry part of the load of the bus-bar. By limiting the motion of the lever arm it is possible to limit the load which the battery will carry under extreme conditions. With this system close regulation of the load on the converter is obtained, as is evidenced by the load diagram, Fig. 83. This diagram was taken in the sub-station of the Lewiston & Auburn Electric Railway on October 7, 1905.

The Protection of Converters. — In the design and installation of circuit breakers, the inductance of the system is usually relied on to prevent an excessive rise of current during the interval of time elapsing between a short circuit and the opening of the circuit breaker. This, however, is not sufficient protection; for an excessive short circuit in the system, say during light load when only one machine is operating, will often cause a flash, accompanied by a shrill sound near the commutator of the converter. At first one might think that a reactance coil of low ohmic resistance could be placed in series with the breaker to minimize this effect; but a coil of constant reactance, resistance, or self-inductance could not entirely meet the conditions, owing to the variability of the time constant of the circuit. For instance, the self-inductance and resistance would vary with the distance from the sub-station

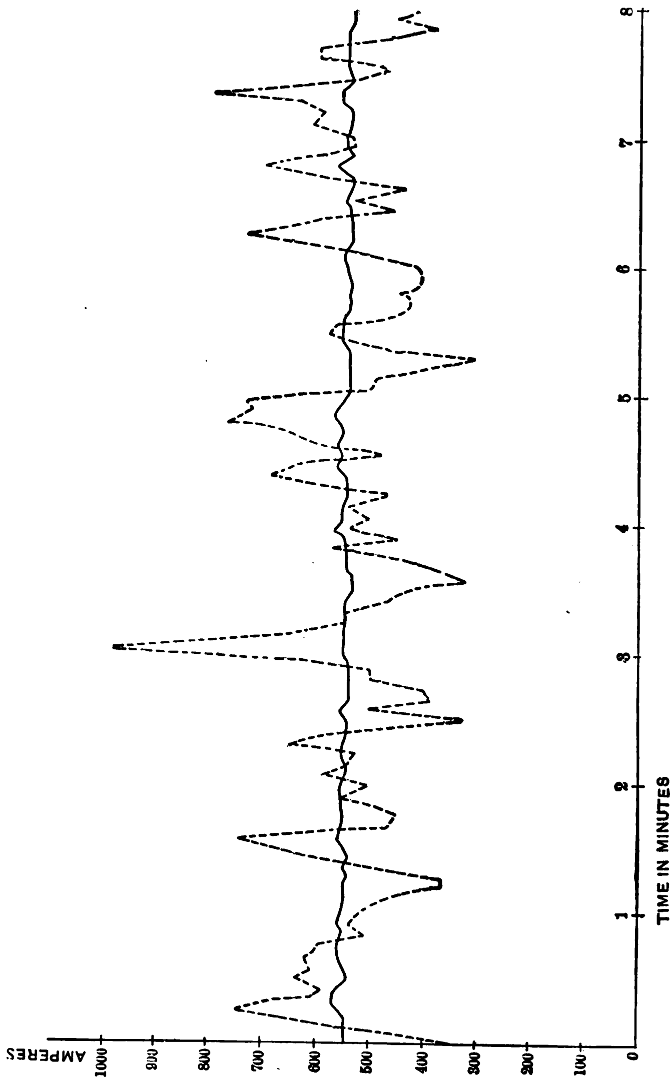


Fig. 83. — LOAD DIAGRAM SHOWING REGULATION WITH CARBON REGULATOR.

in which the short circuit occurred. Proper conditions, however, might be approximated and a coil designed which would partially protect the converter.

Where sub-stations are equipped with storage batteries which float on the system, there is a tendency for the storage batteries to bear the brunt of the load, in case of short circuit, permitting the converter circuit breaker to open, followed shortly by the opening of the battery circuit breaker. This, however, does not always prevent the converter from flashing over, owing to the fact that the velocity of chemical action at the electrodes of the battery, and the limitations of the velocity of migration of the ions of the electrolyte are insufficient to prevent this action. Theoretically, the converter bus-bar voltage would drop, the battery carrying the peak of the load. As a matter of fact, the battery does not always perform this function.

Noiseless Operation of Converters. — The operation of converters is usually accompanied by a shrill and disagreeable sound. It is not caused by the commutator, by the slip rings, or by air passing through the crevices of the armature, as is usually supposed, but is purely an electromagnetic phenomenon. It is probably the result of vibrations set up in the armature core teeth by the varying electromagnetic conditions of the circuit.

That this tone is caused by magnetic action may be illustrated by the following simple experiment performed by the writer. A converter was driven by a separate belt-connected shunt motor, and the speed was adjusted to 1,800 revolutions per minute. The converter was a four-pole machine, so that this corresponded to a frequency of sixty cycles. The converter field coils were unexcited and the machine operated practically without noise. Upon exciting the field coils, however, this shrill tone became audible, and then increased in intensity until upon over-excitation it became very loud. This would seem to indicate that the phenomenon is purely magnetic, and that it might be obviated or at least modified by proper design. The desirability of such modification must be evident in the case of sub-stations located in residential sections.

Maintenance of a Rotary Converter. — The successful performance of a rotary converter under various conditions of load depends almost entirely upon the amount of care bestowed upon the direct-current brushes. The writer has had occasion to study for several months the operation of 1,500-kilowatt rotaries built by the Westinghouse Electric and Manufacturing Company. The result of these observations has proved conclusively that these machines, where their maintenance is good, will readily stand overloads as high as 100 per cent for a short interval without the slightest signs of distress. After carrying an overload of 25 per cent for several hours (fluctuating load) the temperature was never higher than 40° C. If, however, the brushes and the commutator surface are not maintained in good condition, the inability of the machines to carry severe overloads is quite marked. This, however applies to all forms of commutating apparatus. To obtain efficient service from a rotary the following directions should be observed:

Directions for Efficient Operation. — 1. At moderate intervals use a piece of sandstone on the commutator until it is bright, smooth, and free from burnt commutator segments. Sandstoning a commutator requires from three to six hours' work, according to its condition.

2. Every three days go over direct-current brushes wiping off copper dust, sandpapering brushes that are burned in any way and which do not bear on the commutator over the whole brush surface. About one third of the brushes will have to be sandpapered each time.

3. With the same frequency go over alternating-current brushes, drawing a rag under them several times, so that the brushes will snap back in place, shaking out the dust. About once a month it will be necessary to take off the alternating-current brushes to clean them thoroughly, to clip off bad ends, and file off any uneven wear. If alternating-current rings need sandpapering, wait until the machine, if operating, is cut out and has slowed down to about half speed. Then apply sandpaper, pressing it against the slip ring with a flat piece of wood.

4. Never under any circumstances apply sandpaper to the slip rings of a rotary operating on the line. The sandpaper, covered with metallic dust, is likely to come into contact with two of the rings, forming a short circuit.

5. Keep the machine clean and free from metallic dust by frequently applying compressed air and clean rags. This dust collects in crevices of machine. The crevices between the connecting lugs of a 1500 Kw. Westinghouse Commutator are shown in Fig. 84.

6. If the machine sparks when the commutator is in prime condition and the direct-current brushes are properly maintained, look to the tension of brushes. This should be about 2.5 pounds. Under some conditions, such as when the brushes chatter under load, it is necessary to apply a little more tension. If brushes do not all have the same

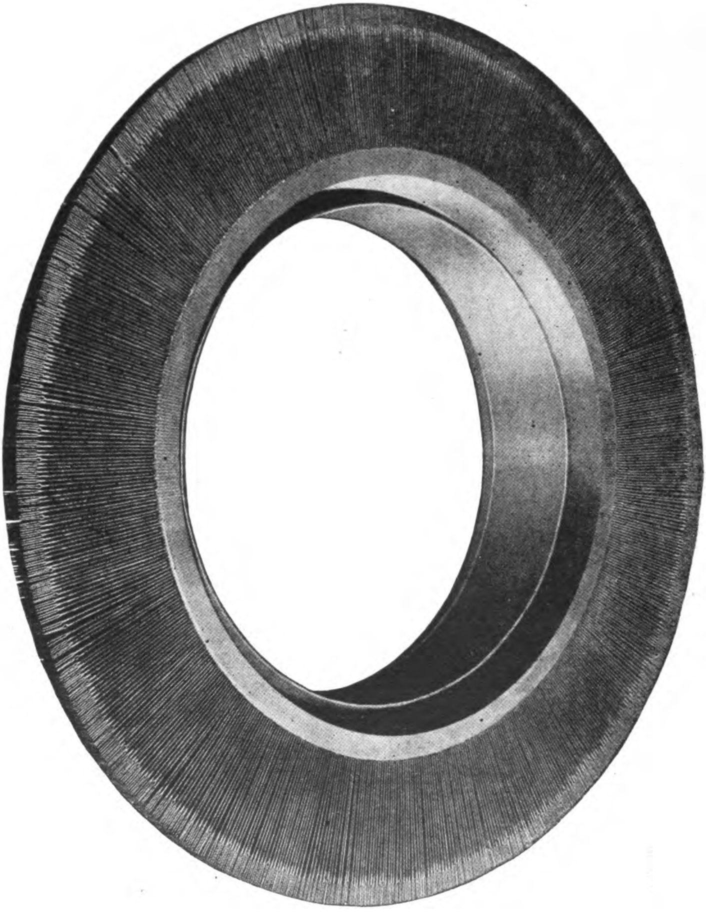


Fig. 84. — WESTINGHOUSE 1500 KW. CONVERTER COMMUTATOR, SHOWING CONNECTING LUGS.

tension, one or two may carry the entire load of a rocker-arm and spark quite viciously.

7. See that the rocker-arm is placed so that sparking will be a minimum at normal load. Also note that rocker-arms are placed equidistant. These conditions are usually looked after by the manufacturing companies when machines are first installed.

8. When the machine is operating, occasionally wipe off the commutator and slip rings with rags slightly moistened with oil, after which wipe again with dry rags. Do not use any more oil than is absolutely necessary on the commutator. Slip rings should be oiled more frequently than the commutator. Under normal load oiling at about hourly intervals will suffice.

9. When a machine has been operating and is being disconnected from the service, wipe off the commutator and slip rings so that oil will not coagulate.

10. Keep all bearings replenished with oil and see that they do not heat excessively.

When it is necessary to repair commutator a set of clamps similar to Fig. 85 is convenient.

How to Sandpaper the Direct Current Brushes. — In order to properly sandpaper a brush so that it will accurately fit the commutator the following method may be adopted: Two sizes of sandpaper are necessary — a coarse and a fine quality. This paper should be cut in strips about two inches in width and applied to the brush, as in Fig. 86. Usually all the brushes are removed, except the one being sandpapered. Pressing the brush against the paper and keeping the paper flush with the commutator surface, it should be drawn along that surface. The

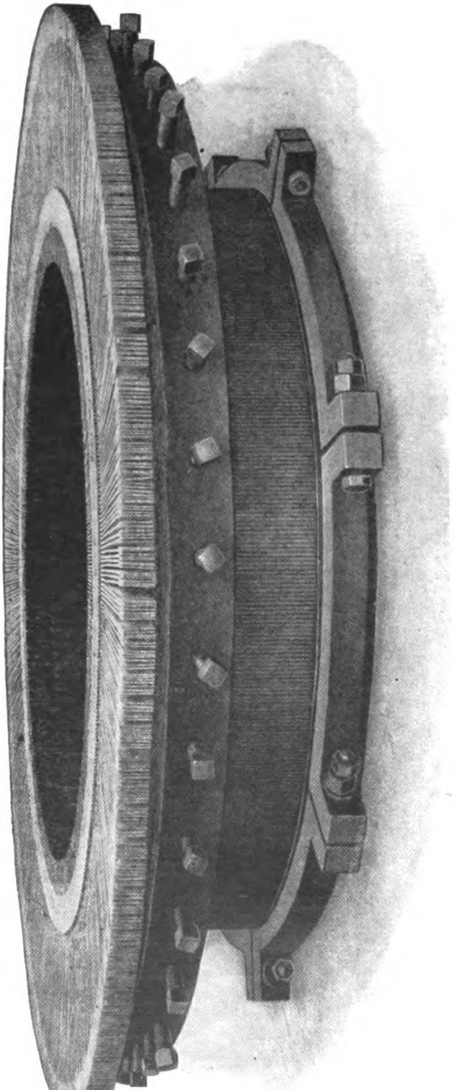


Fig. 85.—CLAMPS MOUNTED ON A 1500 KW. WESTINGHOUSE CONVERTER COMMUTATOR.

brush should then be raised, the paper slid back and the operation repeated. This should be continued until the brush fits the commutator accurately. Then the surface

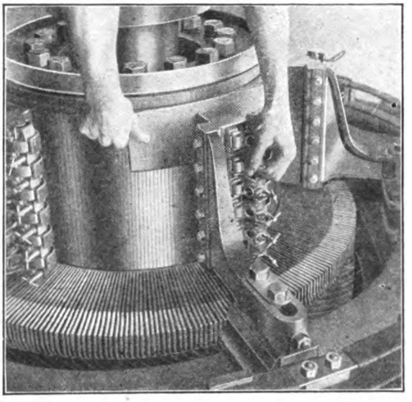


Fig. 86.—HOW TO SANDPAPER THE BRUSHES OF A CONVERTER.

of the brush should be finished in a similar manner with fine sandpaper.

If possible, a large piece of sandpaper surrounding the commutator should be applied, all the brushes bearing on its surface. The rotary, if driven by an induction motor, could then be started in operation and the whole work done in a few minutes. This method is obviously not applicable where a separate starting set is employed. The former operation may seem tedious, but it pays in the increased efficiency of operation of the rotary.

CHAPTER VII.

THE ROTARY CONVERTER.

Rotary Converters. — The rotary converter is the connecting link between alternating and direct-current systems. Converters possess one field and one armature, the latter being supplied with both alternating-current collector rings and a direct-current commutator. (See Fig. 87 for General Electric Converter.) This combines in a single machine the functions performed by two machines, namely, — a motor and a generator. A rotary converter may be considered as an alternating-current synchronous motor driving a direct-current generator, or as a direct-current motor driving an alternating-current generator. The converter makes possible the use of alternating current for power transmission, and direct current for distribution, thus saving the additional cost of copper which would be excessive if direct current alone was used. When a converter is employed to change direct current into alternating, it is characterized as an inverted converter. In practice converters are often termed "rotaries."

The armature windings of a converter are closed and resemble those of a direct-current generator, with the addition of alternating-current slip rings. (See Fig. 88 for formed coil of Westinghouse Converter.) These slip rings are connected to the armature windings at definite points having the proper phase relation. For each pair of

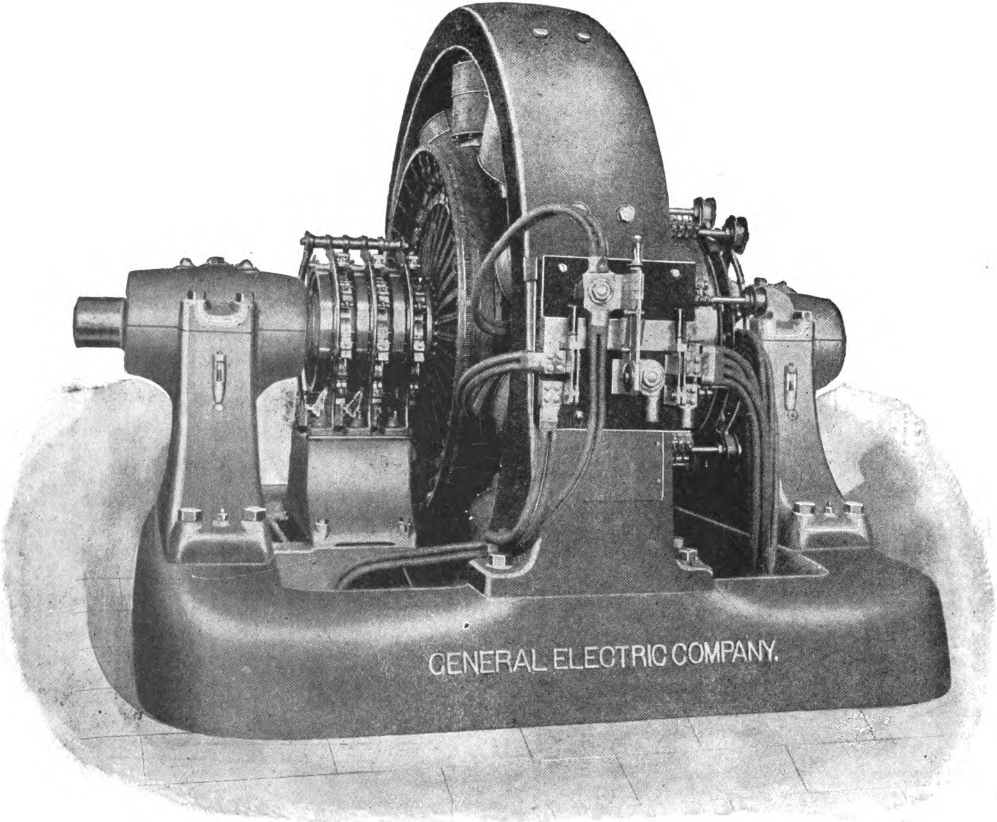


Fig. 87.—ROTARY CONVERTER.

poles there are a number of taps made in the armature winding corresponding to the number of phases. For instance, with a two-pole, three-phase machine, there are three taps spaced equidistantly 120 electrical degrees apart; while, with a four-pole, three-phase machine, there would be six taps spaced equidistantly around the armature, two taps being allowed to each slip ring.

With a two-pole direct-current motor, to construct a three-

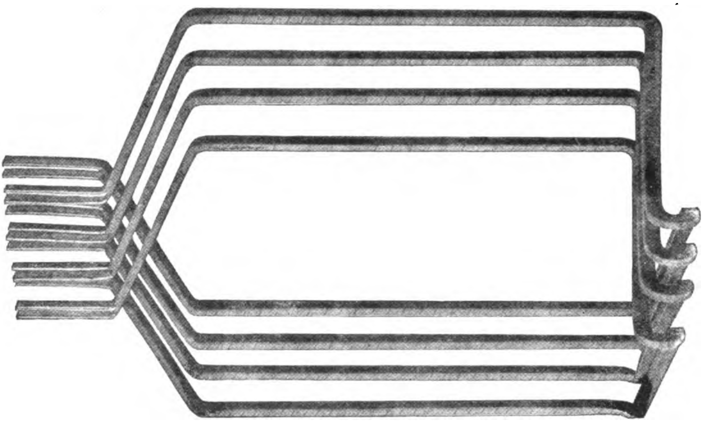


Fig. 88.—FORMED COIL OF CONVERTER.

phase rotary, it is simply necessary to tap the armature windings at three points 120 degrees apart and to connect these three points to three slip rings. The armature taps of a large machine should be spaced equidistantly, otherwise the instantaneous E.M.F.'s, which will be induced in the sections of the armature windings connected in parallel between adjacent slip rings, will not be similar in magnitude, and will not have the same phase relations. As an example of a three-phase machine may be cited the case of the 1500 kw. rotary converters manufactured by the

Westinghouse Manufacturing Company. These machines are provided with twelve poles and three slip rings. Figs. 89 and 90 show the armature windings of these converters. Each slip ring has one tap to the armature winding for each pair of poles, or six taps in all, the total number of taps for the three slip rings being eighteen.

It is customary with converters of large capacity to have equipotential points on the armature windings in similar phases cross-connected. This tends to distribute the load properly over the converter windings. Converters are manufactured for operation on single-phase, two-phase, three-phase, six-phase and twelve-phase, although single-phase and twelve-phase machines are seldom used. Two-phase machines have four collector rings, three-phase machines have three collector rings, and six-phase machines have six collector rings.

Rotary converters may be separately excited, but they are generally self-excited, being shunt or compound wound according to the nature of the service. In railway work where the load is variable and light, as in the case of inter-urban propositions, converters are sometimes compound wound in order to maintain the direct-current voltage constant, and to compensate for the drop in the supply circuit as the load increases. On the other hand, with large city problems, where flexibility of manipulation is desired, the converters are operated without their compound coils.

Voltage Relations. — The ratio of alternating-current voltage to direct-current voltage in a rotary converter depends upon the number of phases, upon the wave shape of the alternating current supply, upon the lead given to the direct-current brushes, and, to a slight extent, upon

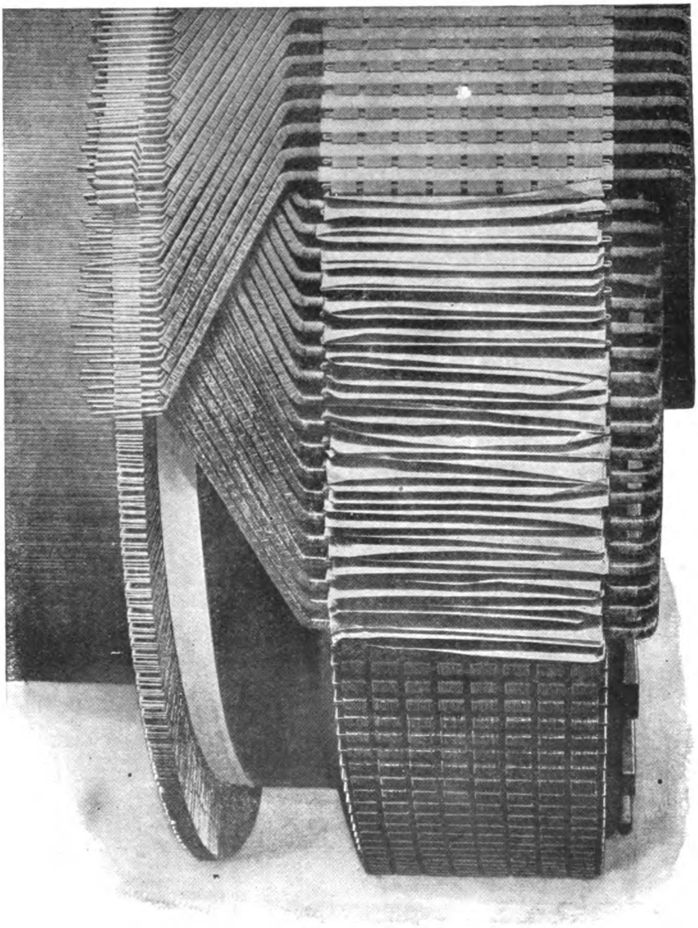


Fig. 89.—(Commutator Side) ARMATURE WINDINGS OF WESTINGHOUSE 1500 KW. CONVERTERS.

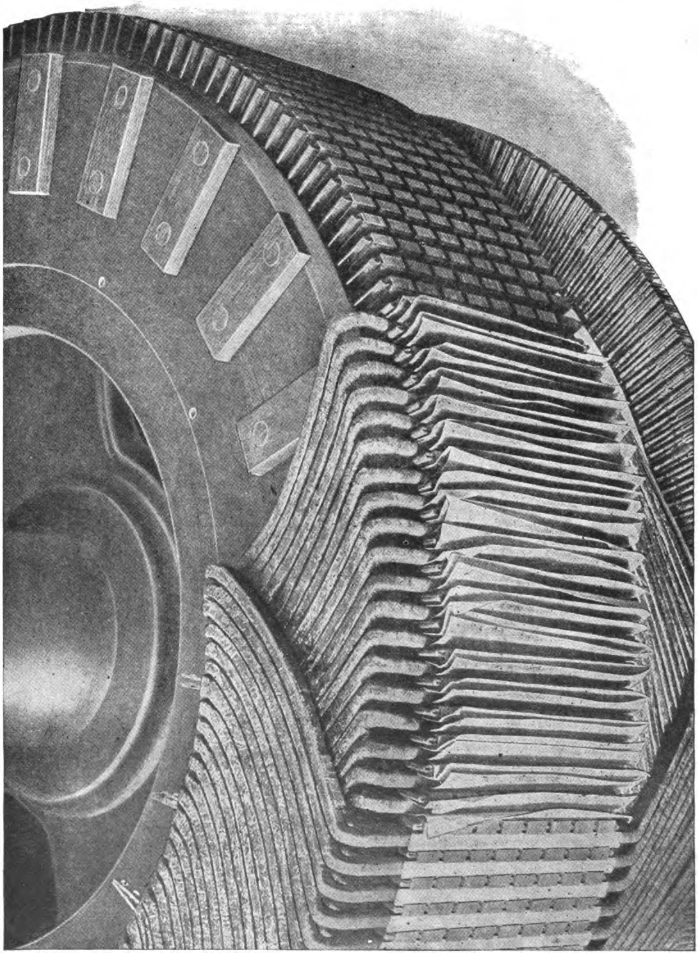


Fig. 90.—(Slip Ring Side) ARMATURE WINDINGS OF WESTINGHOUSE 1500 KW. CONVERTERS.

the excitation of the field. In any given machine the direct-current voltage depends practically upon the alternating-current voltage supplied.

To find the ratio which exists between the direct-current E.M.F. and the alternating-current E.M.F.

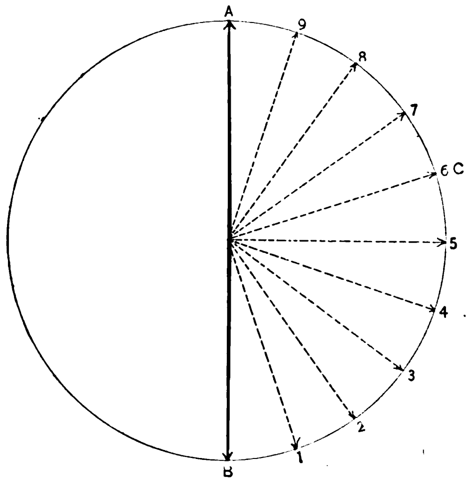


Fig. 91.—INSTANTANEOUS E.M.F.'S OF CONVERTER.

Let E_d = the direct-current voltage, *i.e.*, the voltage between any two successive direct-current brushes;

E_a = the alternating-current voltage, *i.e.*, the voltage between any two successive slip rings of an "*n*" ring converter;

e = the maximum E.M.F. generated in any single armature coil;

c = the number of coils per pole pitch. The electrical angle 2π is subtended between the centers of two poles of the same polarity.

If we consider the distribution of the magnetic flux to follow the sine law, then the E.M.F. generated in any coil of the armature winding is a sine function of the time, and it varies as the cosine of the angle subtended between its position and a point directly under the center of a north pole. The angle must be measured in electrical degrees.

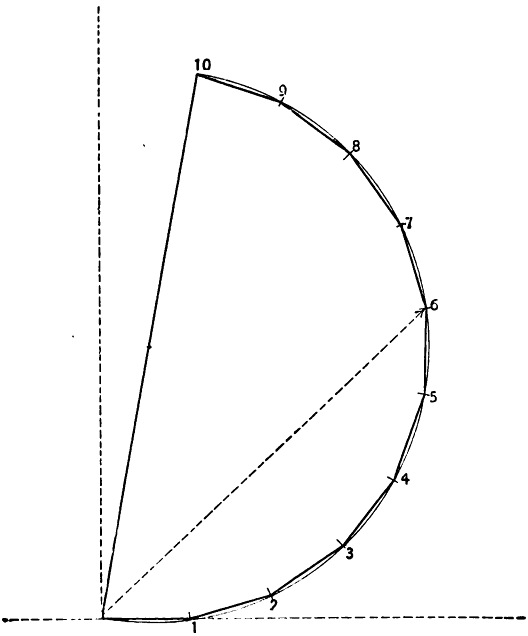


Fig. 92.—RESULTANT E.M.F. OF CONVERTER.

Consider the coil to be displaced at an angle of a electrical degrees from the center of a north pole. Its instantaneous E.M.F. is $e \cos a$ volts. The E.M.F.'s induced in the consecutive coils will differ in phase by a constant amount represented by the angle π/c electrical degrees, as shown in Fig. 91. In order to determine the resultant alternating-current pressure between any two points of the armature winding, add vectorially the E.M.F.'s of all of the coils included between those two points. Thus, taking any two points at a span in electrical degrees equal to that of two successive direct-current brushes, we have the resultant pressure equal to E_d, as in Fig. 92. In Fig. 92 to find the maximum voltage for any smaller group of coils, construct the resultant 0–6 of their individual E.M.F.'s.

In an actual machine the number of coils c is large, and the regular polygon 0–6–10 which results from the vectorial addition of their E.M.F.'s, becomes almost a circular arc. To find the voltage relations lay off on a suitable scale $MN = E_d$, Fig. 93, and construct a semicircle MRN with MN as a diameter. The distance between taps for successive slip rings is $2\pi/n$ electrical degrees. Lay off $MOP = 2\pi/n$. Then,

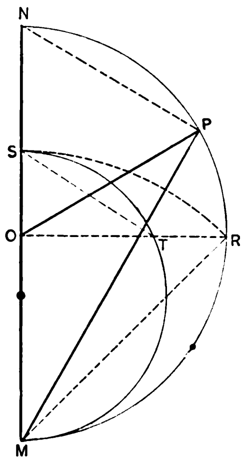


Fig. 93. — E.M.F. RELATIONS OF CONVERTER.

$$MP = E_a\sqrt{2}.$$

This may readily be obtained by the following graphical construction.* Erect the perpendicular OR at O, and with M as a center describe the arc RS, intersecting MN at S, and on MN with MS as a diameter construct the semicircle MTS, intersecting MP at T. Then,

$$MR = MS = \sqrt{2}\,MO.$$
$$MS\,/\,MN = \sqrt{2}\,MO/2\,MO = 1/\sqrt{2}$$
$$MS = MN\,/\,\sqrt{2}.$$

* This method of treatment was suggested by M. O. J. Ferguson in the *Electrical World and Engineer*, vol. xliv. p. 733 (1904)

But the semicircles are similar and are similarly situated with respect to M. It follows that

$$MT = MP\sqrt{2}.$$

Therefore, $$E_a = MT.$$

Therefore, MT represents the value of the effective alternating-current voltage between successive rings as obtained by the graphical method.

The formula for the ratio of the voltages is determined as follows:

$$MT = MP/\sqrt{2} = MN \cos PMN/\sqrt{2}$$

$$MT = \frac{MN}{\sqrt{2}} \sin \tfrac{1}{2} MOP.$$

The effective voltage between successive rings is, therefore,

$$E_a = \frac{E_d}{\sqrt{2}} \sin \frac{\pi}{n}.$$

By substituting the numerical values in this formula, or by the graphical construction, the coefficient by which the voltage between successive direct-current brushes must be multiplied in order to get the effective alternating-current voltage between successive slip rings is found to be, for

2 rings	0.707
3 rings	0.612
4 rings	0.500
6 rings	0.354

In practice these values vary slightly, owing to the fact that the flux in the air gap is not sinusoidally distributed.

Current Relations. — Assume in the following discussion that a rotary converter has its field excited so as to cause the alternating currents in the armature coils to lag 180 degrees behind the alternating E.M.F. generated in them.

Let I = the effective alternating current flowing in the armature between two successive slip rings.

I_a = the direct current carried by one direct-current brush.

n = the number of rings.

The currents in the armature coils vary with the same frequency as those of the alternating-current supply, but they differ widely in wave shape. All the coils, including the coil c, Fig. 94, between two taps for successive collector rings carry an alternating current in addition to this direct current $\frac{I_d}{2}$. This alternating current has its zero value when a point, P, passes under a direct-current brush, the point, P, being half way between two successive taps. The coil, c, is displaced from the point, P, at an angle of β electrical degrees. Then the alternating current in the coil, c, will pass through zero $\beta/2\pi$ of a cycle later than the direct current. The angle gives the time relations of the current, which are shown in Fig. 95.

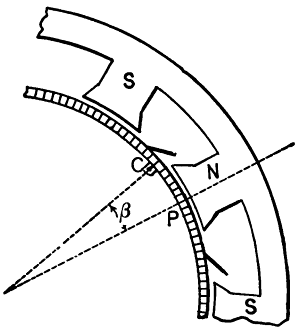


FIG. 94.—CURRENT RELATIONS IN CONVERTER.

To determine the relation between the alternating current and the direct current consider that the converter is mechanically and electrically perfect, *i.e.*, that the direct-current output equals the alternating-current input. Then,

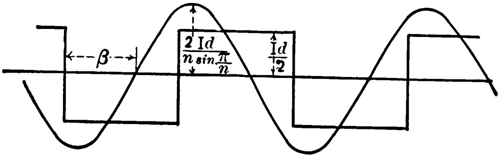


Fig. 95. — CURRENT RELATIONS IN A CONVERTER.

for a portion of the armature winding covered by each pair of poles,

$$E_d I_d = n E_a I_a. \quad \ldots\ldots\ldots\ldots \quad 1$$

Substitute for E_a its value.

$$E_a = \frac{E_d}{\sqrt{2}} \sin \frac{\pi}{n} \quad \ldots\ldots\ldots\ldots \quad 2$$

$$E_d I_d = n \frac{E_d}{\sqrt{2}} \sin \frac{\pi}{n} I_a \quad \ldots\ldots\ldots \quad 3$$

$$\therefore \quad I_a = \frac{\sqrt{2}\, I_d}{n \sin \frac{\pi}{n}} \quad \ldots\ldots\ldots\ldots \quad 4$$

The wave form of the current in the given coil, *c*, can be obtained by taking the algebraic sum of the two currents,

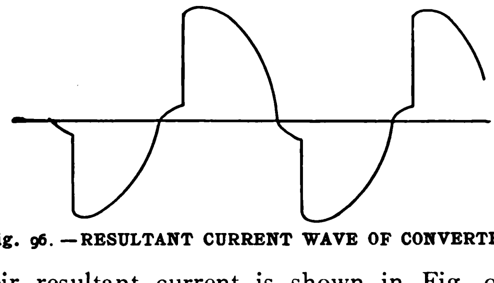


Fig. 96. — RESULTANT CURRENT WAVE OF CONVERTER.

and their resultant current is shown in Fig. 96. Each coil has its own particular wave form depending upon its angular displacements in electrical degrees from the point, P.

The coils at the points where taps are connected to slip rings carry the maximum current, and the coils at the point, P, midway between the taps, carry the minimum current.

Heating of an n-Ring Converter.* — To determine the heating in the armature coils of an n-ring converter:

Let E_d = the direct-current voltage between any two successive direct-current brushes;
E_a = the maximum alternating-current voltage between any two successive slip rings;
I_d = the direct-current output;
I_a = the maximum alternating current in each phase;
n = the number of collector rings dividing the armature into n-phases.

The maximum alternating-current voltage, E_a, between any two slip rings is: $E_a = E_d \sin \frac{\pi}{n}$, and the effective alternating-current voltage will be $\frac{E_a}{\sqrt{2}} = \frac{E_d}{\sqrt{2}} \sin \frac{\pi}{n}$. The effective alternating-current value will be $\frac{I_a}{\sqrt{2}}$.

Assume the power factor to be unity, and let p_a equal the alternating-current power input to each phase:

$$p_a = \tfrac{1}{2} E_a I_a = \tfrac{1}{2} E_d I_a \sin \frac{\pi}{n}. \qquad \text{1}$$

* This method of treatment is similar to that outlined by Mr. Alfred Hay in his excellent volume on Alternating Currents, published by D. Van Nostrand Co., N. Y.

Let P_a equal the total power input on the alternating-current side, and let P_d equal the power output on the direct-current side. Consider that the losses of the converter are negligible, *i.e.*, that the alternating-current power input equals the direct-current power output.

Then, $$P_a = P_d \qquad (2)$$

and $$\frac{n}{2} E_d I_a \sin\frac{\pi}{n} = I_d E_d \qquad (3)$$

$$\therefore \; I_a = \frac{2\, I_d}{n \sin\frac{\pi}{n}} \qquad (4)$$

A and *D*, Fig. 97, are the positions of two taps leading

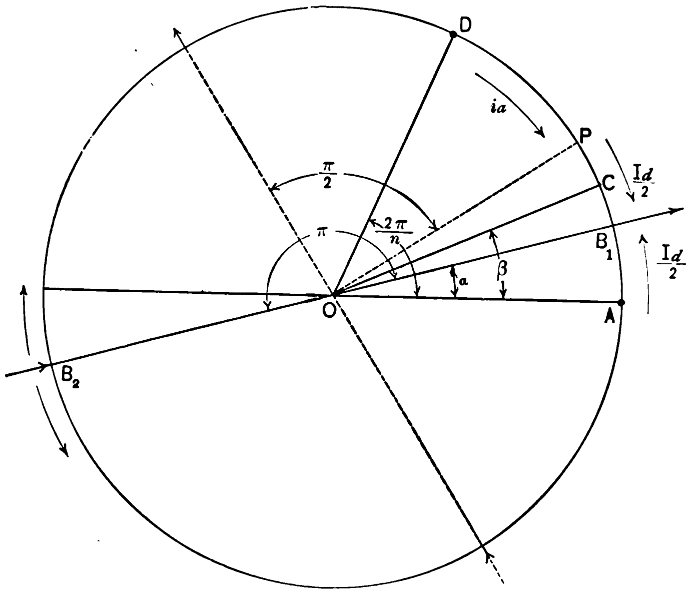


Fig. 97.—HEATING OF AN n-RING CONVERTER.

to two successive slip rings, and B_1 and B_2 are the positions of two successive direct-current brushes making at the time, t, an angle, a, with OA. Let i_a = the instantaneous value of the alternating current supplied to the slip rings, AD. Then,

$$i_a = I_a \sin(a + \psi) \quad . \ . \ . \ . \ . \ . \ . \ . \quad (5)$$

(The angle ψ is as yet unknown.)

To determine ψ, notice that both the alternating current, I_a, and the alternating-current voltage, E_a, reach their maxima values when the point, P, which is midway between the taps, A and D, is in line with the middle of the pole pieces, that is, when OP makes an angle of 90 degrees, as shown by the dotted line. In order to save the labor of revolving the armature about O as a center, B_1 and B_2 remaining stationary, until OP is at right angles to the line of the brushes, revolve the brushes to a new position represented by the dotted line, which makes an angle of 90 degrees with OP.

Then,

$$I_a = i_a \quad . \ . \ . \ . \ . \ . \ . \ . \ . \quad (6)$$

$$\sin(a + \psi) = 1 \quad . \ . \ . \ . \ . \ . \ . \ . \ . \quad (7)$$

$$a + \psi = \frac{\pi}{2} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \quad (8)$$

$$\therefore \quad \psi = \frac{\pi}{2} - a \quad . \ . \ . \ . \ . \ . \quad (9)$$

From Fig. 97, at this instant of time, *i.e.*, the new position of the brushes,

$$a = \frac{\pi}{n} + \frac{\pi}{2} \quad . \ . \ . \ . \ . \ . \quad (10)$$

$$\psi = -\frac{\pi}{n} \quad . \ . \ . \ . \ . \ . \ . \quad (11)$$

$$\therefore \quad i_a = I_a \sin\left(a - \frac{\pi}{n}\right) \quad . \ . \ . \quad (12)$$

Now consider a portion of the winding as the coil, c, and let the angle, COA, equal to β. Then, when $a < \beta$, the current in the coil, c, is

$$i_a + \tfrac{1}{2} I_d = \quad \tfrac{1}{2} I_d + I_a \sin\left(a - \frac{\pi}{n}\right) \quad . \quad . \quad . \quad . \quad (13)$$

When $a > \beta$ the current in the coil, c, becomes

$$i_a - \tfrac{1}{2} I_d = -\tfrac{1}{2} I_d + I_a \sin\left(a - \frac{\pi}{n}\right) \quad . \quad . \quad . \quad . \quad (14)$$

Let I be the total current in the coil, c. Then the value of the square of the current in the coil, c, will be

$$I^2 = \tfrac{1}{4} I_d^2 + I_a^2 \sin^2\left(a - \frac{\pi}{n}\right) \pm \tfrac{1}{2} I_d I_a \sin\left(a - \frac{\pi}{n}\right) \quad (15)$$

$$\sin^2\left(a - \frac{\pi}{n}\right) = \tfrac{1}{2}\left[1 - \cos 2\left(a - \frac{\pi}{n}\right)\right] \quad (16)$$

Then,

$$I^2 = \tfrac{1}{4} I_d^2 + \tfrac{1}{2} I_a^2 - \tfrac{1}{2} I_a^2 \cos 2\left(a - \frac{\pi}{n}\right) \pm I_d I_a \sin\left(a - \frac{\pi}{n}\right) (17)$$

The plus sign in the last term of equation (17) corresponds to $a < \beta$ and the minus sign to $a > \beta$.

To obtain the mean rate of heat production in the coil, c, we must find the mean value of I^2 between two successive poles by integrating equation (17) between the limits of 0 and π.

Then,

$$\tfrac{1}{4} I_d^2 + \tfrac{1}{2} I_a^2 - \tfrac{1}{2} I_a \int_0^\pi \cos 2\left(a - \frac{\pi}{n}\right) \pm I_d I_a \int_0^\pi \sin\left(a - \frac{\pi}{n}\right) (18)$$

In the least term of this equation (18), the plus sign is taken when $a < \beta$, and the minus when $a > \beta$. Then, rewriting the last term, we have

$$+ I_d I_a \left\{ \int_0^\beta \sin\left(a - \frac{\pi}{n}\right) da - \int_\beta^\pi \sin\left(a - \frac{\pi}{n}\right) da \right. \quad (19)$$

Integrating equation (19), and dividing by the base to get the mean ordinate, we have

$$-\frac{2}{\pi} I_d I_a \cos\left(\beta - \frac{\pi}{n}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

Integrating the remainder of equation (17), we have

$$\tfrac{1}{4} I_d^2 + \tfrac{1}{2} I_a^2 - \frac{2}{\pi} I_d I_a \cos\left(\beta - \frac{\pi}{n}\right) \quad . \quad . \quad (21)$$

Equation (21) gives the mean value of the square of the current in the coil, *c*.

Fig. 98 represents a series of curves plotted from equa-

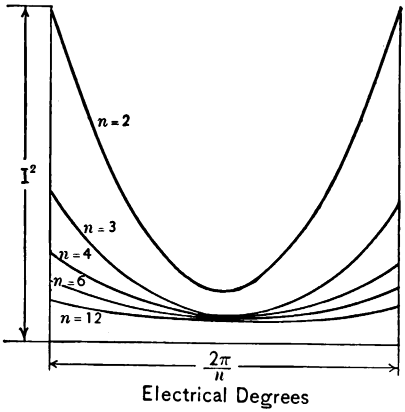


Fig. 98.—HEATING CURRENT VALUES IN CIRCUITS.

tion (21), I_a having the value given in equation (4), n being taken as 2, 4, 6, and 12 respectively, and B having for its extreme values of 0 and $\frac{2\pi}{n}$, thus corresponding to the distance between two taps for successive slip rings. The ordinates are the same for all the coils, and the abscissæ in each case represent the electrical angle $\frac{2\pi}{n}$.

These curves show clearly the rapid decrease in the total rate of heat production, and the increase in the uniformity of the heat generated in the different coils as the number of slip rings is increased.

Capacity of a Converter. — It is apparent from the curves in Fig. 98 that the same converter will have different capacities for the same temperature rise according to the number of slip rings. The following table of capacities is calculated from the formula, the armature being assumed to have a closed winding:

CONVERTER CAPACITIES.

Use.	KW. Capacity.
Direct-current generator	100
Single-phase converter	85
Three-phase converter	134
Four-phase converter	164
Six-phase converter	196
Twelve-phase converter	227

Hunting of Rotary Converters. — It is essential for good running characteristics that a converter armature contain small self-induction. If the self-induction be great the time constant of the circuit is correspondingly large, and the operation of the converter is sluggish. In other words, the armature does not respond quickly to changes in the angular velocity of the prime mover. If the armature self-induction, however, be small the armature responds quickly to changes in the period of current flow. This change in angular velocity in the converter, if not occurring as rapidly as the prime mover, causes the armature current to surge, which distorts the field flux. This tends to aggravate the surging of the converter armature and the effect may become so violent as to throw the converter out of step. This phenomena is termed hunting. With a converter armature rotating in synchronism, we can consider a rotating field to exist in the armature circuit. This rotating field we can imagine to remain stationary and the armature to rotate. This produces poles on the armature which bear a fixed position relative to the field poles. When there is a change, however, in the angular velocity of the prime mover, this armature field undergoes a series of changes while the armature is following the change in speed of the prime mover. The result of this shifting of armature flux across the pole face is to cause the hunting previously mentioned.

To remedy hunting in a converter various so called anti-hunting devices have been developed. The function of these devices is to neutralize the self-induction and to act also as a damper for the armature flux, to prevent its shifting. Obviously the most effective form of damper is one which combines both these elements. When the self-induction of the armature has been reduced to a minimum the time constant of the circuit will likewise have a minimum value. The time constant may be expressed in the convenient form

$$T = L/R,$$

where L equals the coefficient of self-induction of the circuit and R equals its resistance.

Anti-hunting devices are of three kinds, namely, a copper grid spanning the adjacent pole tips of the converter, a form of grid mounted in the pole face, or built up in the form of a circular grid surrounding the pole shoes, and what is known as the squirrel-cage damper. Where a damper is built in the face of the pole shoe as that of the

Westinghouse Company, Fig. 99, it is very effective as a preventative against hunting. This form of grid is built up in the form of a rectangle with several cross-bars, Figs. 100–101, which is mounted in slots in the pole face and trued up in position, as in Fig. 102. This damper acts as the closed secondary of a transformer neutralizing the self-induction of the armature besides serving to damp the oscillation of flux across the pole face.

When two or more converters are operated with current supplied by one or more generators, the hunting of one converter may cause trouble with the others. In such a case dampers should be placed on the field poles of the generator, as well as on those of the converter, and it is not advisable to operate the converters from a common bank of transformers.

When running an inverted converter from the direct-current side, anything that tends to cause the alternating current to lag behind its E.M.F. produces racing of the machine. These lagging currents demagnetize the field which causes the armature to race, as in the case of a shunt motor with weakened fields. These lagging currents should be avoided, as converters have been raced to destruction as the result of a short circuit on the alternating-current system. In order to prevent racing, speed-limiting devices have been developed which cut the machine off the circuit when an abnormal rise of speed occurs.

Regulation of Converters. — The direct-current pressure depends practically upon the pressure of the alternating-current supply, so that the regulation is obtained by varying the alternating-current pressure. The fields of a converter are generally excited with current taken from

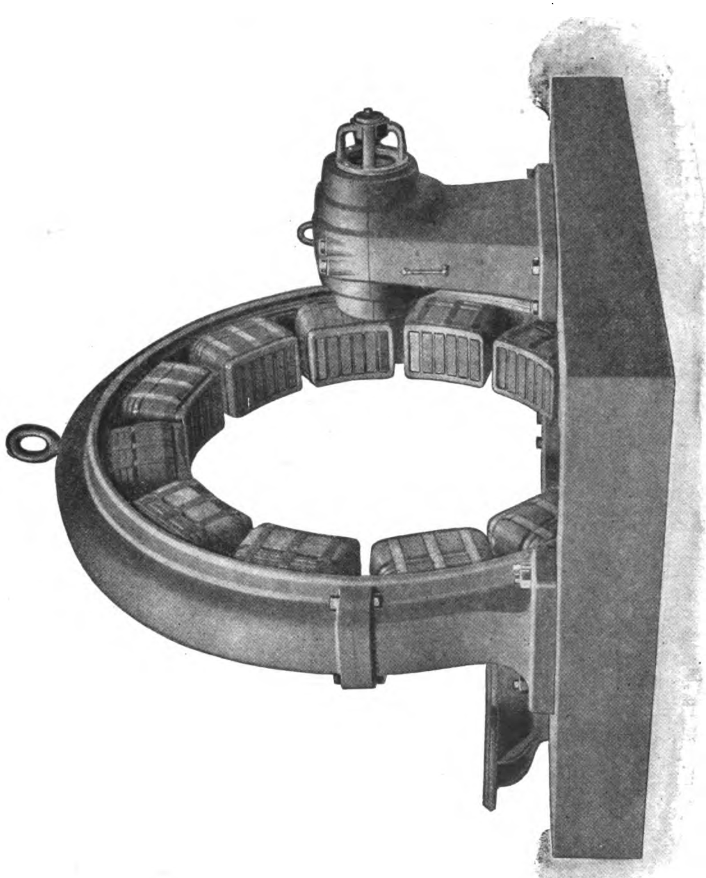


Fig. 99.—POLE GRIDS IN FINAL POSITION.

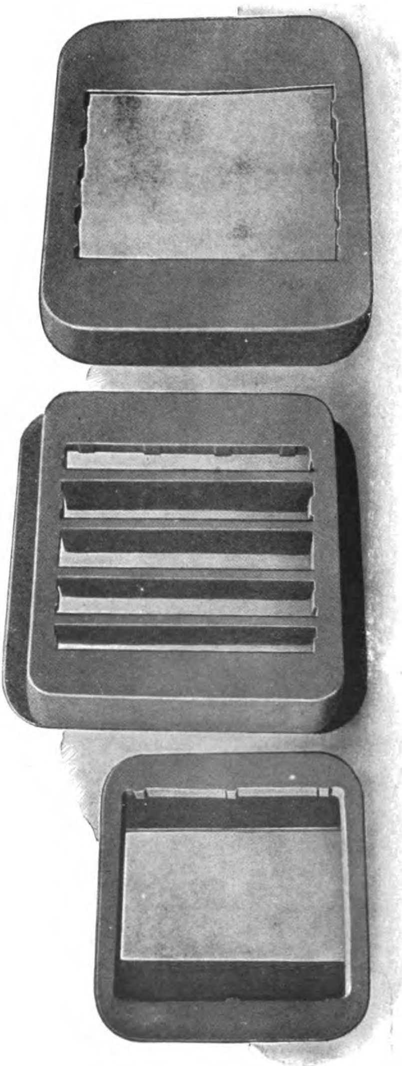


Fig. 100.—POLE GRIDS USED TO ELIMINATE HUNTING.

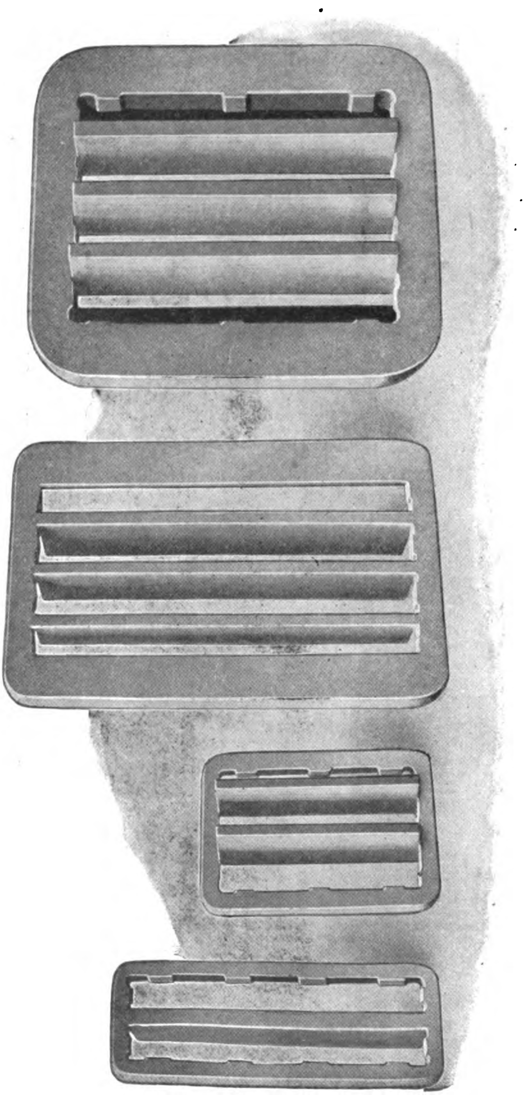


Fig. 101.— POLE GRIDS USED TO ELIMINATE HUNTING.

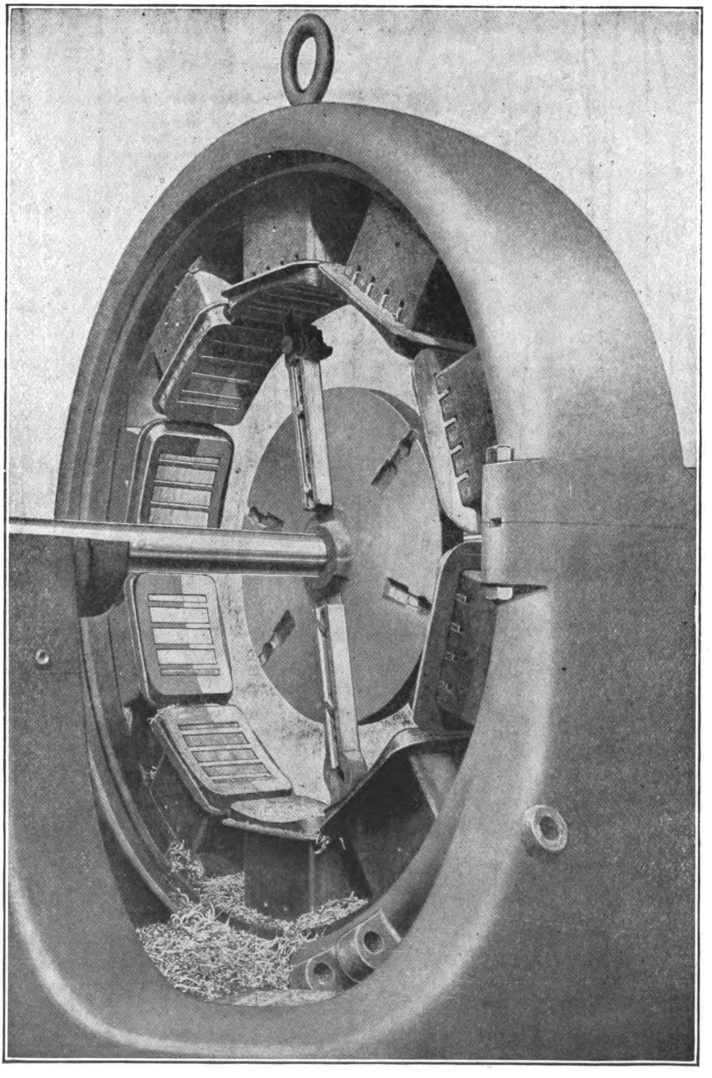


Fig. 102.—METHOD OF FACING POLE GRIDS.

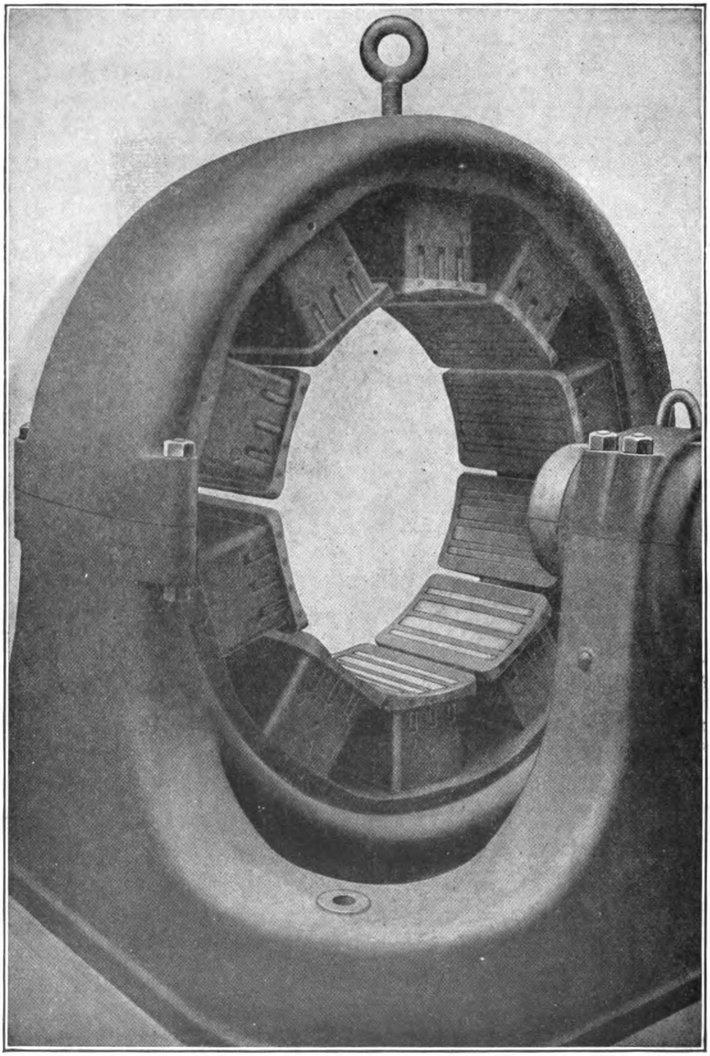


Fig. 103. — SMALL CONVERTER WITH POLE GRIDS (WESTINGHOUSE).

the direct-current brushes. By varying this exciting current, leading or lagging currents are set up in the armature, and the power factor of the alternating-current system is changed. This will vary the voltage of the alternating current supplied to the slip rings through a limited range, and thus it varies slightly the direct-current voltage. This method of regulation is used extensively in large, power sub-stations.

The several methods by which regulation is accomplished are transformer loops, potential regulators, induction regulators, and the compounding of the field coils. In general, transformers that are furnished with converters have additional taps or loops connected to either primary or secondary windings for the purpose of securing a range in voltage. This range is usually small, and changes can generally be made only when the converter and the transformers are not in service.

The Potential Regulator or Stillwell's Regulator. — This consists of a boosting transformer, whose primary is connected across the secondary terminals of the step-down transformer as shown in Fig. 104.

The secondary of the boosting transformer is connected in series with the converter and the secondary winding of the step-down transformer, and it is provided with a set of contact blocks mounted on a face plate. These blocks are traversed by a contact arm, thus varying the amount of the secondary winding of the regulator in the circuit. The primary of the regulator is generally provided with some form of reversing switch, which enables the voltage to be increased or diminished. When these regulators are employed in polyphase systems, a single-phase regulator is connected in each phase, but the contact arms are connected together so that one lever controls all the phases.

The Induction Regulator. — This method is employed by the General Electric Company. The induction regulator consists of a regulating transformer connected in the

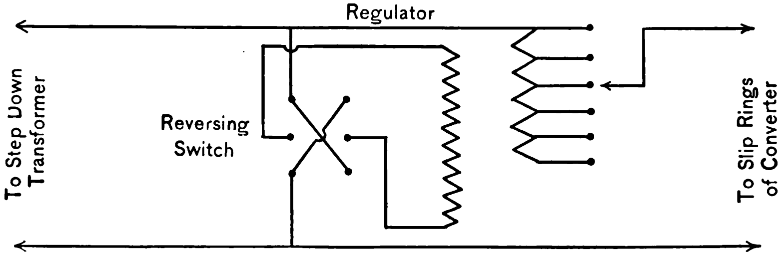


Fig. 104. — ELEMENTARY DIAGRAM OF STILLWELL REGULATOR.

circuit in the same manner as the Stillwell Regulator. The windings of the induction regulator are polar and the ratio of transformation can be altered by rotating or shifting the axis of the primary and secondary windings with respect to each other. The primary windings are placed in slots that correspond in general appearance to the stator of an induction motor, and the secondary winding is placed in what corresponds to the rotor. By rotating the secondary windings through an angle corresponding to the distance between two successive poles, the voltage induced in them can be increased or diminished from a zero value. Thus the induction regulator will operate as booster or crusher without opening the circuit.

The shifting of the secondary is accomplished by means of a small direct-current motor mounted upon the regulator, flexible leads being connected to the secondary windings.

The Compound Method of Regulation. — This consists in the addition of series coils to the field poles of the generator. It has already been explained that a mere strengthening of the field flux will produce only a very slight rise in voltage on the direct-current side, unless there is a corresponding rise on the alternating-current side. To effect this rise suitable reactance coils are connected in series with each phase of the converter. The currents in the armature of the converter consist of two components; one, an energy component in phase with the E.M.F., supplied to the slip rings; the other, a wattless component, leading with respect to the E.M.F., when the field strength is too great, or lagging when the field strength is too small. Consider the voltage supplied by the step-down transformers to be uniform, then the only means by which the direct-current voltage can be raised or lowered to any extent is by raising or lowering the alternating-current voltage supplied to the slip rings.

The voltage at the slip rings of the converter is made up of two components, *i.e.*, the voltage necessary to force the current consumed by the converter through the inductance between itself and the generator, and the voltage of the generator. The resistance of the line is also an element, but we shall assume it to be negligible in this discussion.

First, if the power factor is unity, *i.e.*, the current in phase with the impressed E.M.F., then the volts induced in the inductance due to self-induction combine with the generator volts in such a manner that the voltage impressed on the slip rings of the converter is practically that of the generator. In other words, when the power factor is unity the inductance may be considered as having no appreciable effect on the voltage supplied to the converter.

Second, if the power factor is less than unity, *i.e.*, the current is lagging with respect to the impressed E.M.F., then the volts induced in the winding due to self-induction combine with the generator volts in such a manner as to reduce the voltage impressed on the slip rings of the converter.

Third, if the power factor is greater than unity, *i.e.*, the current leading with respect to the impressed E.M.F., then the volts induced in the winding due to self-induction combine with the generator volts in such a manner as to increase the voltage impressed on the slip rings of the converter.

The volts induced in the inductance owing to self-induction lag 90 degrees behind the current inducing them. To make this discussion clearer consider the following graphic construction:

Let E_g = generator volts.
E_c = voltage impressed on successive slip rings of converter.
E_i = volts induced in the winding due to self-induction.

In Fig. 105 the current is in phase with E_g, and the power factor is, therefore, unity. E_i lags 90 degrees behind

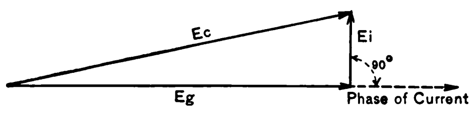


Fig. 105.—CURRENT IN PHASE WITH GENERATOR E.M.F.

the current, and E_c is the resultant of E_g and E_i added vectorially. In actual practice E_i is small compared to

E_g, and E_c is practically equal to E_g, as stated under the first condition.

In Fig. 106 the current lags behind E_g, and cos θ represents the power factor. E_i lags 90 degrees behind the

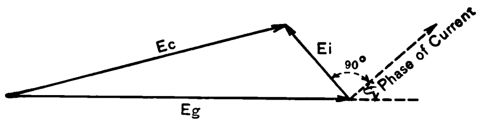


Fig. 106.—CURRENT LAGS BEHIND E.M.F.

current, and the value of E_c, the resultant of E_g and E_i added vectorially, is reduced, as stated under the second condition.

In Fig. 107 the current is leading E_g, and cos θ repre-

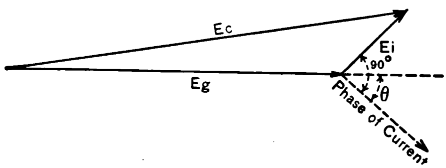


Fig. 107.—CURRENT LEADS E.M.F.

sents the power factor. E_i lags 90 degrees behind the current, and the value of E_c, the resultant of E_g and E_i added vectorially, is increased, as stated under the third condition.

It is evident, therefore, that if we can cause the current to change from lagging at no-load, to leading at full-load, the voltage will increase from a value less than the generator voltage at no-load to a value greater than the generator voltage at full-load, thus compensating for the direct-current drop and giving a uniform direct-current voltage output. This is the function of the series field, it makes the field ampere turns increase with load and, therefore, sets up lagging currents at no-load, which decrease with and change to leading currents at full-load.

The functions of a series coil used in the compounding of rotary converters is as follows:

(1) The series coil has the effect of automatically changing the ampere turns applied to the field;

(2) The varying of the ampere turns causes lagging currents when the field excitation is less than normal, and leading currents when the excitation is greater than normal;

(3) The volts induced in the winding or choke coils tend to lower the voltage supplied to the slip rings of the converter when the current is lagging, and to raise the voltage when the current is leading.

The conditions for the compounding of a rotary converter are

(1) A series field connected so as to assist the shunt field;

(2) Suitable inductance or choke coils introduced into each phase of the alternating-current circuit.

SPECIFICATION OF WESTINGHOUSE 1500 KW. CONVERTER.

Fifteen hundred kw., 600 volts (d.c.) six phase, 3000 alts. twelve poles.

Performance Specification No. 14,309, Pittsburg, Pa., June 23, 1905.

For Standard Performance.

General Description. — This Rotary Converter will be wound for direct current at an E.M.F. of 600 volts. It will have 12 poles, and the frequency will be 3000 alternations per minute (25 cycles per second) at its normal speed of 250 revolutions per minute. The collector rings will be connected for 6-phase current at approximate 420 volts.

General Construction. — This machine will be of the Two Bearing Type. The external frame will be divided in a horizontal plane to allow access to the windings.

Normal Full-Load Rating. — The normal full-load rating of this machine will be with a direct-current load of 2500 amperes at 600 volts.

Excitation. — The field will be compound wound, the shunt being arranged for self-excitation.

Efficiency. — At its normal direct-current voltage, the power factor of the alternating current being 95 per cent or higher, the machine will have an efficiency of 90 per cent at one-quarter load; 94½ per cent at one-half load; 95½ per cent at three-quarters load; and 96 per cent at full load. These efficiencies are based on I^2R losses in armature and field coils, armature iron loss and friction. These losses are to be determined separately.

Temperature. — The machine will operate for twenty-four hours at its normal full-load rating, with a rise in temperature in no part to exceed 40 degrees Centigrade; and at twenty-five per cent. greater load for twenty-four hours the rise in temperature will not exceed 50 degrees Centigrade; and at fifty per cent greater load for one hour the rise in temperature will not exceed 60 degrees Centigrade, temperature to be measured with a thermometer. In all of the above temperature tests the field current must be adjusted so that the power factor of the alternating current received is not less than 95 per cent.

Commutation. — The brushes having been properly adjusted, there will be practically no sparking due to variation of the load within the limits of no-load and 25 per cent over-load. The machine will run at normal full-load for twenty-four hours with practically no sparking or burning of the brushes and without blackening of the commutator. It will not be necessary to shift the position of the brushes if the load be increased from no-load to 50 per cent over-load, nor will there be serious sparking if the load be increased temporarily to 75 per cent over-load.

Field. — The field frame will be made of cast iron, sound and free from blow-holes. The pole pieces will be of laminated steel, the pole pieces and field winding being so proportioned as to reduce the armature reaction and self-induction to a low limit. The shunt field coils will be wire wound and the series field coils strap wound. They will be arranged for good air circulation. The insulation of the field coils from the frame will consist of several layers of fibrous material, and will be substantial and permanent. The field coils will be painted with a moisture-proof and oil-proof compound. After completion, the insulation of the coils from the frame will be subjected to a momentary puncture test of 2500 volts alternating E.M.F.

Armature. — The armature will be of the slotted drum type. The core will be built of laminated steel of high magnetic quality. The sheets of steel will be dovetailed accurately to the spider. The laminated core thus built up will be held firmly between two end plates. The armature winding will consist of strap wound coils, formed and insulated before being placed in the slots. The coils will be held in the slots by retaining wedges of hard fibre. The insulation of the armature conductors will consist of sheet material of high insulating quality, applied in over-lapping layers. This will be held in place with tape, and the whole will be treated with a moisture-proof and oil-proof compound. After completion, the insulation of the armature winding from the core will be subjected to a momentary puncture test of 3500 volts alternating E.M.F.

Collector. — The collector will be of special brass, and will be of ample size for the maximum current to be carried. The brushes will be of copper.

Commutator and Brushes. — The commutator will be made of bars of hard drawn copper, insulated from each other by mica. The number of bars will be such that with the normal voltage the average difference in potential between two adjacent bars will not exceed 10 volts. The proportions of mica and copper will be such that the two will wear at practically the same rate. The commutator bars will be held in position at one end by a cast-iron ring having a V-section, and at the other end by a ring of a similar section, firmly held in position by bolts of ample strength. The leads from the armature coils will be thoroughly soldered to the necks of the commutator bars. These connections will be made in a workmanlike manner and will have a greater carrying capacity than the armature conductors. The arms carrying the brushes will be strong and rigid. The brushes will be of carbon. The brush holders will be of the sliding shunt type. They will be of such size as to give ample surface contact for the brushes in the boxes, and the brushes will be of such size and number as to carry the full-load current of the machine continuously, without undue heating, and a 25 per cent over-load for 24 hours without injurious heating.

Ventilation. — Throughout the armature spider, core and windings, large and open ventilating ducts will be provided. The design of the rotating armature will be such as to set up a forced circulation of air through these ventilating spaces. Space will be left between the field coils so that a free circulation of air may be maintained while the machine is in operation. The end windings of the armature will be so arranged that the air will circulate freely among them, thus keeping their temperature very low.

Starting. — This rotary converter will be designed to start by an induction motor or by direct current.

METHODS OF STARTING.

(*a*) **By Induction Motor.** — A type "C" induction motor of ample capacity, with its revolving part mounted directly upon an extension of the armature shaft of the rotary converter, will be provided for bringing the armature up to synchronous speed. In order that the operation of starting, accelerating, and synchronizing may produce a minimum disturbance to the voltage of the supply circuit, the starting motor will be so designed that the maximum line current required at any time during the operation of starting and accelerating will be approximately — per cent of the line current taken by the rotary converter at full-load, and the current of the starting motor will have a power factor of approximately — per cent.

(*b*) **By Direct Current.** — A rheostat of ample capacity will be provided, so that the armature of the rotary converter may be brought up to speed in a manner similar to the starting of a direct-current power motor.

Approximate Weight (Net). — Total, — lbs. Heaviest Piece, — lbs.

NOTE. Figs. 108 and 109 show views pertaining to Westinghouse 1500 kw. converters. All of the views of the elements of this machine were procured through the courtesy of Mr. Charles F. Scott. Frequent reference to this machine may be found throughout the text. Also numerous illustrations of the working parts have been inserted.

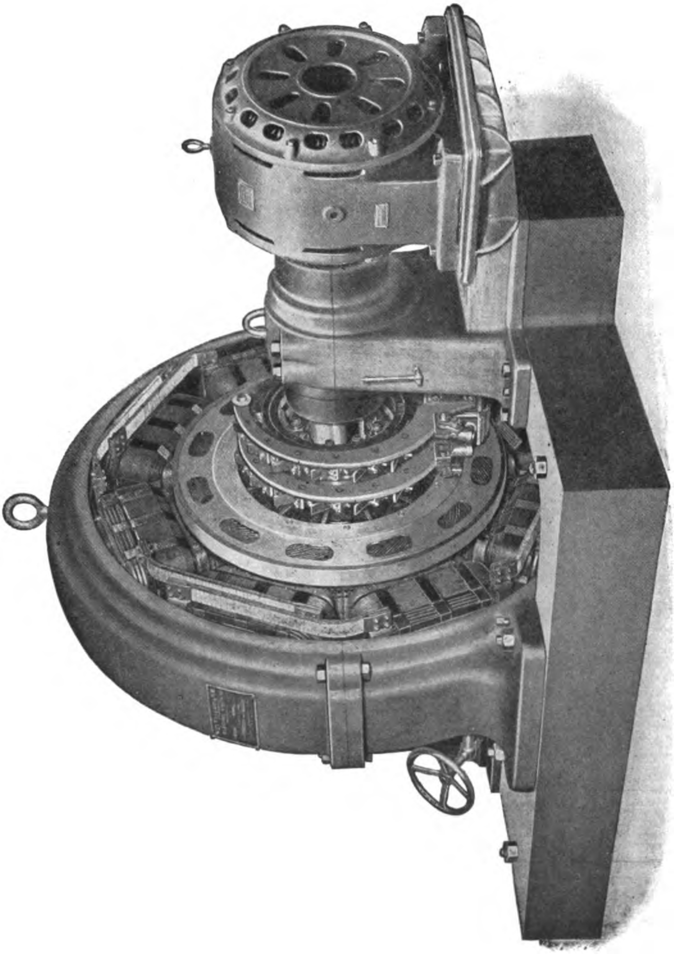


Fig. 108. — A. C. SIDE OF WESTINGHOUSE 1500 KW. CONVERTER.

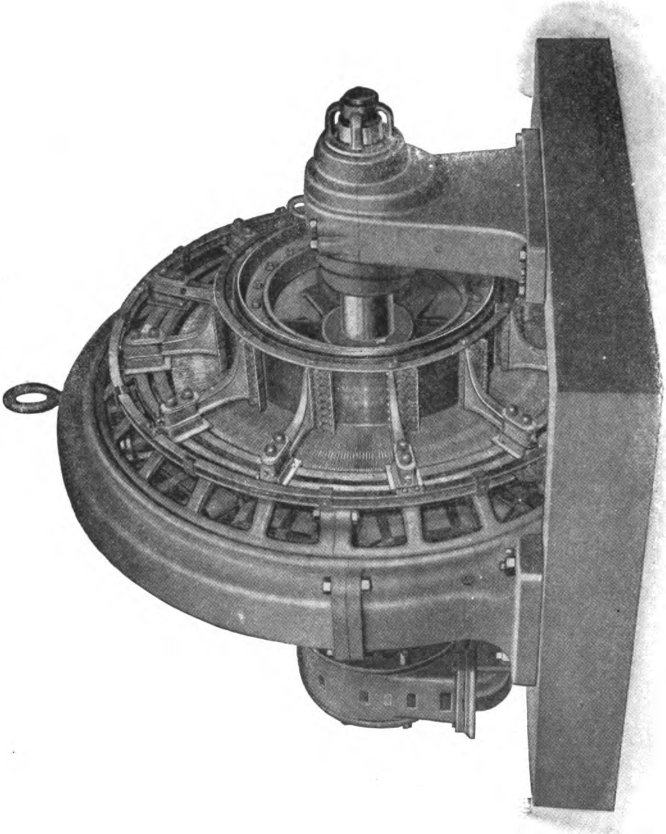


Fig. 109.—D. C. SIDE OF WESTINGHOUSE 1500 KW. CONVERTER.

CHAPTER VIII.

TRANSFORMERS.

Transformers. — One of the most important advantages of the alternating over the direct current, is the ease and simplicity with which the transformation from a low to a high voltage, or vice versa, may be accomplished. This transformation is effected by means of a transformer. The alternating-current transformer consists of one magnetic circuit linked with two electrical circuits. One of these, the primary, receives electrical energy; the other, the secondary, delivers electrical energy. The magnetic circuit is built up of laminated iron surrounded by two windings. One of these windings, the primary, is supplied with alternating currents, and the other, the secondary, delivers alternating currents. The transformer is the most efficient piece of electrical apparatus in use.

Transformers are of two general types, termed core and shell types. In the core type the magnetic circuit is surrounded by the electrical circuit. In the shell type the electrical circuit is surrounded by the magnetic circuit.

Ratio of Transformation. — The ratio of transformation is represented by τ, and is the ratio of the number of turns in the secondary to the number of terms in the primary. This is the same as the ratio between the voltages of the primary and the secondary, provided the losses are considered as negative. Then

$$\tau = \frac{\text{secondary turns}}{\text{primary turns}} = \frac{\text{secondary voltage}}{\text{primary voltage}}.$$

Transformers in which this ratio τ is greater than unity are called "step-up" transformers, and those in which τ is less than unity are called "step-down" transformers. Step-up transformers find their greatest use at the generating stations where they are employed to raise the voltage generated by the alternators to the high potential demanded for economical power transmission. Step-down transformers are employed chiefly at the sub-stations to lower the high potential of the transmission line to a suitable value for the rotary converters.

Transformer Losses. — Transformer losses may be divided into two classes, those due to core losses and those due to copper losses, according as to whether they occur in magnetic or electrical circuits of the transformer. Good commercial transformers have, as stated before, very high efficiencies, averaging above 95% and often attaining 98%.

Core Losses. — Core losses are due to eddy currents and hysteresis.

If the core of a transformer were made of solid iron, very strong eddy currents would be induced in it. These currents would not only heat the iron but would tend to demagnetize it, and thus would require large currents in the primary to set up the counter E.M.F. These eddy currents are prevented to a large extent by forming the core from laminated iron stampings insulated from each other by the natural oxide or by Japan lacquer. The value of this eddy current loss P_e, perfect insulation between the laminæ being assumed, is

$$P_e = kvf^2l^2B_m^2,$$

where

k = constant defending the resistivity and reluctivity of the iron.
v = volume of iron in cu. cm.
l = thickness of laminæ in cm.
f = frequency.
B_m = maximum flux density per sq. cm.

In practice k equals approximately 1.6×10^{-11}.

The hysteresis loss P_h is the amount of power necessary to carry the iron through its cyclic changes and according to Steinmetz's law,

$$P_h = 10^{-7}\, vf\eta\, B_m^{1.6},$$

where

v = volume in cu. cm.
f = frequency.
B_m = maximum flux density per sq. cm.
η = hysteretic constant.

In iron of good quality η varies from 0.0001 to 0.00025.

Copper Losses. — Copper losses are due entirely to the I^2R drop in the transformer coils. Their value P_c is,

$$P_c = I_p^2R_p + I_s^2R_s,$$

where

I_p = current in primary winding.
R_p = resistance of primary winding.
I_s = current in secondary winding.
R_s = resistance of secondary winding.

Efficiency of a Transformer. — The efficiency of a transformer follows, the significance of the symbols being self evident.

$$\text{Efficiency} = \frac{P_s}{P_p} = \frac{V_s I_s}{V_s I_s + P_h + P_e + P_c}.$$

Where the transformer is artificially cooled the power consumed by the cooling device must be added to the denominator in determining the efficiency of the transformer.

Regulation. — The regulation of a transformer is the drop in voltage between no-load and full-load secondary voltage divided by the no-load secondary voltage expressed as a percentage. The conditions are that the primary voltage and frequency shall be maintained constant, and that a sine wave be maintained. The regulation may be determined by direct experiment or by some indirect method. The direct experiment is difficult to perform as it is almost impossible to maintain the primary voltage constant, and it may be impossible to provide a proper load. Of the indirect methods the one devised by Kapp is considered one of the most satisfactory.

Kapp's Diagram. — In determining the regulation by this method the transformer is assumed to possess a constant resistance, and a constant self inductance. This assumption is practically correct in any given transformer.

The values of the resistance and inductance are determined by test. The secondary of the transformer is short circuited through an ammeter of negligible resistance, and adjusting the primary impressed voltage until the full-load current is obtained. A voltmeter is then placed across the secondary, the transformer being open circuited. The voltmeter reading is taken when the primary pressure corresponds to the value it had in the previous test. The impedance equals

$$\frac{\text{Voltmeter reading in open circuit test}}{\text{Ammeter reading in short circuit test}}.$$

The resistance is then measured, and the impedance is analyzed into its reactance and resistance.

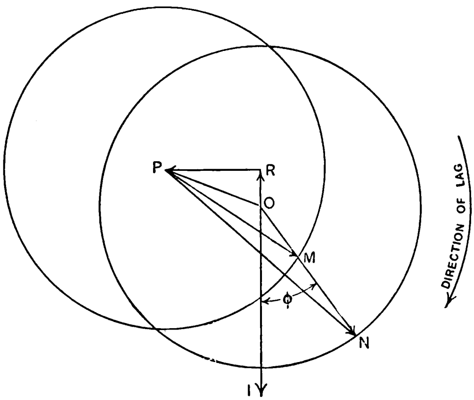


Fig. 110. — KAPP'S DIAGRAM.

Having now the equivalent resistance and equivalent reactance of the transformer, we will proceed to Kapp's diagram. Consider the case of a transformer under full load. In Fig. 110, let OI represent the direction of the current at full load, and with O as a center construct a circle with a radius ON equal to the value of the secondary terminal pressure at full load. Draw ON at an angle ϕ with the direction of OI. Cos ϕ is the power factor of the transformer at the given condition, *i.e.*, full load. Lay off OR, the full-load resistance voltage drop in phase with the current but in the opposite direction. Lay off RP, the full-load reactance voltage drop, at right angles to OR. At P as a center construct a circle with a radius $PM = ON$. Draw PN, which represents the value of the secondary at no load, then the regulation $= \frac{PN - PM}{PN}$. The values OR and PR have been greatly exaggerated in the figure in order to make the construction clear. Their actual values are very small compared to the values of the primary and secondary voltage.

Westinghouse 550 kw. Air-Cooled Transformer. — In Fig. 111 is shown a bank of Westinghouse 550 kw. air blast, 25 cycle transformers, for use in generating stations or sub-stations.

Transformers of this type are intended for continuous service, and are so designed that their temperature is kept low by means of an air blast. Both the high-tension and low-tension coils are divided into many flat coils. These coils are divided into sections. The sections are assembled to form a coil. The coil is completely insulated and the leads are attached. The high-tension conductor is a flat copper ribbon wound concentrically with only one turn per layer. The layers are separated from each other by a continuous strip of a specially prepared insulating material (in addition to the cotton covering of the conductor), while the coils are insulated individually and are separated by insulating barriers. The sections of each coil are insulated by a shield of high insulating strength. The completed coil is covered by a moisture proof insulation. The low-tension coils are wound and built up in the same manner as the high-tension ; the conductors, however, are of a rectangular cross section. This type of construction is very strong both mechanically and electrically. The coils are so assembled that every conductor has at least one side and, where required, both sides exposed to the air blast.

Fig. 111. — WESTINGHOUSE THREE-PHASE TRANSFORMER.

The insulation of the transformer is impervious to moisture and has great strength and durability. It also permits a ready discharge of heat generated in the winding. The coils are dried at a temperature above the boiling point of water in a vacuum which thoroughly removes all moisture. The coils are then treated with a special insulating material and are placed in drying ovens where the insulation becomes hard and strong. They are then taped with an overlapping covering of linen and again are treated and dried. This is repeated several times, depending on the voltage of the transformer.

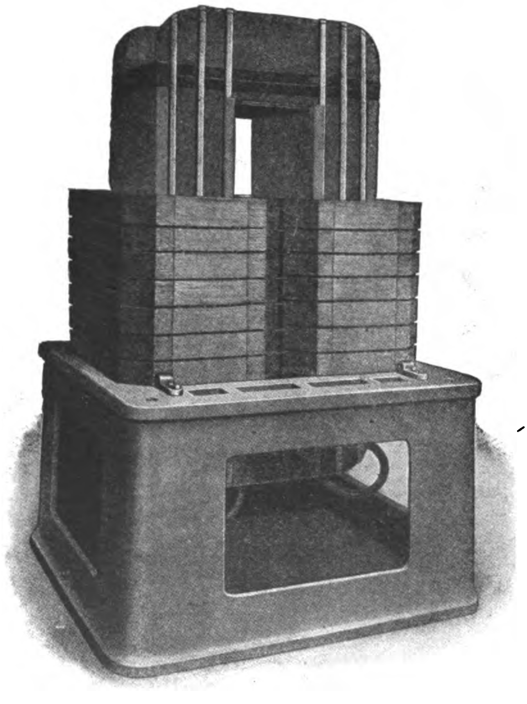


Fig. 112.—CORE OF THREE-PHASE TRANSFORMER.

The core (Fig. 112) is built up of the best quality of magnetic steel previously treated to prevent aging. Japan lacquer is used to separate the laminations and thus lower the eddy current loss. Air ducts are provided at proper intervals and are so constructed that the cooling air is forced through them and around the core. Fig. 113 shows the assembly of the laminations and the ventilating ducts in the iron.

The high-tension terminals are mounted at the top of the case and the low-tension at the bottom. Fig. 114 is the bottom view showing the low-tension terminals and also the ventilating ducts in the coils.

The case, or mounting, is made of cast iron plates bolted together, and dampers are provided to regulate the flow of air for cooling.

The air blast which cools these transformers is provided by a fan driven by a direct-connected motor, the fan supplying air to ducts over which the transformers are mounted. The arrangement of the ventilating ducts and the passage of the air is illustrated in Fig. 113.

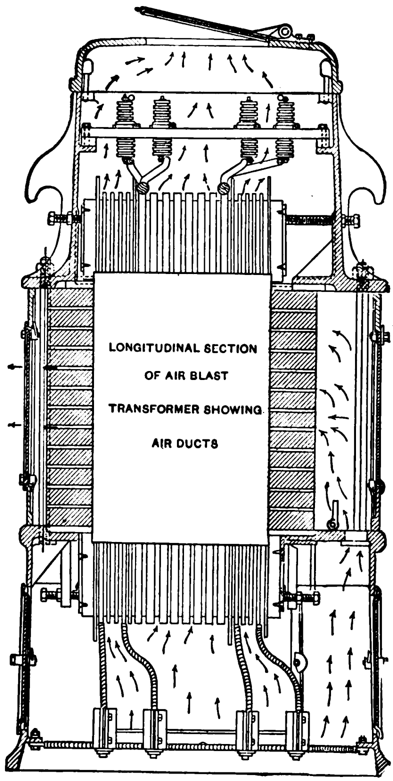


Fig. 113. — VENTILATING DUCTS OF TRANSFORMER.

Transformer Connections. — Transformer connections may be divided into two general classes, the delta or mesh connection and the star or "Y" connection.

Fig. 115 shows the arrangement of transformers when connected in delta and Fig. 116, when in "Y."

When transformers are connected delta to delta or star to star, the resulting voltage E_s is approximately equal to

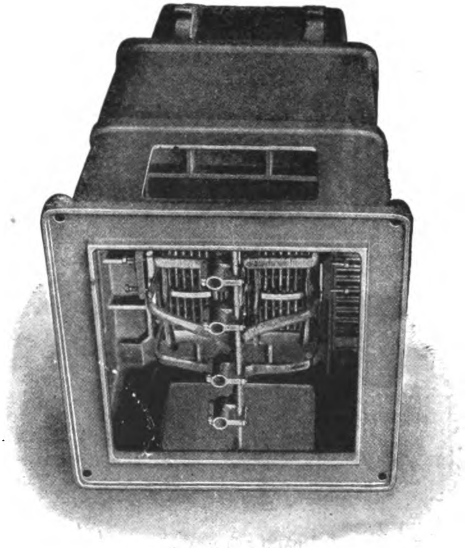


Fig. 114.—SHOWING TRANSFORMER TAPS.

the impressed voltage E_p, providing both have the same number of turns. If the connections are delta to star, then $E_s = \sqrt{3}\ E_p$, and when star to delta,

$$E_s = \frac{E_p}{\sqrt{3}}.$$

Transformers for three-phase work may be connected in either delta or star fashion. The delta is generally preferred, for if one of the fuses blow out or a coil burns out the supply of current would still be maintained, the other two phases carrying the load. With a star connection the failure of a coil would completely disconnect one of the

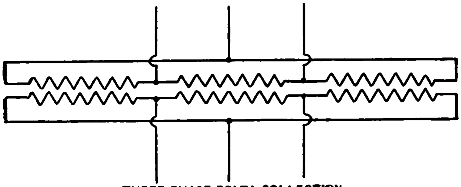


Fig. 115. — TRANSFORMER CONNECTIONS.

leads and cut off the supply to two phases. Thus a breakdown with star connection would be more serious than with delta connection. But where very high voltages

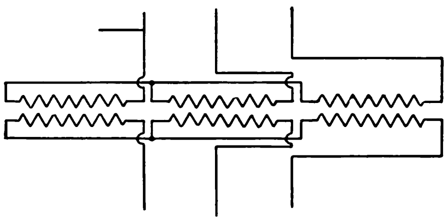


Fig. 116. — TRANSFORMER CONNECTIONS.

are dealt with, the dielectric stress on each coil is reduced by adopting the star connection, as the phase voltage then becomes $\frac{1}{\sqrt{3}} = 0.577$ of the line voltage.

Scott's Two-Phase to Three-Phase Connection. — A system of transformer connection was devised by Mr. C. F. Scott, which permits the transformation from four-wire two-phase to three-wire three-phase. The diagram of the connections is shown in Fig. 117. Suppose that in any given case we desire to step down from 1000 volts two phase to 100 volts three phase. Consider that one of the transformers has a ratio of 10 to 1 with a tap at the middle point of the secondary and that the other transformer has a ratio of 10 to $\frac{\sqrt{3}}{2}$ or 10 to .867. One terminal of the secondary of the latter is connected to the middle point of the secondary of the former and the three remaining terminals are the three-phase leads. The principle is as follows: Consider the secondary only. The alternating-current pressures in the primaries are at right angles to each other, therefore the pressure induced in the two secondaries will be at right angles. The pressure in the second transformer is not only at right angles (perpendicular) to that of the first, but is connected at the middle point of the first. Add these pressures vectorially (Fig. 118) and complete the triangle which is equilateral, and whose sides make an angle of 60 with

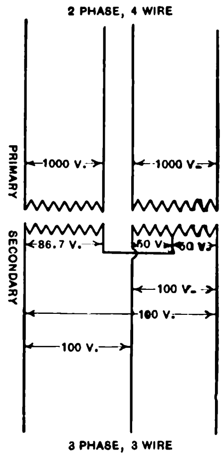


Fig. 117.—SCOTT'S TRANSFORMER CONNECTIONS.

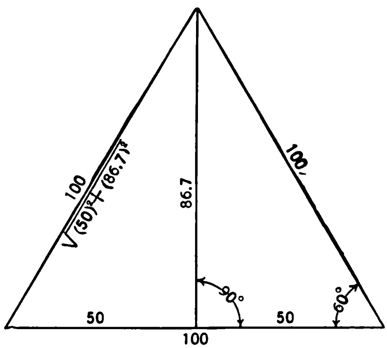


Fig. 118.—VOLTAGE RELATIONS OF SCOTT'S TRANSFORMER COILS.

each other. The pressures represented by the three sides are equal and at 60° with the others. This transformer is suitable for use as a three-wire three-phase system.

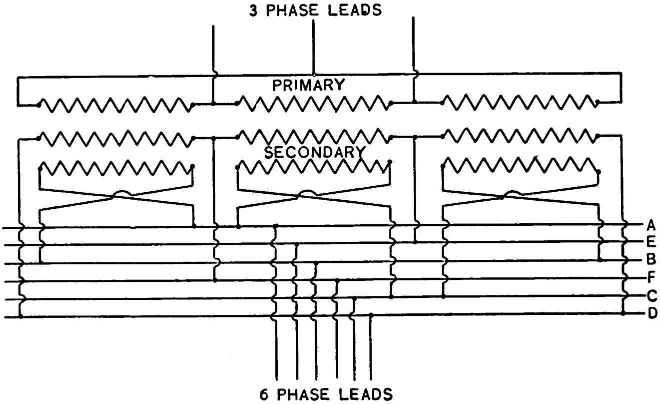


Fig. 119.—THREE- TO SIX-PHASE TRANSFORMER CONNECTIONS.

Three-Phase to Six-Phase Connection.—A rotary converter wound for six phase has a much larger capacity than the same machine wound for three phase. Transformers are constructed to tranform for three phase to six phase. Each transformer has two secondary coils and one primary. One secondary of each transformer is first connected in Δ and the other secondaries are connected in Δ but in the reverse order. Fig. 119 shows the diagram of the connections. The connection may be either star or delta. These two Δ's are connected in the reverse order, that is they are at an angle of 180°, as shown in Fig. 120. In

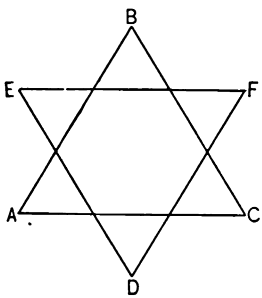


Fig. 120. — SHOWING VOLTAGE RELATIONS OF TRANSFORMER.

Fig. 120 the triangle ABC represents one delta and the triangle DEF, which is turned through an angle of 180°, represents the other.

Transformer Taps. — Transformers are usually provided with additional taps that permit of a slightly lower or higher voltage, which may be used for a starting motor or to obtain a small increase or decrease in the speed of the converter. This is in case the converter be started by means of an induction motor.

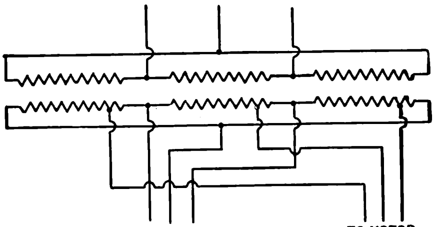


Fig. 121. — SHOWING LOW VOLTAGE TAPS.

Fig. 121 shows the connections of transformers furnished with taps in delta for providing the lower voltage to the starting motor. This is represented graphically in Fig. 122*a*, where AB equals the value of the voltage supplied to one phase of the converter and A′B′ equals the voltage supplied to the motor. The letters ABC represent the three phases of the converter and A′B′C′ the phases of the motor.

When a higher voltage is supplied to the motor than to the converter the conditions are shown graphically in Fig. 122*b*. Here ABC represents the converter phases and A′B′C′ the motor phases as before. AB equals the voltage supplied to one phase of the converter and A′B′ that supplied to one phase of the motor. These diagrams show the principle by which higher or lower voltages may be obtained from a transformer.

Heating of Transformers. — Commercial transformers are generally enclosed in cases of cast iron or partly perforated sheet metal. When the former is used the trans-

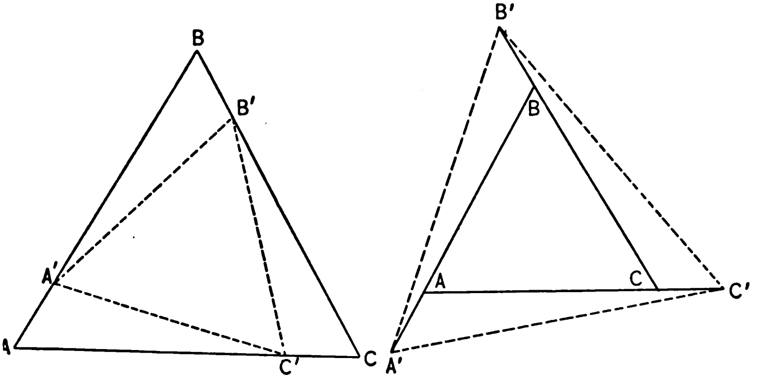


Fig. 122a. Fig. 122b.

HIGH AND LOW VOLTAGE TAPS.

former is usually entirely immersed in oil. The oil not only aids the insulation but improves the transfer of heat to the casė and maintains the transformer at a more uniform temperature. The permissible rise of temperature of the coils is about 50° C.

In large transformers it is difficult to prevent an excessive rise in temperature as the natural convective currents produced by the heating of either the air or oil are not sufficient to carry off the heat. This makes it necessary to use some artificial means to accomplish this. In large sizes the transformers are cooled either by air blast or by oil water-cooled.

Air-blast transformers are cooled by blowing air by means of a fan or a blower operated by a motor, through suitable ventilating ducts provided in both core and coils.

Oil water-cooled transformers are immersed in oil, and near the top of the case in the oil is fitted a coil of thin-walled brass tubing, through which cold water is circulated by means of pumps. The hot oil rises to the top, gives up its heat to the water, and sinks to the bottom of the tank, thereby maintaining a good circulation.

There has been considerable disagreement as to the relative advantages of oil and air for the cooling of transformers. The oil must be entirely free from moisture in order to give satisfactory results, and it is difficult to obtain oil free from moisture. One of the most important reasons for the use of oil is its insulating property. Four parts of moisture in ten thousand will reduce the breakdown voltage to one-half ; thus it is evident that transformer oil must be free from moisture. It has been urged against oil-insulated transformers that they constitute a large fire risk. It is certainly advisable to place large oil-insulated transformers in fire-proof compartments at some distance from the machines, and arrangements should be made to drain off the oil if necessary.

For any voltages over 33,000, the oil insulated and water-cooled type of transformer is alone practicable. Oil for use in transformers will be considered later.

CHAPTER IX.

INSULATING OILS.

Oils. — At the present time the use of oil in high-voltage transformers is considered absolutely essential, and a very large proportion of the low-voltage transformers are oil insulated and cooled. It is now an almost universal practice to use oil in small house transformers. Oil also finds an important field of usefulness in oil switches and oil circuit-breakers where it possesses numerous advantages. Mineral oils are preferred to vegetable or animal oils, and are used almost exclusively.

Insulation. — All oils whether mineral, vegetable, or animal, when pure, are good insulators. There is a wide range in the insulating qualities of different mineral oils, but this seems to be due not to the chemical composition of the oil but to its purity. An oil to be pure must be free from acid, alkali, water, or foreign matter of any kind. The method usually employed in determining the insulation value is to test its dielectric strength.

Flash Point and Fire Test. — The Flash Point of an oil is the temperature to which it must be heated in order to give off gases which burn when ignited. By the Fire Test of an oil is meant the temperature at which the oil itself takes fire and continues to burn.

NOTE. In the present chapter the author is indebted to Mr. C. E. Skinner's article entitled "Transformer Oil," published in the *Electric Club Journal* (May 1, 1904); and from Mr. S. T. Kintner's article entitled "Treating of Transformer Oil" in the same paper (October, 1904).

Evaporation. — Mineral oils begin to evaporate at a temperature slightly below their flash point, and the evaporation is very rapid at and above their flash point.

Moisture. — Moisture in oil lowers its dielectric strength to a marked degree. A series of tests were performed by Mr. C. E. Skinner on the effect produced in the breakdown voltage of a given oil, varying the amount of water present. The conditions of the test were: terminals, one-half inch balls, gap, .075 inch; frequency, 133 cycles; and a sine wave form. The results obtained are plotted in the curve shown in Fig. 123.

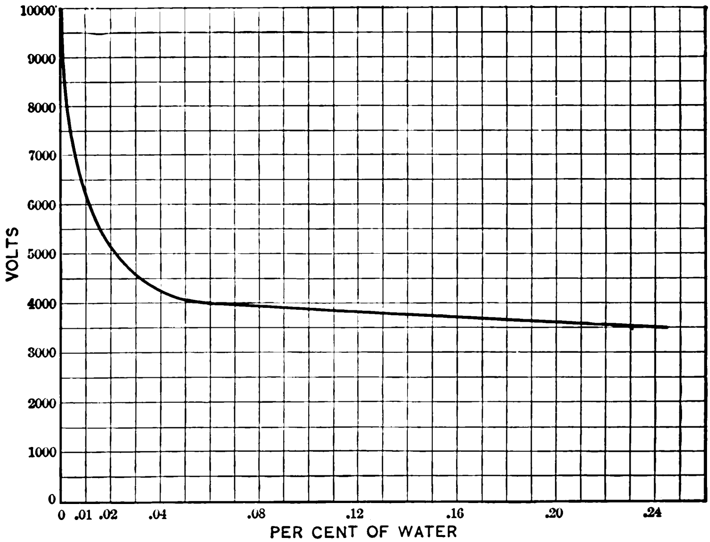


Fig. 123. — **VARIATION OF BREAKDOWN VOLTAGE DUE TO PRESENCE OF MOISTURE.**

Viscosity. — By viscosity is meant the fluidity of the oil. This viscosity is not a function of the specific gravity, but in general the less the specific gravity is the greater is the fluidity. The specific gravity of insulating oils is high being almost that of water. They should flow readily without heating.

Color. — For convenience oil should be water-white in color, but this is not necessary, and the color of the oil does not appear to affect its insulating properties. Water-white oil usually results from chemical treatment, and it is better to use a darker oil than to run the risk of affecting insulating values by chemicals in the oil.

Sulphur. — The action of sulphur, although not fully understood, is highly detrimental to the dielectric strength of the oil. In some experiments it has been found that the presence of a small amount of sulphur in oil will ruin its insulating properties in a very short time.

Deposit. — In actual service it sometimes occurs that a dark deposit will form in the oil. This deposit is itself a good insulator, being composed almost entirely of varnishes and dust. The only harm it can do is to impede the circulation, and all that is necessary is occasionally to clean the parts on which the deposit forms.

Insulation Test. — The insulating value of an oil is usually obtained by immersing a spark gap in the oil, the gap being of a known length, and then gradually raising the potential until a breakdown occurs. In making this test the following cautions should be observed:

The spark gap terminals should always be of the same shape and well polished, since roughness or points on the terminals will greatly change the results;

The gap should always be at the same depth in the oil, for the variation in pressure due to the variation in depth will produce a variation in the results;

The testing voltage should always be applied in the same manner. It is preferable to fix the gap and apply a uniform increasing voltage until a breakdown occurs;

A fresh sample of oil of a definite volume should be used in each test.

The frequency and wave form should be kept constant and several tests should be made of each sample.

Flash Point and Fire Test. — There are two general types of apparatus on the market for making these tests, the open cup and the closed cup. The open cup method is preferable for use with oils that have a high flash point. The following precautions should be observed:

1. The rate of heating should be uniform;
2. The cup should be a deep one and only half filled;
3. The quantity of oil should be the same in each test;
4. The testing flame should be of a uniform size, a gas flame about one quarter of an inch in length being preferable;
5. The testing flame should be applied at the edge of the cup, the mixture of air and vapor being more complete;
6. Draughts should be carefully avoided;
7. The thermometers should be standardized.

Evaporation Test. — A convenient method for obtaining the amount of evaporation of a given oil is to place several grams in a porcelain crucible and heat several hours over a water bath and determine the percentage of evaporation by the loss in weight.

Tests for Moisture. — The simplest test for moisture in oil, and a good one, is to thrust a small piece of iron just below red heat into a cup containing a small quantity of oil. Any hissing or crackling noise indicates the presence of moisture.

Another test is to take a sample of oil and shake it with anhydrous copper sulphate. A bluish tinge in the copper sulphate will indicate the presence of moisture in the oil.

Cold Test. — The cold test may be made by placing a test tube containing a sample of oil to be tested in a freezing mixture and noting the temperature at which the oil ceases to flow when the tube is turned on its side.

Treatment of Oil for Moisture. —The necessity of having the oil free from moisture is apparent from the curve on page 234, and as there are innumerable ways in which the oil may collect moisture, its treatment for the removal of the water is of very great importance. The separation of oil and water may be affected by six different methods: — (1) by mechanical separation; (2) by capillary attraction; (3) by electrostatic force; (4) by heating; (5) by a vacuum and heating; (6) by dehydrating.

(1) *Mechanical Separation.* When the oil contains considerable moisture its greater density will cause the water to settle and it may be drawn off from the bottom of the tank. The separation in this case is not thorough enough for high voltage work.

(2) *Capillarity.* A separator has been devised which allows the passage of the oil over a disc that allows the water to pass through and retains the oil. This method, like the first, is not sufficiently complete.

(3) *Electrostatic Force.* A strong electrostatic field will tend to hold the water and allow the oil to pass to the

weaker portion of the field, but this method *also* produces only a partial separation.

(4) *Heating.* Moisture can be removed from oil by heating it to a temperature above that of boiling water and maintaining it there for a considerable period. With large quantities of oil it requires from ten days' to two weeks' heating to remove all the moisture. This method darkens the oil's color, tends to decompose it, and is highly detrimental to the oil.

(5) *Vacuum and Heating.* If in the previous method the oil is kept under a partial vacuum, the boiling point of the water will be lowered and it is possible to remove the water completely. This method is inconvenient, however, owing to the length of time required and the difficulty of maintaining the vacuum.

(6) *Dehydrating.* Moisture can be removed from oil by treating it with suitable chemical agents for absorbing the water. Lime is employed as the dehydrating agent and is mixed with the oil in suitable tanks. After treatment the oil is passed through a filter in order to remove any particles of lime or other foreign substances and is then ready for use. This method does not injure the quality of the oil in any way, and is cheap and rapid. An apparatus has been developed by the Westinghouse Company which employs this principle in conjunction with method (2) described above.

Westinghouse Oil-Treating Apparatus. — This outfit circulates the oil to be dried through a tank in which is placed a disc (described under capillarity) over which all the oil passes. The disc separates out the excess water. The oil is then pumped into a treating tank in which is placed lime.

While in this tank the oil is kept in circulation by means of a pump. The oil after treatment passes through a filter of dry sand, which thoroughly removes any particles of lime or other foreign matter it may still retain. There are a number of other satisfactory dehydrating agents, and in some instances where special precautions are employed they may prove more advantageous than lime. Dry sand has been found to be a very good filter; sometimes bone black or Fuller's earth are added, these tending to clarify the oil. This outfit is provided with a pump and motor. It is compact and portable and with it a thousand gallons of oil a day may be thoroughly dried.

The oil should be tested from time to time to see that the dehydrating material has not depreciated in strength.

Specifications for Transformer and Switch Oil. — Practically the only difference between oil which is to be used for transformers and that to be used for oil switches is in the viscosity and cold tests. Switch oil should be slightly heavier in order to prevent its being thrown by the opening of the switch and that it may quench the arc sooner. The heavier oil is not so easily displaced by the arc. Oil switches may in some rare cases be exposed to cold. This will tend to coagulate or solidify the oil and will interfere with the operation of the switch.

The specifications are as follows:

1. The oil shall be pure mineral oil obtained by fractional distillation of petroleum unmixed with any other substance and without subsequent chemical treatment;

2. The flash test of the oil shall not be less than 180° C. (356° F.);

3. The fire test shall not be less than 200° C. (392° F.);

4. The oil must stand an insulation test of at least 40,000 volts with a spark gap of ¼ inch between two balls ½ inch in diameter;

5. The oil must be entirely free from moisture;

6. The oil must not contain acid or alkali or sulphur compounds;

7. The oil must not show an evaporation of more than 0.2% when heated at 100° C. (212° F.) for eight hours;

8. The oil must be as fluid as possible and the color as light as can be obtained in untreated oil;

9. The oil must be free from any dirt or deposit.

In this list no cold test is given. The value of the cold test must be determined separately for the conditions in any given case. These specifications are only general.

CHAPTER X.

AUXILIARY SUB-STATION APPARATUS.

Auxiliary Sub-Station Apparatus. — Auxiliary Sub-Station Apparatus may be divided into three general classes: first, that apparatus employed in connection with the measurement of power, *i.e.*, voltmeters, ammeters, wattmeters, power factor meters, etc; second, that apparatus employed in handling the power, *i.e.*, switches, rheostats, circuit breakers, etc.; third, that apparatus employed integral with the converter, *i.e.*, synchroscopes, oscillators, speed limit devices, etc.

Ammeters, voltmeters, and wattmeters are too well known and have been described too often to need any further description here. The types of apparatus described in this chapter are as follows:

1. Power Factor Meters.
2. Synchronism Indicators or Synchroscopes.
3. Automatic Synchronizers.
4. Circuit Breakers.
5. Time Limit Relays.
6. Knife Switches.
7. Field Switches.
8. Air Switches.
9. Oil Switches and Circuit Breakers.
10. Reverse Current Relays.
11. Lightning Arresters.
12. Field Rheostats.
13. Oscillators.
14. Speed Limit Devices.

Power Factor Meter. — The power factor meter is an instrument designed to automatically indicate the power factor of alternating-current circuits. The principle of the power factor meter is as follows: Consider the coils *M* and *N*, Fig. 124, to be arranged at right angles to each other. This arrangement of four coils is for a quarter-phase circuit, a three-phase instrument having three coils. The coil *N* carries a current in phase with the current in one phase of the circuit, and the coil *M* carries a current $\frac{\pi}{2}$ degrees out of phase with that in the coil *N*. That is, the coil *M* is connected to one phase and the coil *N* to the other of a quarter-phase system. The current in the coil *N* will be a maximum when that in the coil *M* is zero, and these coils will produce a rotating field of the same frequency as that of the circuit to which the instrument is connected. A small coil *C* is pivoted so that it can rotate, and these bring its axis in line with that of the coil *M* or *N*. This coil *C* carries a current in phase with the voltage of one leg of the circuit whose power factor is to be determined.

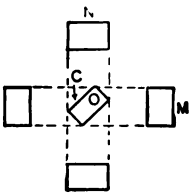


Fig. 124. — POWER FACTOR METER.

In the direction *OM* the field will be zero when the current in the coil *N* is zero, and in the direction *ON* the field will be zero when the current in the coil *N* is maximum. Thus between these two points a zero field can always be found between the maximum and zero of the current in the coil *N*. The small coil *C* will be attracted or repelled by the field of the coils *M* and *N*, and it will take up a position in which its zero field will occur at the same time as the zero of the rotating field. Thus, if the current in the coil *C* is in phase with the current in the coil *N*, it will take up a position with its axis in line with *OM*, while if the current in the coil C is up at 90° with the current in the coil N, it will take up a position with its axis in the line ON, and for any other phase relation it will take up some intermediate position. The movable coil will thus shift to a position which corresponds to the angle between the currents in the coil C and the coil N. This angle corresponds to the difference in phase between the current in the coil C (*i.e.*, a current in phase with the voltage), and the current in the coil N (*i.e.*, a current in phase with the current in the circuit). Therefore if a pointer is attached to the coil C and moved up a scale divided correctly, it will indicate the power factor of the circuit. Fig. 125 shows the diagram of the connection for a Westinghouse three-phase power factor meter with transformers. The two transformers in series with the leads are the current transformers, and the one in shunt with the leads is the potential transformer.

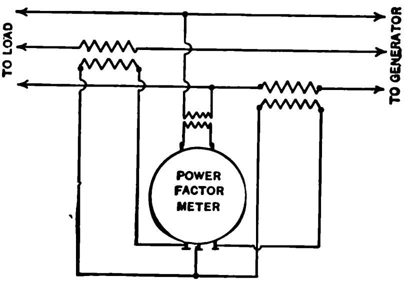


Fig. 125.—CONNECTIONS FOR POWER FACTOR METER.

Fig. 126.—WESTINGHOUSE POWER FACTOR METER.

Fig. 126 illustrates the Westinghouse power factor meter. In this instrument the coil C is replaced by a movable piece of iron, this iron being magnetized by a stationary coil in a manner similar to the field of a revolving field generator. This movable performs the same functions and simplifies the construction of the instrument by obviating the necessity of carrying current to a movable coil. The instrument will indicate the power factor for either leading or lagging currents, and also will indicate when power is delivered in the reverse direction.

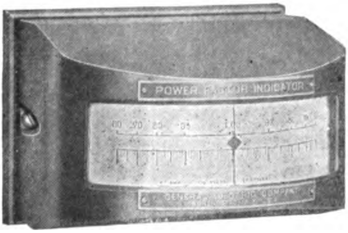


Fig. 127.—G. E. POWER FACTOR METER.

Fig. 127 shows the General Electric Company's power factor meter. This instrument is the horizontal edgewise

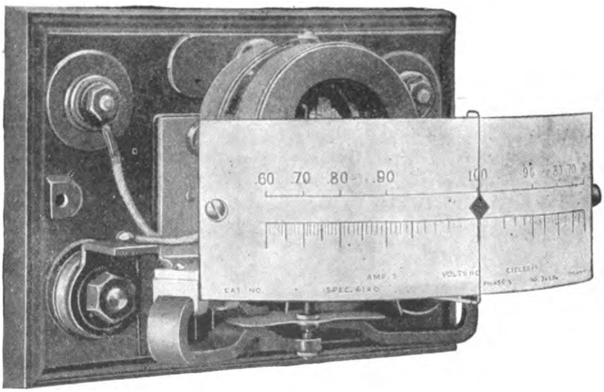


Fig. 128.—G. E. POWER FACTOR METER.

type to be used on three-phase circuits. Figs. 128 and 129 show the instrument with the cover removed. It is customary to use these instruments on railway circuits with both current and potential transformers. However, for circuits up to 200 amperes capacity and 2500 volt pressure they may be employed without transformers.

The Synchronism Indicator. — The synchronism indicator or synchroscope is a device that possesses numerous advantages over synchronizing lamps. A device used in synchronizing two or more alternating-current machines should

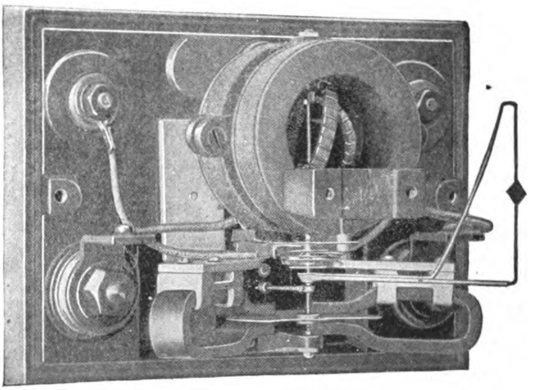


Fig. 129.—G. E. POWER FACTOR METER.

do three things; first, it should indicate whether the starting machine is running faster or slower than the running machine; second, it should indicate the amount of difference in speed; and third, it should indicate the exact instant of synchronism of the starting and running machine. Lamps when used for this purpose perform the second function well, the third only approximately, and the first not at all.

These three requirements are fully met by the synchronism indicator or synchroscope. Fig. 130 is a cut of the

Westinghouse synchroscope. If the incoming machine is rotating too fast the pointer rotates in one direction, if too slow in the opposite direction. When the machines are in phase the pointer remains stationary in a vertical position. Fig. 79, on page 162, shows the General Electric Co.'s synchronism indicator. The pointer of this instrument moves around a dial and the angle of the pointer's displacement shows the difference between the starting and running machine. The indications are similar to that of the Westinghouse synchroscope previously described. A complete rotation of the hand denotes a gain or loss of one cycle in the frequency of the starting machine as compared with the running machine.

Fig. 130.—SYNCHROSCOPE.

The construction of this synchronism indicator is similar to that of a small motor, the field of the motor being energized from the synchronizing basis excited by the machine that is running. On page 161, Fig. 78, may be found a diagram of the connections of the General Electric Synchroscope Co. Referring to this diagram, connections to the field are made by binding posts *A* and *B* shown in the wiring diagram. The motor armature is of the drum type, and consists of two coils fastened rigidly at right angles to each other. The junction of the two coils is connected through a slip ring to the binding post *E*. The other two terminals are brought out through two additional slip rings and connected to the binding post *D*, thence through a reactance to the binding post *F*. The other terminal is connected to the binding post *C*, and through a resistance to the same binding post *F*. The binding posts *E* and *F* are to be connected to the bus excited by the machine that is being synchronized. The reactance and the resistance are to be mounted behind the board. The reactance is contained in a metal case and a lamp is mounted on the case for the resistance. The diagram of connections are for circuits using ungrounded secondaries on potential transformers.

Automatic Synchronizer. — The automatic synchronizer does away with the uncertainty of throwing hand switches, the operation of synchronizing being automatic. The automatic synchronizer manufactured by the Westinghouse Co. consists essentially of two solenoids, the upper ends of whose movable cores are flexibly connected to either end of a crossbeam pivoted at its center as an ordinary walking beam. The solenoids are connected so that the one receives a maximum current at the instant of synchronism and the other a minimum current at the same instant. Attached to the shaft of the walking beam or crossarm is a contact finger or dip. This contact closes the circuit at the instant of synchronism through a relay switch, which in turn closes the circuit through the closing coil of an electrically operated switch and puts the converter in. To the crossbeam is also attached one element of a dashpot. The other element is connected through a system of levers to an insulating disc mounted on a short shaft in line with the pivot of the crossarm. A small metal segment mounted on the disc is a little longer than the gap between the movable clip and the stationary clip when the clips are at their minimum attention apart. Adjustment is made such that this minimum distance is reached at the same instant of synchronism. The dashpot action on the disc prevents the clips from making contact when the rocking or vibrating motion of the beam is too rapid. Before the incoming machine has approached synchronism the two solenoids will be acted upon equally by currents from the synchronizing transformers, and the beam will take a position midway between its extreme positions. When the machine nears synchronism the beam begins to oscillate as the current in one coil is a maximum when that in the other is a minimum and vice versa. When the vibrations or oscillations become slow enough the dashpot is pulled out to its full length, and this brings metal segment on the insulating disc in position to close the circuit between the clips and thus actuate the relay switch.

If the voltage of the incoming machine differs greatly from that of the bus-bars to which it is to be connected, the synchronizer will not close the contact, since one solenoid will receive a voltage in excess of the other and the beam will be held too low at the moment of synchronism. Thus a machine will not be thrown in unless the voltages are approximately equal and the frequency is right and the machine in phase with the line. The contacts handle only the small current necessary to operate the relay and will last indefinitely. When the synchronizer is operated in conjunction with automatic oil switches, which require time to close, the clips are so arranged that they close the circuit at the proper interval of time before synchronizing.

Automatic Circuit Breakers. — No station could operate successfully for any length of time without the use of some automatic circuit-opening mechanicism. Fuses require an appreciable length of time to open the circuit, which in the case of a severe short circuit may produce serious

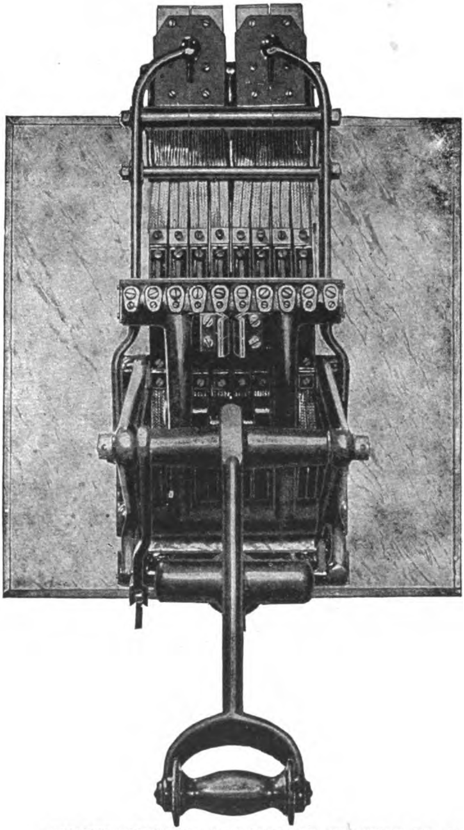


Fig. 131.—WESTINGHOUSE AUTOMATIC CIRCUIT BREAKER.

damage. "Circuit Breakers" are provided with some form of a tripping coil which, when the current reaches some predetermined limit, will disengage or trip a catch and allow the switch breaker to open.

Fig. 131 shows a Westinghouse Automatic Circuit Breaker, Type C, of 8000 ampere capacity, suitable for direct or alternating currents. A swinging arm moved by a handle through toggle joints, carries a U-shaped brush of laminated copper. The two ends of this copper brush press upon and make contact with two copper blocks mounted on the base when the circuit breaker is closed,

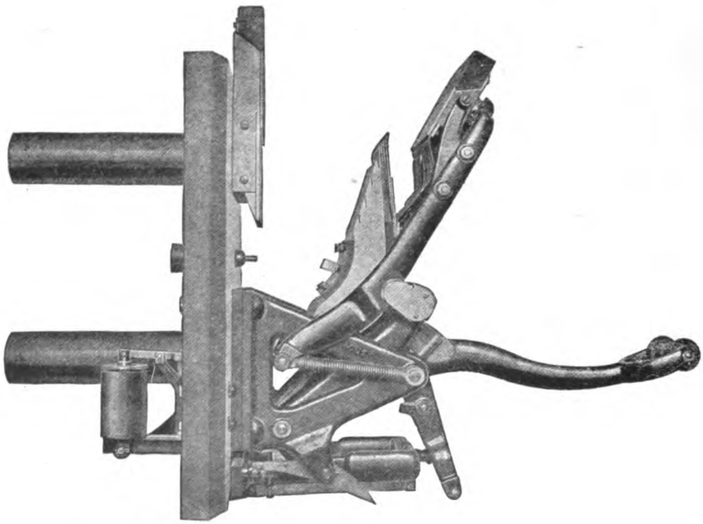


Fig. 132.—WESTINGHOUSE AUTOMATIC CIRCUIT BREAKER.

these blocks being connected to the line. The swinging arm also carries a carbon block upon its upper end which makes a contact with a second carbon break set in the base and connected to the line. When the circuit breaker opens the current is shifted through low resistance copper shunts to the carbon contacts, and no arc is formed between the copper contacts but between the carbon. The pressure in closing the breaker is sufficient to throw it out when tripped. Fig. 132 shows another position of this circuit breaker.

These circuit breakers are provided with a tripping coil which can be set to trip the switch between the limits of 20% less or 50% greater than the rated current capacity.

Time-Limit Overload Relays. — All electric generating

Fig. 133.—TIME-LIMIT RELAY.

or transforming apparatus is designed to carry overloads of a given magnitude for a predetermined length of time. In order, therefore, that a circuit breaker protecting say a converter may not open the circuit instantly when an overload occurs, they are provided with what are termed "time-limit overload relays." The spindle of the tripping coil of the relay is connected to a bellows whose action is similar to that of a dashpot. These are adjusted so that when the overload occurs it will take from 1½ to 5 seconds before the air in the bellows has been squeezed out and the spindle is allowed to release the catch opening the circuit breaker. This allows the circuit breaker to control a fluctuating load.

The action of the circuit breaker is not altered by the addition of the overload relay, except that when tripping coil begins to act a predetermined time is allowed to elapse before the breaker opens. When time limit relays, Fig. 133, are used in sub-stations, they are usually set for a short time to allow the line to clear itself. If this is not done at the end of the time limit, the breakers will open. In the central station the relays are set for a longer time and thus allow the breakers in the sub-station affected to open first and clear the trouble.

Knife Switches. — Knife switches are used almost exclusively on the direct-current side of railway systems, and are connected in series with the D.C. circuit breakers. In closing the circuit the circuit breaker is thrown in first and then the knife switch is closed completing the circuit. In opening the circuit the breaker is tipped out, thus breaking the connection, after which the switch may be opened. Knife switches may be used to open the circuit in case of emergency or the failing of the breaker to work. Knife switches are also employed on the field exciting circuits.

Fig. 76 on page 157 illustrates a 3600 ampere quick break knife switch manufactured by the General Electric Company. This switch is designed for 600 volt railway service. It consists of two or three elements according as to whether it is single or double throw. In the single-throw switch the leading blade is attached directly to the handle, and the following blade is attached to the leading blade by means of a stiff coil spring as shown. When the leading blade is withdrawn from the clips to an angle of about 30 degrees, its heel releases the following blade which is then forcibly opened by the spring being under tension, thus making an extremely quick break. Both the blades are of equal current carrying capacity. In the double-throw switch of this type two following blades are provided, one on each side of the main blade. Only one of these blades is active in either position. The blades are seated by means of a groove at the heel into a common steel ring. Both blades are tied together by this ring and turn on a common pivot, which is located intermediate between the leading and following blades at the center of the ring.

Fig. 77 on page 158 illustrates a starting switch for direct-current motors, motor generator set, or rotary converters. In cases where the starting current is a comparatively small percentage of full-load current and where it is desirable to keep the entire starting mechanism out of circuit after speed is attained. A four-step rheostat is provided with this type of switch, and is mounted behind the board. This type of switch makes a very compact starting device. The blade makes contact consecutively with each set of clips thus cutting the resistance of out of circuit steps. Fig. 134 illustrates two forms of double-throw switches, single pole and three pole. Their mechanical features are self evident.

Field Switches. — A field switch must not only be capable of opening and closing the circuit but should provide some means of automatically shunting a resistance across the field terminals on opening the circuit. Thus allowing the high E.M.F. induced in the field to discharge itself gradually without damage to the field winding. Fig. 135 illustrates a single-pole field discharge switch of the Westinghouse Manufacturing Company.

This switch is of the quick break type and closes the circuit in the ordinary manner. On opening the circuit the leading blade to which the handle is attached is

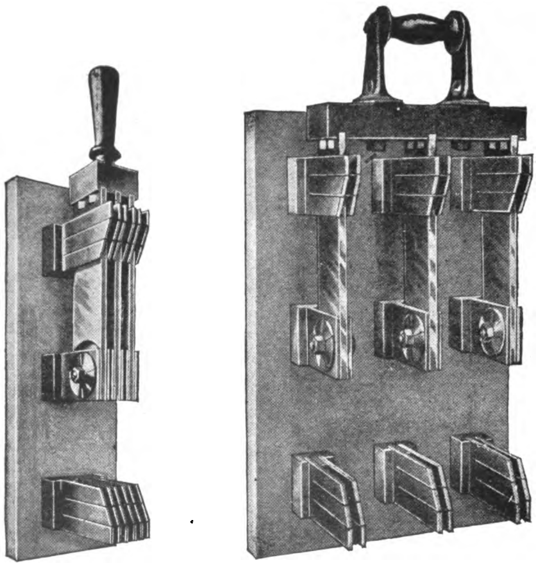


Fig. 134.—DOUBLE-THROW BLADE SWITCHES.

brought in contact with the lower clips before its heel releases the following blade, which is then rapidly withdrawn by the springs thus producing a very quick break. A suitable discharge resistance is connected to the lower clip in such a manner as to be thrown across the field terminals of the converter when the following blade makes contact with the clips.

Westinghouse High Potential Circuit Breaker with Expulsion Tube, for Circuits from 6000 to 40,000 Volts.— This circuit breaker is designed for potentials from 6000 to 40000, volts. As shown in the illustration, Fig. 136, the circuit breaker consists of two hardwood poles, one being longer than the other, mounted upon a marble base, to which are secured the terminals for the main leads or wires. The wood poles are connected by a hinge, so that their extremities are in line at the upper end. On the upper end of each pole is mounted a copper sleeve supporting a round carbon contact block with a hole through its center. The longer pole is provided with spring jaws or clips so that it may be quickly and easily attached to, or detached from, the terminals on the marble base. The short pole has a flexible wire running through its interior; this wire is connected to the copper sleeve at the upper end of the short pole and to the lower clip terminal on the long pole. The sleeve at the upper end of the long pole is connected to the upper clip terminal. These connections make the sleeves at the upper ends of the two poles the terminals of the apparatus.

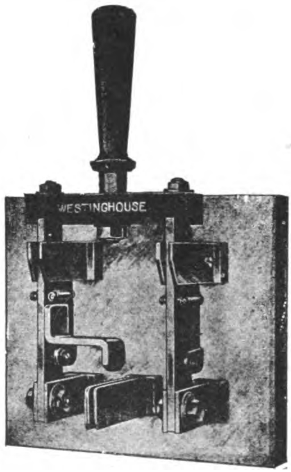


Fig. 135.—FIELD DISCHARGE SWITCH.

Between the carbon contacts is an expulsion tube, through which the fuse wire passes. When the fuse blows, the break is made in the small hole in this tube which greatly limits the expansion of the arc. A strong draft is created which extinguishes the arc and practically prevents it from rising above the top of the breaker — a very important feature.

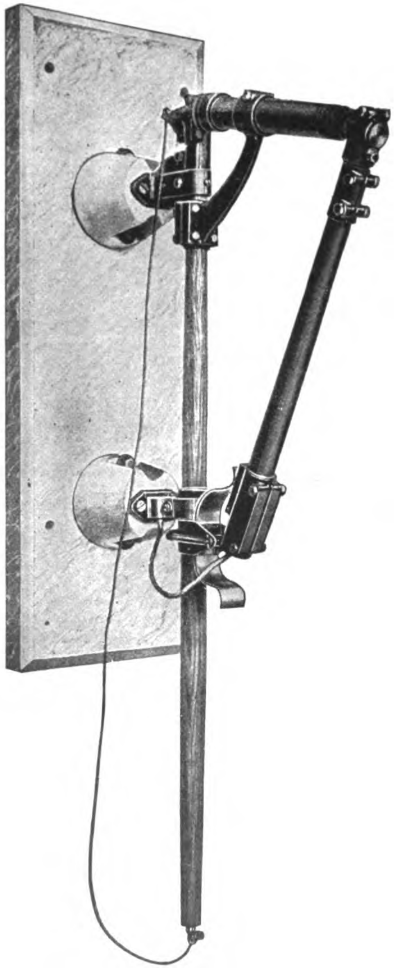


Fig. 136. — HIGH POTENTIAL CIRCUIT BREAKER.

The poles being removed from the base, a wire is inserted through the hole in the carbon tip at the upper end of the short pole and secured to the copper sleeve by a screw and washer. The other end of the fuse is passed through the expulsion tube and carbon tip on the long pole and secured to the copper sleeve by a cam-shaped lock.

The poles, after being fused, are placed in position by taking hold of the lower end of the long pole. When the fuse blows, the short pole is released by the action of the spring at the lower end and falls away from the stationary pole, thus making a very long break. The lock cam has a long string attached to it, by means of which the fuse can be released, if desired, thus causing the short pole to drop in the same manner as when the fuse blows. This feature permits the device to be used as a switch.

Oil Switches and Circuit Breakers. — A distinction should be drawn between oil switches and oil circuit breakers. The former are essentially knife switches immersed in oil, while oil circuit breakers have contacts immersed in oil, and these contacts tend to separate, being held in position by means of triggers or toggles. Circuit breakers should be designed to reduce the amount of oil to a minimum consistent with safe operation, thus reducing the fire risk in places where they are located. Oil switches possess certain advantages over air switches. When the contact points are drawn apart the oil flows in between them and smothers the arc, and also prevents surface leakage. An oil switch opening an alternating-current circuit always smothers the arc at the zero point of the current wave. With an air switch the arc is composed of copper vapor when copper contacts are used, this being highly conductive and tending to maintain the arc. The insulating qualities of a given oil are practically constant, provided it is kept free from moisture; on the other hand, air varies greatly in conductively depending upon the humidity, temperature, and atmospheric pressure. Air switches are cumbersome whereas oil switches are compact. These advantages combine to make the oil switch superior to air switches in almost every respect where high potential circuits are to be operated. There are, however, certain instances where air switches are preferable owing to conditions of economy in first cost, where space is not a factor, and where the simplest mechanism is essential.

A simple form of oil switch designed by the General

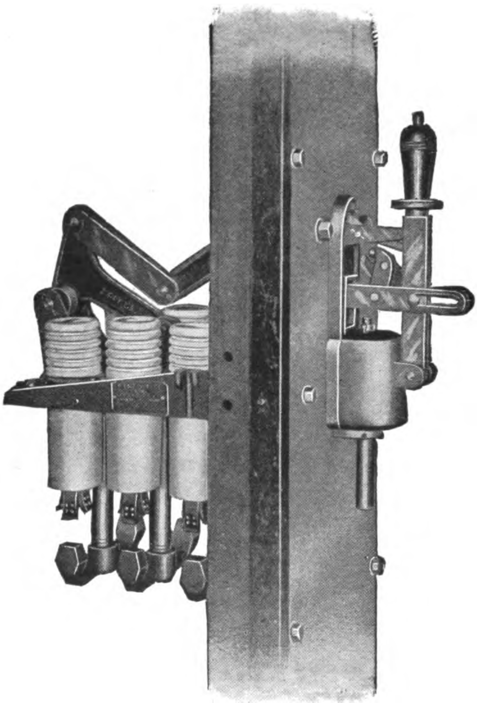


Fig. 137.—G. E. OIL SWITCH.

Electric Company for rupturing loads which under emergency conditions cannot exceed 850 to 1200 kilowatts, three phase at voltage not exceeding 2500, is shown in Fig. 137. This form of switch is used by the Interborough Rapid Transit Company of New York in circuit with the induction motor, driving the direct-current starting set for the converters. This form of switch is known as the Type K oil switch. The switch is closed by hand and tried mechanically. The switch is also provided with an overload coil. The structural features of this device are self evident from Fig. 137, where the oil tanks are removed.

Fig. 138 shows a Westinghouse Type C Oil Circuit Breaker. These circuit breakers are designed to operate on potentials of from 3300 to 33,000 volts. These switches are operated by solenoids controlling a positive, direct-acting, simple lever system. All live parts are immersed in oil, and the open position is maintained by gravity. This type of switch requires only a small quantity of oil, and all its parts are easy to access. There are two stationary contacts per pole, — one for the incoming and the other for the outgoing lead of the same phase. The contacts are mounted on large porcelain insulators, and the leads are brought out at the rear of the switch. The solenoids are operated by a 125-volt direct current. In case of failure of the direct current the switch may be readily operated by hand. The lever arrangement is a simple parallel motion system, which is drawn into the closed position by the solenoid, and held in that position by a toggle joint. This toggle joint is tripped by a tripping mechanism, and the switch opens by gravity, any shock at the end being taken up by the tension springs. The break is made near the surface of the oil, and the final break occurs upon arcing tips, which are easily replaced when worn away.

Each pole of this oil circuit breaker is inclosed in a separate fireproof chamber of brick or concrete. A sheet-metal oil tank encloses each pole so arranged as to be

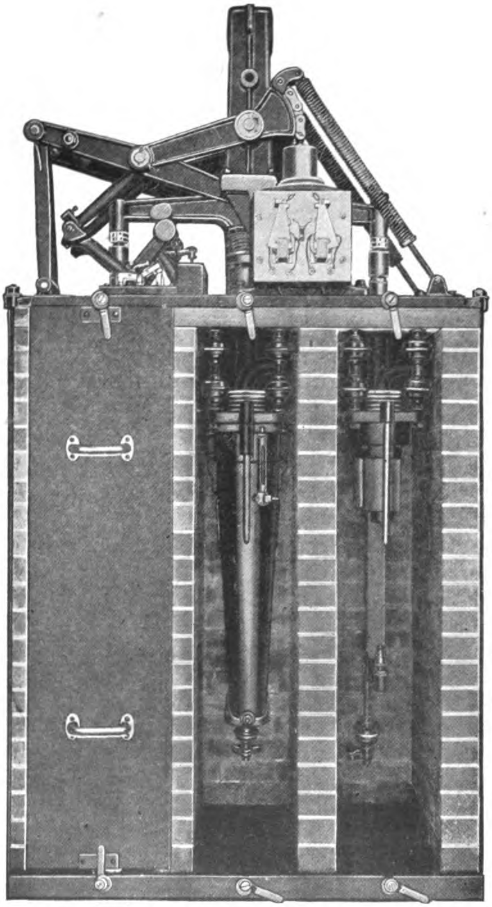


Fig. 138. — WESTINGHOUSE TYPE C OIL CIRCUIT BREAKER.

easily removable. A glass gauge shows the height of the oil, and the tank may be refilled or emptied without removing it. The tanks fit closely all parts of the switch, and leave just room enough for the free operation of the switch in the oil.

A small double-pole (double throw-knife) switch is mounted upon the case, and is operated by the levers. This switch controls the indicating and tripping circuits. The indicating circuit consists of both an electro-mechanical tell-tale indicator and a lamp to show when the circuit is opened or closed.

Oil Circuit Breaker, Type B (Westinghouse).—In Fig. 139 is shown a cut of an Oil Circuit Breaker, Type B, of the Westinghouse Company. The circuit breaker is designed for potentials from 3300 to 22,000 volts. This device is a double-break oil circuit breaker. It is automatic, and may be placed on the back of the switchboard, or arranged for distant control. All the live parts are submerged in oil, and the cases are so shaped that the smallest amount of oil consistent with perfect insulation is used, thereby reducing the fire risk.

Each pole has a separate tank, which may be easily removed without disturbing the others, and the rods carrying the contacts serve also as a barrier between the two points where arcing is likely to occur.

This circuit breaker is designed mainly for switchboard service. The construction of the operating lever makes the setting of the triggers entirely independent of the thickness of the switch panel. Only the operating handle, automatic tripping device, and releasing trigger are on the front of the switchboard, all the high-tension wiring being behind.

The circuit breaker may be set by means of a screw to open anywhere between the limits of 70% to 150% of normal rated load. The tripping coils are energized from secondaries of series transformers, the primaries being connected in the circuit controlled by the circuit breaker.

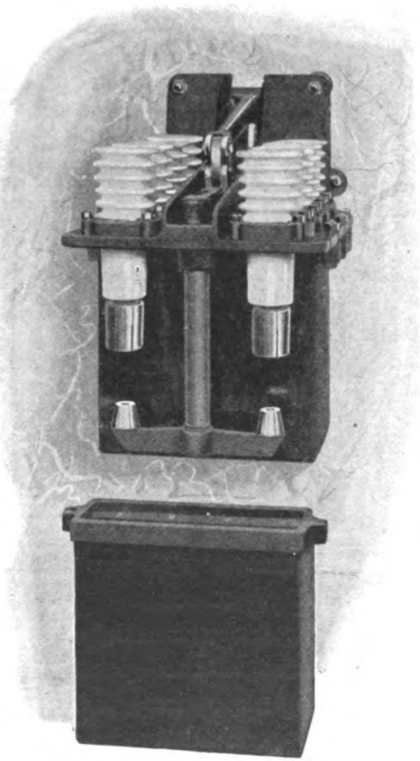


Fig. 139.—WESTINGHOUSE TYPE B OIL CIRCUIT BREAKER.

The circuit breaker may also be tripped by pressing an insulated button in the end of the operating handle, or by pushing up the core of the tripping coil.

An important feature of the circuit breaker is the arrangement of levers which prevents the circuit being held closed during an overload or short circuit on the line. This is accomplished by means of two levers, one within the other. The operating handle is attached to the outer lever, the inner one extends through and is attached to the rods carrying the contacts. The two levers are held together by a trigger, which may itself be released by the tripping coil. After an overload or short circuit, has caused the tripping coils to act, and if the overload or short circuit still continues when the breaker is closed, the tripping coil will operate the trigger, which releases the inner lever, thus opening the circuit without danger to the operator.

Oil Circuit Breaker, Type J (Westinghouse).—This circuit breaker is manufactured by the Westinghouse Company and is designed for potentials not exceeding 33,000 volts. It is somewhat similar to Type B but is of the double-throw type. All live parts are submerged in oil enclosed in a sheet metal tank and it is built with either two, three, or four poles.

With the handle in the position shown in Fig. 140 both circuits are disconnected from the line. By raising the handle the circuit on the left is connected to the mains; by lowering the handle the one on the right is connected. The circuit breaker cannot be held in a closed position during a short circuit or overload on the line by an arrangement of levers similar to that described under Type B. The breaker may be tripped by pressing the button in the end of the operating handle. It may be adjusted to carry any load between 80% and 160% of its rated capacity. This adjustment is shown at the right and consists of a slide with a pointer attached which can be set and locked at any point on the scale. The main contacts are provided with detachable arcing tips.

Oil Circuit Breaker, Type G (Westinghouse). — The Westinghouse Type G electrically operated, (Fig. 141) three-

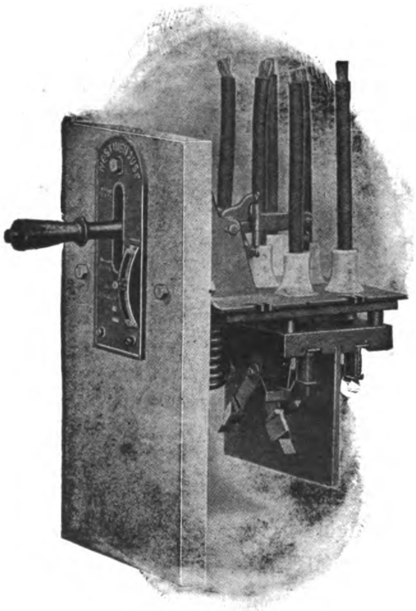


Fig. 140. — WESTINGHOUSE TYPE J OIL CIRCUIT BREAKER.

pole oil circuit breaker is designed for 60,000 volts and 100 amperes, but will carry continuously 500 amperes. It is rated to handle 60,000 h. p. per three-phase circuit, but owing to its substantial construction it will open such a circuit under any conditions of overload, safely withstand-ing the great internal pressure which may occur with a power house of 200,000 h. p. capacity.

The insulation between the ground and the terminals is designed to withstand 150,000 volts and between the poles twice that voltage. The insulation of the terminals ex-

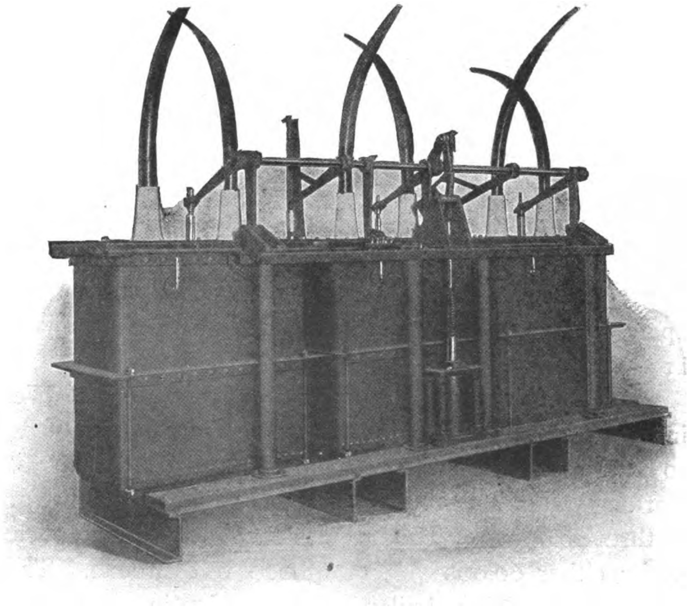


Fig. 141.— WESTINGHOUSE TYPE G OIL CIRCUIT BREAKER.

tends below the oil, large insulating bushing holding the terminals in place.

There are three oil tanks, each requiring 116 gallons of oil, of wrought iron lined with insulating material, with barriers interposed between the stationary contacts. The contacts have renewable arcing tips. The terminal leads with their insulators may be readily removed from the circuit breaker, thus giving access to the contact parts for inspection or repairs.

The three poles of the circuit breaker are mechanically connected together, and are closed by a toggle mechanism operated by a single direct full solenoid. The breaker is held in the closed position by the toggle, and is tripped out by the armature of the tripping coil striking the toggle and thus allowing the switch to open by gravity. Each pole gives a double break, and the vertical distance between the contacts in the open position is 17 inches. The closing solenoid requires approximately 5000 watts direct current, while the tripping magnets require 300 watts. By the use of an overload relay operated from series transformers the circuit breaker may be made automatic in operation. This, however, is not included with the breaker.

Oil Circuit Breaker, Type L (Westinghouse).—The Westinghouse Type L Oil Circuit Breaker (Fig. 142) is designed to handle outputs not exceeding 20,000 kw. at the highest working voltages. These breakers are either of the two-pole or three-pole type. They are designed in two different sizes—for either 60,000 volt or 88,000 volt circuits. These circuit breakers are similar in construction in every respect to those of Type G, except in the matter of insulation which in the 88,000 volt size is correspondingly heavier.

Reverse Current Relays.—The function of a reverse current relay, is to open the main circuit in case the current should change its direction of flow. They are used principally in connection with the circuit breaker controlling the positive feeder between the converter and the positive bus.

So-called return energy relays have been developed for the alternating-current side of the system, but their operation on the whole is not altogether satisfactory.

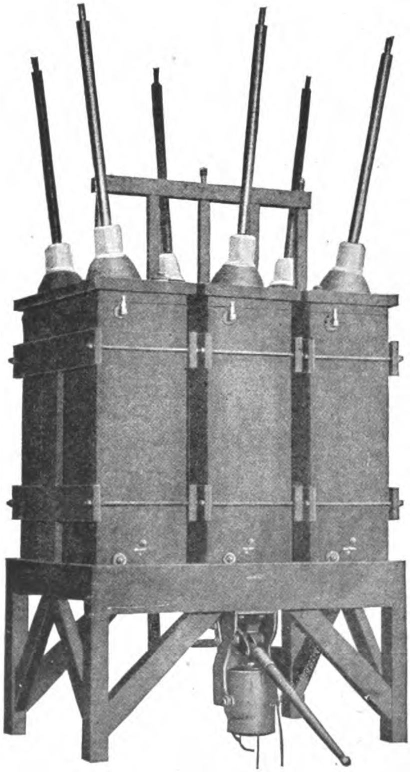


Fig. 142. — WESTINGHOUSE TYPE L OIL CIRCUIT BREAKER.

Reverse current relays usually consist of a soft iron sheet almost surrounding the positive feeder. The polarity of the terminals of this shoe changes from positive to negative, with a change in flux surrounding the feeder caused by a change in current flow. Between the poles of this shoe is mounted an armature whose amount of rotation is limited.

This armature is separately excited from the local station storage battery mentioned in a previous chapter. Attached to the armature is a small arm which makes contact, when the armature is moved in the direction opposite to removal. This contact closes a battery circuit through the tripping coil of the circuit breaker tripping it and opening the circuit.

In case the potential of the converter should become lower than positive bus, there would be a tendency for the current to reverse and flow from the bus to the converter. This changes the polarity of soft iron shell which in turn causes the armature of the relay to move in the opposite direction to normal, closing the contact and opening the circuit breaker. These relays are set supposedly to operate at a reversal of current 15%. In practice, however, they are set at 25%, as they would otherwise be too sensitive.

See Fig. 143 for complete overload relay.

Lightning Arresters. — The function of a lightning arrester (Fig. 144) is to permit the passage of static discharges to the earth, and it should avoid interrupting the service. The arrester should present a low resistance to a static charge and at the same time a high resistance to the normal voltage. An arrester must also prevent the continuance of the arc after the static charge is passed.

Lightning arresters are of many different forms, which may be divided into three general classes with respect to the suppressing of the arc. These classes are first, non-arcing; second, magnetic blow out; third, moving part.

In the nonarcing type of arrester the generator current does not continue to follow the discharge, and the arresters are automatic in action and do not leave the line unprotected at any time. Their principle of operation is based upon the fact that an alternating-current arc cannot be maintained over a short air gap when the electrodes consist of certain metals or their alloys. They consist of a number

Fig. 143.—REVERSE OVERLOAD RELAY.

of cylinders of these peculiar metals having a short air gap between them. The cylinders are mounted in a base of insulating material, the air gaps being in series. A static discharge will readily pass through to the ground, but the currents from the generator cannot follow as it is impossible to maintain the arc. In the magnetic blow-out type, if the static discharge in passing to the earth forms an arc and the line current follows it, the line current will pass

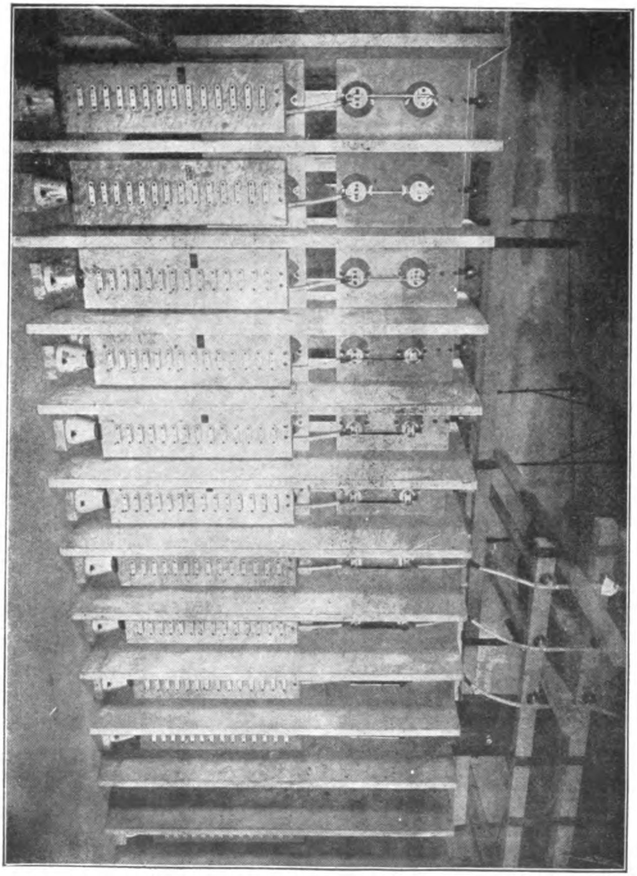


Fig. 144. — LIGHTNING ARRESTERS.

through a coil shunted around a part of the resistance pencil and the magnetic field set up by the coil will blow out the arc. The arrester consists of a high resistance pencil usually of carbon, around which is placed the coil which is in shunt with the pencil and a spark gap between one end of the pencil and the ground connection.

In the moving part type, the short circuit produced by discharge passes through a non-inductive resistance which is partly shunted by a solenoid operating a plunger through which, by means of a flexible connection, the current is passing through a small spark gap to the ground. The current violently lifts the plunger, thus drawing out the arc and rupturing it, when the plunger immediately drops to its normal position.

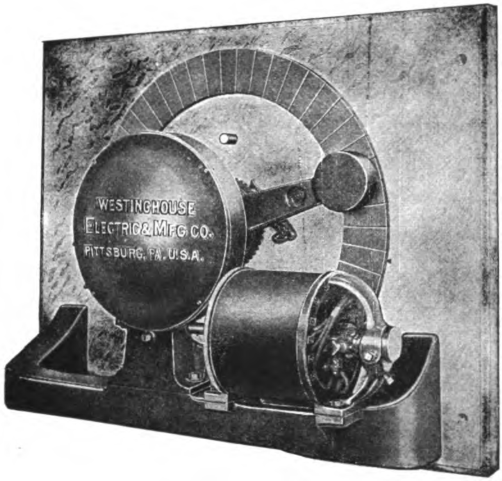
Choke Coils. — It is a well-known fact that the frequency of a static discharge is of a very high oscillatory character. Thus a coil of a few turns of heavy wire that would present comparatively very little impedance to the normal current and frequency would present a very high impedance to a static discharge. Coils of this type are known as choke coils, and when connected in circuit with some form of lightning arrester offer a very satisfactory and reliable means of protecting apparatus from lightning. Choke coils, may be constructed of copper wire or strips in either a flat spiral form or in the shape of a round helical form.

Field Rheostats. — The field rheostats may be operated by hand if space and location permit, but usually it is found necessary to employ some form of auxiliary control. This method frees the operating board of the face plates of the rheostats and makes it possible to mount the rheostats' base plates for an entire station on a separate panel near their resistance.

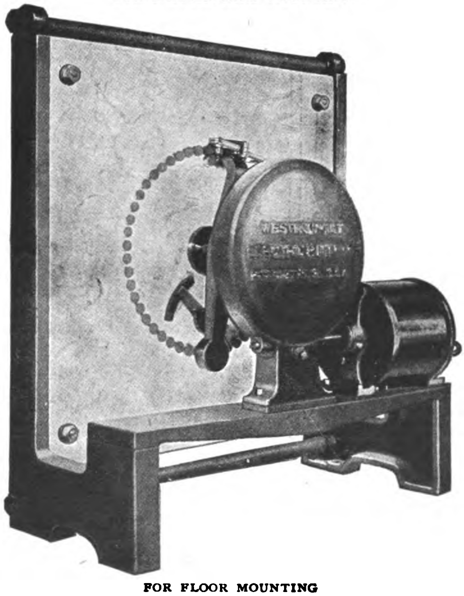
The form of the resistance used in these rheostats may be divided into three classes: bobin, bar, and gird type depending upon their current-carrying capacity. Fig. 145 illustrates the face plate, operating motor, and contact block of Westinghouse two types of generator field rheostats, the one at the top for switch board mounting, and the other for floor mounting. The resistances for these rheostats are mounted in frames behind the panel and are connected to the contacts. A cut-out switch is provided with each face plate to open the circuit when the contact arm assumes either of the limiting positions. The face plate is also provided with a device which indicates whether the contact of the contact arm is between or fully on the stationary contacts.

Oscillators. — The oscillator is the means of producing a periodic motion of the armature and shaft of a rotary converter parallel with the shaft. The armature of a converter running with its shaft horizontal will take up under normal conditions a fixed position without any tendency to move or oscillate in the direction of its length. This tendency of the armature to remain in one position will tend to wear grooves in the commutator and slip rings which is detrimental to that smooth, even surface which is necessary for sparkless operation; nor is it beneficial for the bearings. Oscillators are divided into two classes: *mechanical* and *magnetic* depending upon their operation.

Mechanical Oscillator. — This form is self contained and is mounted on one end of the shaft. The device consists of a steel plate provided with a circular ball race in which travels a hardened steel ball. The plate is not quite parallel with the end of the shaft and is backed by a spring. The ball is normally at the bottom of the race. The



FOR SWITCHBOARD MOUNTING



FOR FLOOR MOUNTING

Fig. 145.—FIELD RHEOSTATS.

machine is leveled up so that the shaft is slightly inclined toward the oscillator. The steel plate is adjusted so that when the ball is at the bottom it just comes in contact with the shaft. As the armature revolves the ball is carried up and the spring compressed, this drives the armature away toward the other limit of its travel. It continues to move until the other forces stop its travel and start it back to its normal position, where it again comes in contact with the ball and the operation begins over again.

Magnetic Oscillator. — This device consists of an electro-magnet mounted upon one of the bearing housings in such a manner as to attract the end of the shaft. When the circuit is closed the magnet attracts the end of the shaft and when the circuit is open the armature tends to return to its normal position depending upon the leveling of the shaft. A make and break device called an interrupter is placed in series with the magnet. The frequency of the action of the interrupter is controlled by a dash pot which can be adjusted so as to vary the rate of the oscillations.

Speed Limiting Device. — In cases where conditions are such that converters may be subject to periods of operation from their direct-current sides, it is advisable to insure the converter against any possibility of racing or running away, caused by weakened fields due to a short circuit on the alternating-current side or to some other cause.

This may be accomplished by a device consisting of a centrifugal switch which is mounted upon the end of the armature shaft within a pair of incircling copper rings. The action of the switch is similar to that of a centrifugal governor. When the revolution per minute exceeds a certain predetermined limit the switch arms fly out and short circuit the two rings. This completes an auxiliary relay circuit, which serves either to open the direct-current circuit breaker or to operate an alarm. This device is known as a "speed-limit relay."

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