Performance of Motor-Generator Sets

For the Chicago, Milwaukee & St. Paul Railway

F. T. Hague

SERVICE REQUIREMENTS of generators in high-voltage, direct-current railway operation are not essentially different in theory from those in the usual low voltage electrifications, except that certain operating characteristics, such as flashing on severe overloads, heretofore usually considered inherent in all commutating machinery, change from the category of relatively harmless operating difficulties on low-voltage machines, to positive liabilities in the case of machines built for higher voltages. The concentration of large powers at high voltage in a single generating unit emphasizes the necessity of protecting a machine against itself by materially improving its commutating performance, and necessitates a revision of the standards of satisfactory operating characteristics which have heretofore been commercially acceptable on low-voltage installations.

DIRECT-CURRENT generators have been used as the source of power supply to railway systems for more than 30 years, and during this period have undergone a continuous development, tending towards improvement in performance. The early introduction of commutating poles and the later development of commercial forms of compensating-pole face windings are now landmarks in the evolution of commutating machinery, and form the basis of all further improvements which tend to place railway generators on the same high plane of reliability as other forms of commercial electrical apparatus. Recent improvements in railway generators have been in the direction of increasing the momentary overload commutating capacity so as to enable a machine to withstand the overloads and short-circuits which are incident to this severe class of service. This improvement has been brought about by the consistent development, to a very high plane of efficiency, of all the component parts of generator construction, and particularly by the use of a type of magnetic circuit construction which allows the commutating pole's effectiveness to be maintained at loads well up to the short-circuit value.

It is not possible theoretically, however, to obtain the same margin of momentary commutating capacity on machines of all ratings at 3000 volts, because of certain fundamental mechanical limitations (such as safe commutator speed and distance between brush arms) which handicap machines of less than 750 kw rating when run at the speeds which are standard on moderate voltage machines. This is a fortunate circumstance in that, for this special class of service, machines of approximately 1000 kw at 1500 volts are of about the ideal capacity on which to obtain the maximum commutating performance. The recent development of a 3000 volt unit of 2000 kw capacity (two 1500 volt generators in series) which will carry momentary loads of 10 to 12 times normal, without showing distress at the commutator, and which will deliver 20 times full-load current on dead short-circuit without "bucking over", marks a considerable advance in the reliability of operation of high voltage railway generators. The performance of this unit is to be viewed more as an example of the results which are possible on a special high-voltage unit when all conditions of rating, speed and voltage combine to give the most favorable combination, rather than as a criterion for other sizes and types of high-voltage machines which do not have as great theoretical commutating possibilities.

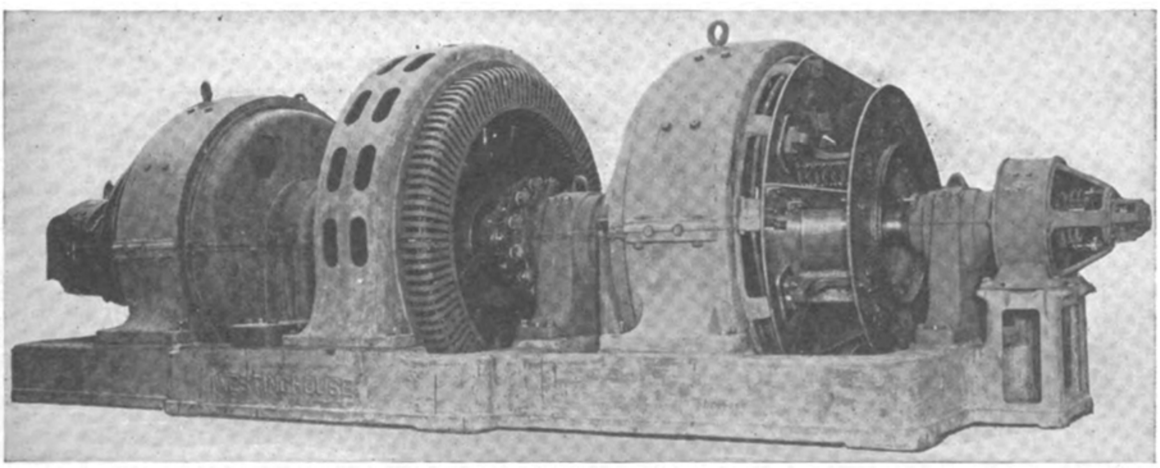

FIG. 1—TWO THOUSAND KW, 3000 VOLT SYNCHRONOUS MOTOR-GENERATOR SET

However, in order to give high-voltage machines these enormous momentary commutating capacities, it is necessary to adopt very conservative designs, in which the best known devices for the improvement of commutation are carried far toward their limits, thus necessitating greater refinements in construction and consequently higher costs. This means, in general, that a machine must be run at a relatively low speed, considering its capacity; that its magnetic circuits must be so generously proportioned as to be free from the detrimental limitations of saturation, even at the most severe overloads encountered, and that the selection of the number of poles and the distribution of the armature windings, etc., must be such as to produce the most favorable electrical combinations. In other words, many desirable commercial considerations must be subordinated to abnormal performance. It is thus theoretically and practically possible for high-voltage direct-

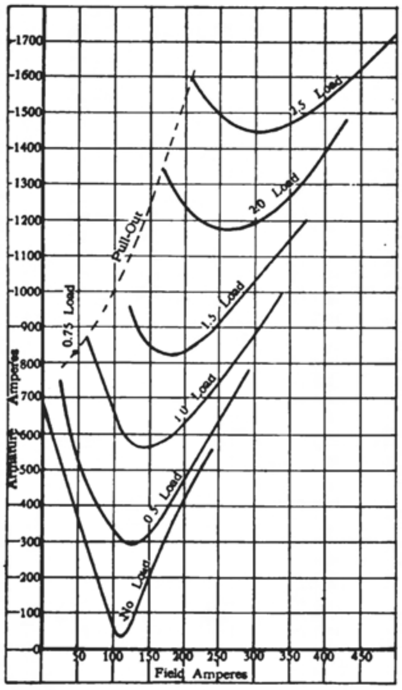

FIG. 2—V CURVES OF SYNCHRONOUS MOTOR

current machines to be given very creditable overload commutating characteristics, provided one is willing to pay the cost of incorporating these features in a special machine.

The performance characteristics of the 2000 kw, 3000 volt, 514 r.p.m. generators, built for the Chicago, Milwaukee & St. Paul Ry., give an indication of the commutating performance of a 3000 volt unit in which very conservative electrical and mechanical design limits have been adhered to. These motor-generator

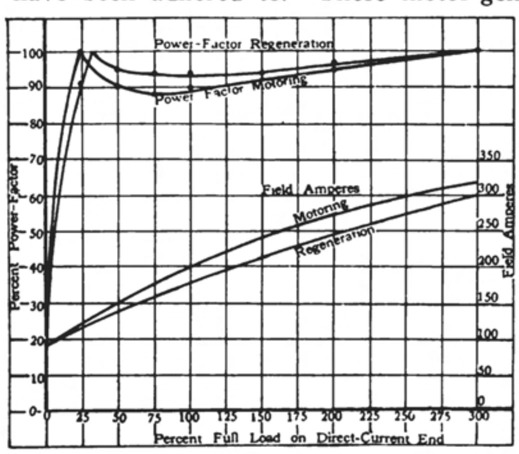

FIG. 3—POWER-FACTOR CURVES OF SYNCHRONOUS MOTOR

The current is lagging below 25 percent load and leading above this value, the transition from lagging to leading producing the sharp bend in the curves.

sets, shown in Fig. 1, consist of duplicate 1500 volt generators, connected in series to form a 3000 volt unit, and have two direct-connected exciters, the larger one supplying excitation to the synchronous motor, and the other excitation to the generators. The primary consideration was a construction which would withstand the electrical and mechanical shocks incident to carrying the extreme overloads which are met in railway service. Three thousand volt service has also presented new problems from the insulation standpoint, particularly in the methods of insulating the exposed commutator surfaces, and has necessitated the development of

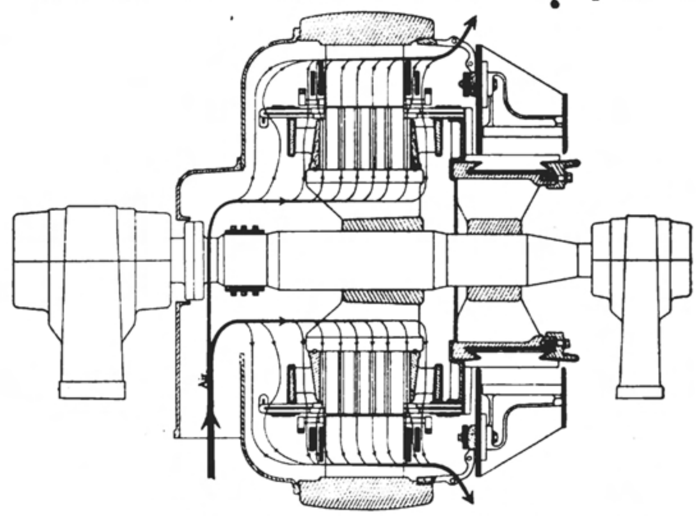

FIG. 4—CROSS-SECTION THROUGH DIRECT-CURRENT GENERATOR
Showing radial ventilation system.

insulation methods considerably more elaborate than those found on lower voltage machines, in order to maintain the same generous electrical as mechanical factor of safety. The service requirement to be met, the distinguishing features of the type of construction employed, and the test characteristics of the set may be summarized as follows:—

CAPACITY

This set has a normal capacity of 2000 kw, 3000 volts, at 90 percent power-factor, and will carry 3000

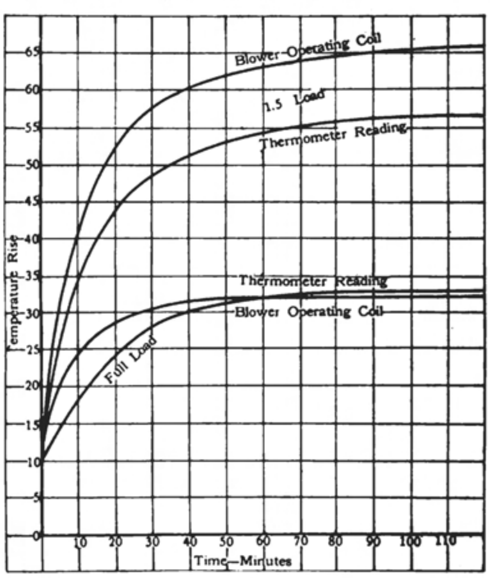

FIG. 5—TEMPERATURE CURVES AT FULL LOAD AND 1.5 LOAD WITH BLOWER

kw for two hours, with a temperature rise not exceeding 55 degrees C. The sets are to operate either direct or inverted (i.e. regenerative or braking) at loads up to 6000 kw for five minutes without injury, with the motor power-factor automatically maintained between unity and 90 percent leading from half load up to 300 percent load. This heavy overload necessitates special provisions to increase the motor field excitation in order that the motor may have a generous margin of overload torque even when the line voltage drops to 85 percent

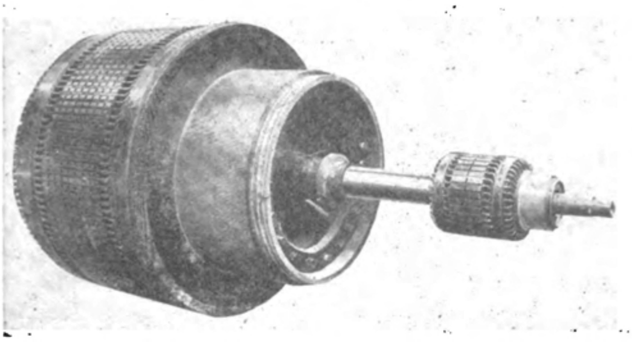

FIG. 6—ARMATURE OF GENERATOR AND EXCITER

normal. It is a characteristic of synchronous motors that the pull-out torque is roughly proportional to the excitation, and inversely proportional to the applied voltage, as indicated by the minimum excitation required for a given load, shown in the motor V-curves, Fig. 2. This overload requirement necessitates a compounding of the motor exciter, such that the motor field excitation automatically increases with the load, in the proper proportion to maintain the specified power-factor. The power-factor adjustment actually obtained is indicated in Fig. 3, which shows that the motoring and regenerative power-factor characteristic are practically identical, and that unity power-factor is reached at about one-half load, and a leading power-factor, varying between unity and 90 percent leading, is obtained up to 300 percent load. As some of the sets may require adjustment of the power-factor characteristic when operating at different parts of the electrified system, it has been arranged to vary this adjustment in a convenient manner by the use of an additional field winding, which is only used when a power-factor adjustment different from the factory setting, is required.

VENTILATION

The generators of this set are of the enclosed type, and are arranged for automatically-controlled forced ventilation at times of heavy overload. This arrangement minimizes the running light losses, by reducing

FIG. 7—MAIN AND COMMUTATING POLES

the machine's windage losses to a minimum during the long periods of light loads, which are inherent to this class of service and during which no forced ventilation is required. This saving of blower losses has been made possible by devising a thermal control system, which automatically starts the blower when the temperature of the direct-current armature winding reaches a limiting value of 75 degree C. The inherent difficulty of any system of armature temperature control is the obvious impossibility of obtaining any direct-reading temperature indicating device. It has been proven possible, however, to very closely approximate the observable thermometer temperature of the armature winding by means of the change in resistance of a small resistance coil mounted on a specially-proportioned and insulated current-carrying conductor in the stator windings. The thermal control system is so arranged that the rise in resistance of this coil actuates a relay, which starts the blower when the armature winding reaches an actual temperature of 75 degrees C. By basing the starting of the blower on the actual temperature of the machine, full advantage is taken of the low ambient temperature in which these machines operate for many months of the year.

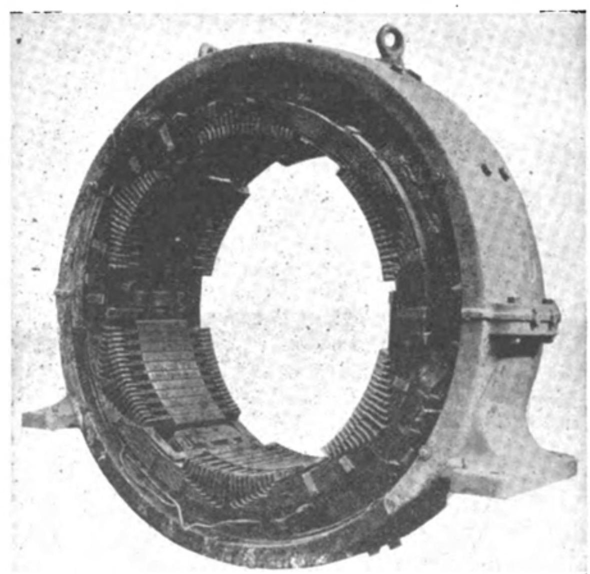

FIG. 8—GENERATOR STATOR CONSTRUCTION

The passage of ventilating air through the machine is arranged according to the radial system, shown in Fig. 4, in which the air is delivered to the inner periphery of the rotor by a double rear end bell, and is passed through radial ventilating ducts in the rotor core and around the under surfaces of the armature windings, and passes out between the field coils to the front of the machine. The core ducts are small blowers in themselves, thus giving the radially-ventilated machine an inherent ventilating force, tending to direct what air is available through the hottest part of the machine, and has a considerable power for pulling air through the core when the blower is stationary. Thus when running without an external blower, a radially-ventilated machine has a very generous continuous rating: possibly from 30 to 50 percent greater than the same machine would have with axial ventilation. The radial ventilation thus provides a very considerable inherent thermal margin of safety in normal operation, and, since the reliability of any thermal control system can never be ideal; the use of radial ventilation assures a freedom from trouble in case of blower failure that is a vital factor in maintaining continuity of service.

TEMPERATURE PERFORMANCE

The thermal characteristics of this set are extremely liberal, as it can carry all of its guaranteed loads without the aid of forced ventilation, and still not exceed a temperature rise of 60 degrees C. This is made possible by the use of radial ventilation and the open armature construction shown in Fig. 6, in which the end windings are arch-bound on themselves circumferentially, and heavily banded down on an insulated coil support. The top and bottom of the coils in the end windings are thus exposed to the ventilating air, resulting in a ready dissipation of the end winding heat, and the minimization of local hot-spots, while still maintaining a very rigid coil bracing, which is amply capable of withstanding all short-circuit stresses.

The heating curve of these armatures, without the blower running, at full load and 50 percent overload, is shown in Fig. 5, which shows reasonably close agreement between the thermometer temperatures of the generator and the temperature indicated by the resistance of the blower operating coil. On full load, the temperatures are so low that no blower is necessary, while at 50 percent overload the temperature indicated by the resistance of the indicating coil is slightly higher than the thermometer temperature of the armature. It is desirable to have incorporated in the indicating device a conservative margin of safety to offset any local hot spots which might exist in the machine. This curve is extremely interesting because of the ready comparison it affords between the short time rating of a high-speed machine and its continuous temperature rating at the same load. High-speed machines necessarily have a relatively small thermal capacity, resulting in a rapid increase in temperature when a heavy overload is applied. It is thus entirely possible seriously to overheat a machine which has exceptionally good commutating characteristics at loads very much below the load where sparking begins to appear on the commutator. The temperature of this machine with the blower in operation, is materially lower than that shown on the curve, the difference representing a virtual increase of machine capacity to handle heavy loads of long duration.

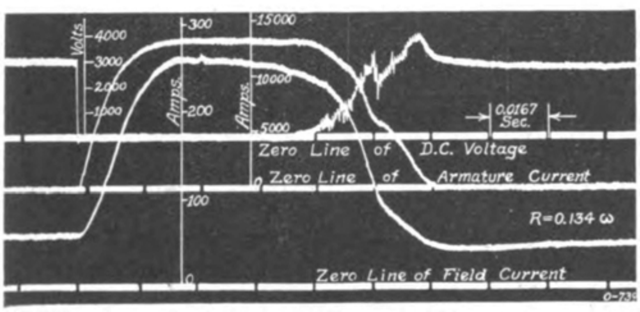

FIG. 9—DIRECT-CURRENT SHORT-CIRCUIT TEST AT 9.25 LOAD

ELECTRICAL CHARACTERISTICS

The generators of this set are of the six-pole, shunt-wound compensated type, and are equipped with a flash suppressor.* The use of shunt-wound machines is rather unusual in low voltage railway work, where non-compensated commutating-pole machines are found satisfactory, because such machines usually have a very decided drooping voltage characteristic. Shunt-wound compensated generators, however, by eliminating all internal electrical distortions have only a very slight droop in voltage under load, and have the decided electrical advantage on a high-voltage outfit of allowing a very clean construction of the stator parts, with ample room for the necessary compensating windings, and allowing a general simplification of the entire stator construction by the omission of the series coil wiring. The slight droop in voltage characteristic insures great stability in parallel operation and is actually no handicap in this class of service, where close voltage regulation is never desired. The operation of shunt-wound generators, when running inverted (regenerative) in parallel with other sets, is inherently superior to that of compound wound generators, which must necessarily run as differential motors. The stator construction of these machines is shown in Fig. 8.

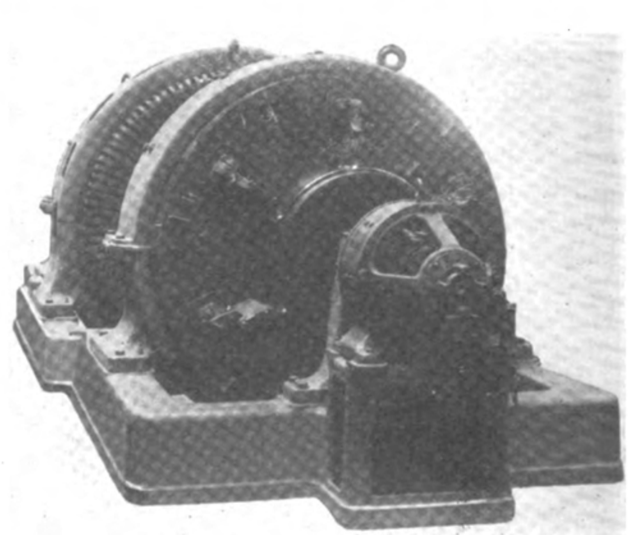

FIG. 10—COMMUTATION AT 9.25 LOAD

The six-pole construction of machines as large as these is rather unusual, when compared with moderate voltage constructions. Flashing at the commutator during overloads, or partial short-circuits, is a severe handicap to a machine's usefulness, and a positive detriment to its reliability, and the use of the six-pole construction is necessary in order to obtain the maximum inherent immunity from flashing, and to allow the requisite freedom in design to meet the unusual commutating performance characteristics which these sets have. The likelihood of flashing in a direct-current machine is fundamentally dependent upon the distance between brush arms, which distance is limited by the mechanical conditions governing commutator peripheral speed. This speed is proportional to the distance be-

*See article on "The Flash Suppressor" by N. W. Storer and F. T. Hague, in the JOURNAL for May, 1918, p. 144

tween brush arms, and the armature frequency in cycles per second or, in other words, the permissible distance between brush arms for a conservative commutator speed is inversely proportional to the armature frequency, or the number of poles. Thus, for a given machine speed, the high-voltage machine must have fewer poles* than a moderate voltage machine, if it is to have the same margin of safety in operation. In order to provide the maximum inherent immunity from flashing, and to obtain the maximum commutating performance of which the machines are theoretically capable, these machines were built with the minimum number of poles which allowed a balanced mechanical design. This is consistent with experience, which has always proven that low frequency machines have better inherent commutating characteristics than higher frequency ones.

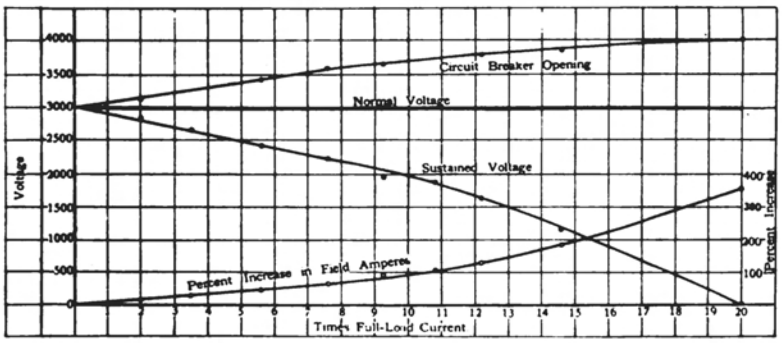

FIG. 11—DIRECT-CURRENT TERMINAL VOLTAGE CHARACTERISTICS

From oscillograph tests. The flash suppressor was not used during these tests.

The commutating pole construction, shown in Fig. 7, is unusual in that the tip of the pole which carries the winding has a large tapered body section insuring an unsaturated magnetic circuit at extreme overloads. The tapered pole body is so proportioned as to utilize to the fullest possible extent all of the space available between the main pole tips for the commutating pole and winding, and allows the rear half of the pole which carries no winding, to be made of very large magnetic section. The momentary overload commutating capacity of a machine is directly dependent upon the maintenance of an unsaturated magnetic circuit as the following considerations will show. Current is delivered from a direct-current generator to its line through the process of commutation, which in order to be successful, requires that each armature coil must have its current completely reversed each time the bars to which it is connected pass under a brush. The reversal of current in an inductive armature coil necessarily involves a change of magnetic energy in the coil, and unless this change is accomplished while the coil is still short-circuited by the brush, it will be evidenced by an arc, as the coil breaks contact with the brush. It is the theoretical function of commutating poles to accomplish this energy change in the commutating coils, and to the extent to which they fail to reverse the load current in the allotted time, sparking results. For perfect operation, the commutating pole strength must increase directly with the load current, and this requires the poles to be proportioned magnetically so as to use the space available for them to the fullest advantage. Commutating poles of tapered body section represent the maximum which can be done to improve the effectiveness of the commutating poles at very high loads. This construction logically involves making all of the magnetic circuits of very generous proportions in order to avoid the detrimental effects of saturation, even at peak loads, and accomplishes its result of extending the commutating limits, only by a considerable increase in size of the various magnetic circuits.

The commutator neck insulation, and the insulation between the necks and the armature winding coil support have always been the weakest points of direct-current armatures from the insulation stand-point, and it was considered necessary to develop an improved type for 3000 volt service. It consists of a moulded mica ring, extending from the rear of the commutator, up along the back of the commutator necks to the armature winding, and extending over the top of the front coil support. This mica is supported and protected by a casting, bolted to the rear of the commutator V-ring. Further protection against dirt is obtained by packing between the commutator necks with a filling material, as shown in Fig. 5, which, after baking, is turned off flush with the necks. The commutator front V-ring is heavily insulated bv asbestos duck, which is impregnated with varnish and baked in place.

TEST COMMUTATING CHARACTERISTICS

The commutating performance of these machines was tested by tripping a circuit-closing switch, thus establishing a circuit through a bank of non-inductive grid resistances, and interrupting this overload current by means of a slow-speed circuit breaker which opened in about 0.10 second. Thus the loads were applied at a much more rapid rate than in normal railway service, because the trolley line has an appreciable reactance which tends to slow down the rate of current increase on partial short-circuits. The commutation of these machines was practically sparkless at loads up to

TABLE I—SUMMARY OF THE DATA OF THE COMPLETE SERIES OF SHORT-CIRCUIT TESTS, MADE AT 3000 VOLTS NO LOAD

Times Load	Circuit Resistance	Sustained D. C. voltage	Percentage increase field amps.	Initial rate of current increase per sec.
1.0	4.5	2900	10	570 000
2.0	2.16	2800	20	620 000
3.5	1.22	2650	30	710 000
5.5	0.78	2450	45	850 000
7.5	0.56	2200	62	840 000
9.0	0.46	1950	90	940 000
11.0	0.39	1850	105	1 050 000
12.0	0.34	1600	125	1 070 000
15.0	0.26	1150	180	1 110 000
20.0	0.13	0	350	1 150 000

*See article on "Factors that Determine Maximum Rating of a Direct-Current Machine" by F. T. Hague in the JOURNAL for Feb. 1918, p. 42.

ten times normal. At currents between 10 and 15 times normal, sparking began, and the brushes emitted some slight fire, which did no damage to the brushes or to the commutator surface, and the machine showed no tendency whatever to flash over. Between 15 and 20 times normal current, a small flash was generated under the brushes which, however, was prevented from going to ground by asbestos board shields mounted on the outer end of the brush rigging, as shown in Fig. 1.

It is thus possible to short-circuit these machines at 3000 volts without any external resistance, and open this dead short-circuit by a slow-speed circuit breaker, as shown in Fig. 9, after a time interval of 0.1 second without any damage to the machines or brush rigging that will prevent them from continuing on in normal service without a shut-down. A visual idea of the commutating conditions may be obtained from Fig. 10, which shows the sparking at the commutator at 9.25 times normal full-load current. This photograph was taken at a lens opening of F-11, which shows more fire on the photograph than is evident to the eye. Photographs of commutating conditions are not capable of correct interpretation, unless the lens opening and the circuit breaker speed are stated, because the film is a light value integrating device, and the slower the circuit breaker speed, the greater the impression on the film.

It has been possible to obtain a complete oscillographic record of the machine's terminal voltage, armature current and field current on various loads, up to the dead short-circuit value. This data shows that the machines have an unusual power of maintaining voltage under very heavy overloads, the voltage regulation being an absolutely straight line on loads up to ten times normal, with only a slight droop at much higher loads. This is the direct result of thorough electrical compensation and the absence of excessive arcing under the brushes, even at the highest currents. This data is plotted in convenient form in Fig. 11, which shows the terminal voltage under sustained load, the voltage rise on the armatures, due to the sudden interruption of current by the circuit breaker, and the percentage increase in field current which takes place on suddenly applied loads up to the dead short-circuit value. The slight departure of the voltage regulation curve from a straight line at currents beyond ten times normal marks the current at which sparking begins to appear on the commutator and the point at which the field current begins to increase in a faster proportion than the load, and in a general way confirms the data shown in the photograph.

As shown in Table I, the rate of current increase on overload is very rapid on compensated generators, because they have a minimum of reactance. The current increases at an initial rate of 570 000 amperes per second, when full load is thrown on the machine, and the rate gradually increases with increasing magnitude of current until, at dead short-circuit, the current increases at the initial rate of 1 150 000 amperes per second. The circuit resistance given in Table I includes the machine's resistance and the brush contact resistance, which amounts to 0.13 ohms total.

Impulse-Gap Lightning Arresters

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THE purpose of a lightning arrester is to protect. To do this, it must act with minimum delay, discharge with maximum freedom and restore normal conditions following a discharge with greatest reliability and minimum disturbance. Lightning arrester development began with the last of these requirements and, during early years, most attention was devoted to methods of stoping the arc following a discharge. Many types of arresters were brought forth, of which nearly all used a simple spark gap and had limited freedom of discharge, due to the use of resistances in one form or another. As power systems grew large, attention was directed more to the development of types having greater discharge rates, culminating in the aluminum electrolytic arrester which, when properly maintained, still remains the most efficient of all arresters, once it has started to discharge.

Here and there, however, cases were noticed where even the best electrolytic arresters failed to give protection and sometimes failed to discharge. This made it clear that in commercial arresters some vital and essential element was lacking. Finally it was realized that this was the quality mentioned first above, namely, speed of action or, technically speaking, low time constant of discharge.

This was made worse by the growing tendency to assume that, because an electrolytic arrester was much more expensive than any other type, it could be made to do all the work itself. Therefore, choke coils have grown smaller and smaller until many commercial forms are of negligible value, and sometimes none are used at all. An adequate choke coil can delay a surge so as to give the standard electrolytic arrester time to discharge, and thus protect the apparatus behind the choke coil. However, by piling up the voltage outside the coil, it would make the danger of breaking down the insulation of the line still greater.

It became evident, therefore, that the vital line of improvement lay in reducing the "time constant" or "dielectric spark lag" of the gaps used with the arresters. A good deal could be accomplished along this line by applying to arrester gaps the principles already learned in connection with measuring gaps for high voltages. In that field, the sphere gap had long dis-