DESCRIPTION OF THE 1500- AND 2000-KW., 3000-VOLT D-C. MOTOR-GENERATOR SETS OF THE CHICAGO, MILWAUKEE & ST. PAUL RAILWAY

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The motor-generator sets described in this article have many interesting features. Considerable space is devoted to the operating characteristics, and the ventilating scheme for the d-c. units is fully described. Regenerative braking on the locomotives has called for features in these units which are unique.—Editor.

The electric locomotives which haul the trains over the mountain divisions of the Chicago, Milwaukee & St. Paul Railway are designed to operate from direct current at 3000 volts. The transmission system of The Montana Power Co., from which power is purchased, and the transmission lines of the railway company are operated at 100,000 volts a-c. In the railway substations transformers and motor-generator sets are employed to change from 100,000 volts a-c. to 3000 volts d-c. power. The transformers reduce the voltage from 100,000 to 2300 volts. The synchronous motor-generator sets which transform the 2300-volt, three-phase, 60-cycle alternating-current power to 3000-volt direct-current power have several features of operation and design which distinguish them from any sets previously used. The distinguishing features are as follows:

1. Heavy overloads for direct operation and for reversed operation during regenerative braking.
2. Compounding of the motor exciters so as to furnish the most advantageous excitation required by the wide variations in the load.
3. 3000-volt d-c. operation.
4. Ventilation of the d-c. generators.

There are two sizes of sets used: nine 1500-kw. 600-r.p.m. and twenty-three 2000-kw. 514-r.p.m., or a total of 59,500 kw. distributed in fourteen substations along the 440 miles of main line through the picturesque mountainous section, extending from Harlowton, Montana, on the east to Avery, Idaho, on the west. The substations are distributed along the route at average intervals of about 32 miles, and the motor-generator sets are distributed as follows: ten substations each containing two 2000-kw. sets; three substations three 1500-kw. sets; and one substation three 2000-kw. sets. One set is a reserve in each station. Fig. 1 shows a 2000-kw. set with direct connected fans on the generators, while Fig. 2 shows the same set equipped with a separate blower for ventilating the generators. The 1500-kw. sets are practically the same except for size and speed. They may be described as three unit, four

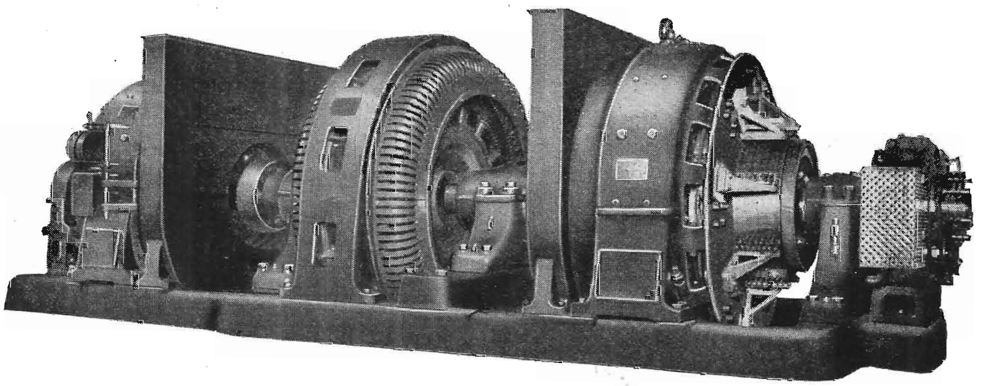

Fig. 1. 2000-kw. Motor-generator Set, with Direct Connected Fans

bearing sets with two direct connected exciters, one of which furnishes excitation for the two generators, and the other for the motor. The rotor shaft of the motor is directly supported by two bearings. This shaft extends through these bearings and carries a half coupling at each end for coupling to the shafts of two duplicate d-c. generators. Each generator shaft is supported by an outboard bearing, and is provided with an extension beyond the bearing which carries an exciter armature. Great care was taken in designing the couplings, shafts, etc., to successfully stand the mechanical strains imposed by heavy overloads and short circuits on the machines.

consisting of, say, 50 loaded cars. It takes a drawbar pull of approximately 15,000 pounds to haul such a train on level track free from curves. The locomotive will develop this tractive effort and move the train at a speed of 24 miles per hour taking about 1000 kw. electrical energy from the trolley and the generator of the motor-generator set. If now a 2 per cent grade (a rise of 2 feet per 100 feet of track) is encountered, the drawbar pull will be increased to 115,000 lb., which at a speed of 14 m.p.h. would require 4100 kw. from the motor-generator set or 274 per cent load. When the top of the hill is reached the train will coast down on the other side. If the grade has a 2 per cent

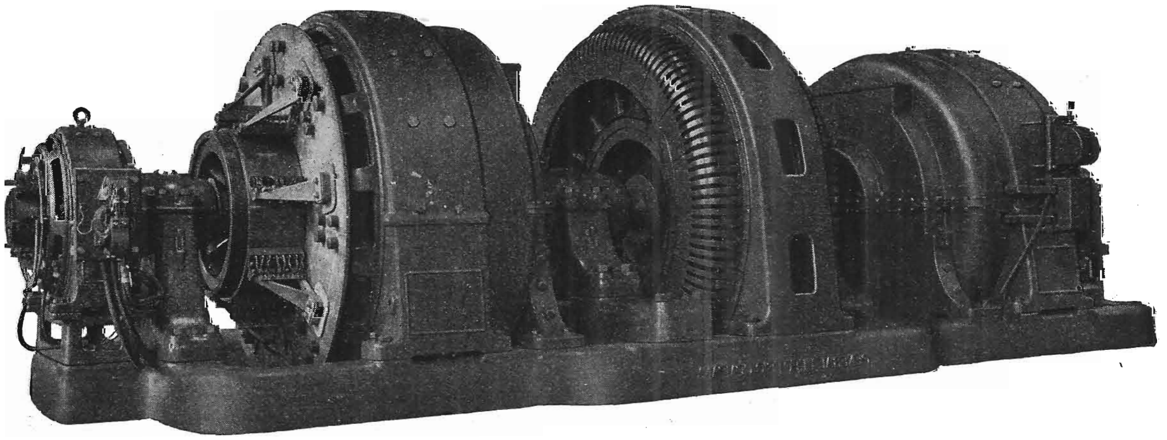

Fig. 2. 2000-kw. Motor-generator Set. Ventilating Air is Provided by a Separate Blower

slope, the train will exert a push or tractive effort of approximately 85,000 pounds on the locomotive. If now the fields of the series motors on the locomotive are energized by current from the small "control motor-generator set" in obedience to the regenerative control, the motors will act as generators returning 2600 kw. electrical energy to the trolley. The train will run at approximately 16 m.p.h. under these conditions. If there are no other trains in the section, this energy will be delivered through the motor-generator set back into the alternating-current system to be used elsewhere.

Capacity

The sets are designed for either direct or reversed operation, the capacity being expressed in terms of direct-current output for direct operation, and direct-current input for reversed operation. They are capable of carrying their rated load continuously with a maximum temperature rise in any part not to exceed 35 deg. C.; 150 per cent load for 2 hours with a temperature rise not to exceed 60 deg. C.; and 300 per cent load (with 85 per cent normal voltage at the motor terminals for direct operation) for five minutes without injury. The following data will be of interest, and will aid in comparing the capacity of these sets as expressed in kilowatts, with the capacity expressed in terms of train service.

The 1500-kw. set weighs about 50 tons and occupies a floor space of approximately 200 sq. ft. Consider a 2500-ton freight train

Heavy Overloads and Compounding of Motor Exciters

To perform their duty in a manner similar to that described above the motor-generator sets are required to operate at loads, under certain conditions, varying from 300 per cent load for direct operation down to zero and up to 300 per cent load in the opposite direction during regenerative braking. Other sets have been built in which the load varied from zero up to 300 per cent for direct operation only, the *excitation* of the synchronous motors being controlled dif-

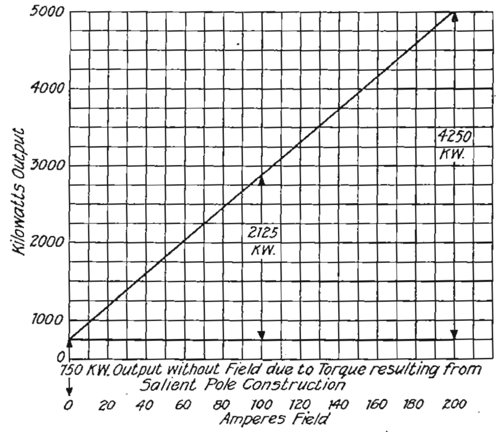

Fig. 3. Breakdown Tests. Synchronous Motor ATI-12-1900-600-2300 Volts. Line Voltage Held Constant at 2300 Volts. Amperes Field Varied from 0 to 200

ferently in various installations. In some cases it has been set at a fixed value, which naturally must be great enough to take care of the maximum overload. This results in a wide range of power-factor for the different loads and low efficiency at the light loads. In others it has been varied by a regulator designed for voltage or power-factor control. In still other cases, as in the present one, it has been varied by a compound wound exciter the series fields of which were excited by the line current of the generator of the set. The importance of compounding the exciter, so as to obtain excitation for the synchronous motor, which increases or decreases with the load, is apparent when it is noted that the torque, and hence the maximum capacity, of a synchronous motor, for different values of line voltage and field excitation, can be considered to vary (within the limits of commercial accuracy) directly as the voltage and excitation, or as the product of the two.

Fig. 3 shows the relation of the maximum capacity to the field excitation, when the line voltage is held constant. This curve was taken for one of the 1500-kw. sets. It should be noted that the motor carries nearly 50 per cent load without field, when running at synchronous speed, due to the salient pole construction. From the illustration it is noted that the maximum output, after deducting the output without field, varies directly as the field current.

In Fig. 4 there are presented three curves *A*, *B* and *C* showing the variation of maximum output with changes in line voltage. Curve *A* gives the results of a test without field.

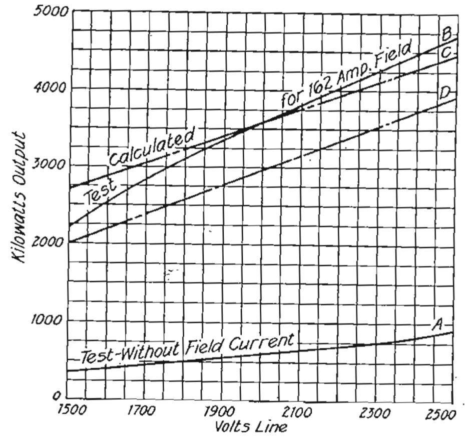

Fig. 4. Breakdown Tests. Synchronous Motor ATI-12-1900-600-2300 Volts. Field Current Held Constant at 0 and 162 Amps. Line Voltage Varied from 1500 to 2500

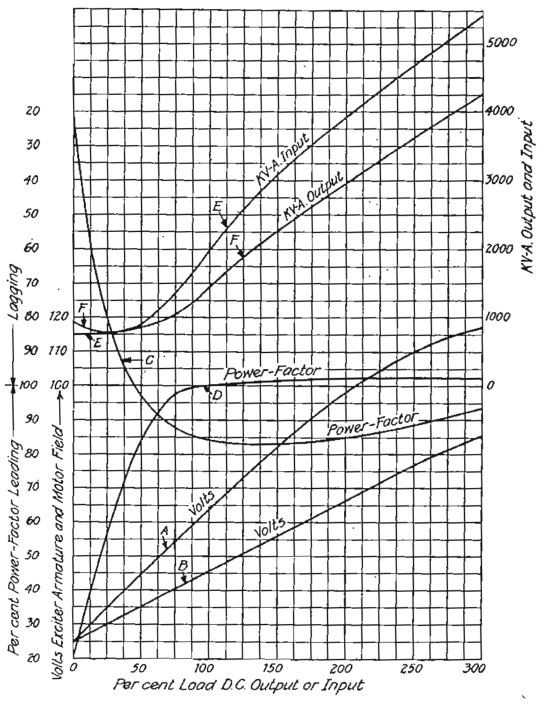

Fig. 5. Compounding Tests. Synchronous Motor ATI-12-1900-600-2300 Volts. Exciter-EC8-6-18-600-25/125 Volts.

A few calculations will show that the maximum output varies as the square of the voltage. Curve *B* gives the results of a test with 162 amperes field, while Curve *C* shows the calculated values of maximum output for the same field current. These calculations are based on the assumption that the maximum capacity varies directly as the voltage. Curve *D* is obtained by subtracting the values of curve *A* from Curve *B*, and is approximately a straight line parallel to Curve *C*.

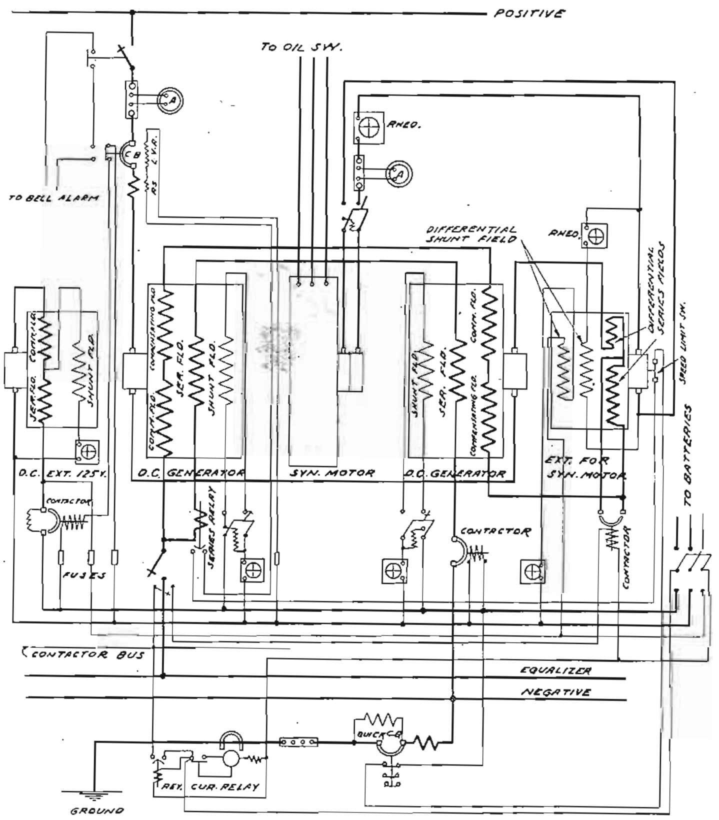

Fig. 6. Diagram of Connections of Motor-generator Sets

In the present installation it was desired to get the highest possible all day efficiency for the variable railway load and also to maintain as near constant voltage on the power company's transmission system as practicable which made it desirable to obtain 1.0 power-factor at about 50 per cent load direct operation. For loads from 50 to 300 per cent it was desired to obtain leading current input. It was also desired to have the motor capable of carrying 300 per cent load with a 15 per cent drop in line voltage. For reversed operation during regenerative braking, it was desired to have the synchronous motor act as a generator returning power to the alternating-current system at approximately 1.0 power-factor. To accomplish these results, it was necessary that the motor exciter of the 1500-kw. set should give 41 volts at 50 per cent load for both direct and reversed operation, 120 volts for 300 per cent load direct operation, and 80 volts for 300 per cent load reversed operation. Fig. 5 gives results of compounding tests at the factory. *A*, *C* and *E* show the voltage, power-factor, and kv-a. input, respectively, for direct operation, and Curves *B*, *D* and *F* for reversed operation.

The exciter is equipped with two shunt and two series fields (see Fig. 6) that give great flexibility in adjustments, which are necessary to meet the requirements of the service. The main shunt field is separately excited from the generator exciter. The second shunt field is self-excited and connected differentially with respect to the main shunt field. The main series field is excited by the line current from the generators and is accumulative (for direct operation) with respect to the main shunt field. This field is short circuited by a contactor operated by a reverse current relay during reversed operation. The auxiliary series field is excited by current from the generators and is differential with respect to the main shunt field for direct operation and accumulative for reversed operation. Both of the series fields are provided with adjustable shunts and are connected in series.

3000-volt D-c. Operation

The direct current voltage of 3000 employed in this installation is the highest ever applied to any extensive railway electrification and is obtained from two duplicate 1500-volt generators operated permanently in series and driven by one motor.

The use of two 1500-volt generators permits practically double the speed of a single 3000-volt generator, resulting in a smaller motor, lower cost, less floor space and smaller weight.

The armatures of all machines of a given size are exact duplicates and interchangeable.

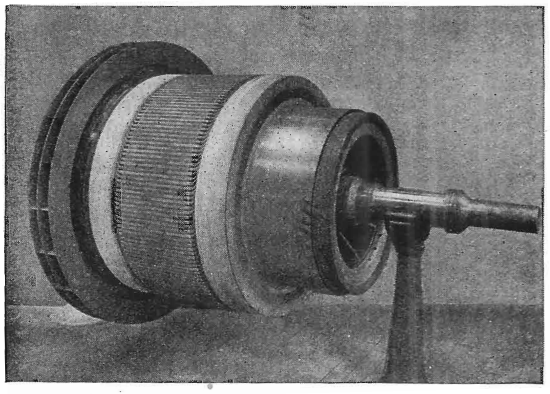

Fig. 7. Generator Armature of Set Shown in Fig. 1 Showing Double Section of Fan

The advantages obtained from interchangeability and standardized manufacture more than offset the slight economy gained by building one machine insulated for 1500 volts and the other for 3000 volts.

The generators are of the multipolar type, separately excited from a small direct connected exciter, and are equipped with compensating, commutating and compound windings operating in series with the armatures.

From the diagram of connections, Fig. 6, it will be noted that all the series fields of both machines are connected on the ground side of the set. This reduces the operating potential strain and in addition permits the easiest possible equalizing between sets.

The armature windings are insulated with mica and asbestos tape. The compensating windings are insulated with mica and fiber. The commutating and compound windings are made up of bare copper so supported on metal spools as to allow free radiation of heat from all surfaces and yet afford ample insulation.

With the heat-enduring character of the insulation and the commutating characteristics obtained by the use of compensating windings in addition to the commutating set, these generators are capable of handling even greater loads than indicated by the guarantees without injury to the insulation or flashing at the commutator.

As a further protection against flashing caused by trolley short circuits or other excessive loads, the front end of the machine is protected by asbestos guards covering the brush-holder yoke and the commutator risers. Barriers are also placed between brush-holder brackets, which prevent arcs from being carried from bracket to bracket under all but the most severe short circuits.

On account of the heavy overloads required in railway work, ventilation of unusual design for this type of machine, but similar to that used on railway motors, was adopted. With this arrangement axial holes through the core replace the usual radial ducts, and air is forced through these holes and over the surface of the armature by means of fans, insuring the positive ventilation of all parts.

The machines for the first seven substations (see Fig. 1.) have a double section fan mounted on the back flange of the armature (see Fig. 7).

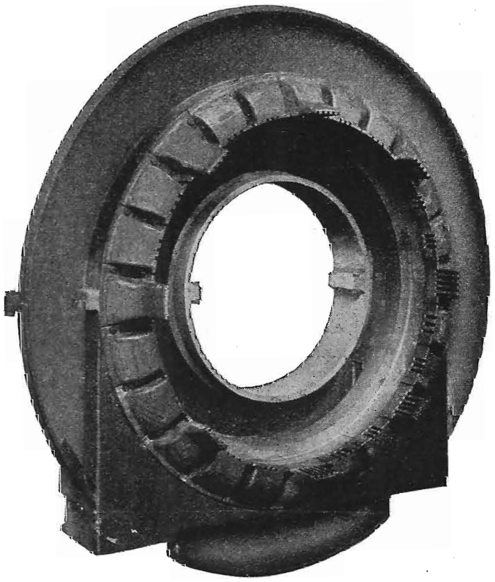

Fig. 8. Air Distributing Chamber Showing Nozzles for Forcing Streams of Air Over Surface of Armature

The outer section draws air in under the commutator and through the axial holes in the core, which in passing cools the under surfaces of front and back end windings as well as the core laminations and windings before passing out through the fan into the discharge case. The inner section of the fan takes air in through the brush-holder yoke openings, drawing it over the surfaces of the fields and armature, and then delivers it into the discharge case. The heated air has sufficient velocity upon leaving the opening at the top of the discharge case to carry it well up above and away from the machines.

The machines for the second seven substations (see Fig. 2) have a modification of the above method so as to use a separate motor-driven blower. With the separate blower the air is forced into a casing at the rear of the armature where it divides between an interior and exterior path. The air for the interior path is blown under the armature core and, on reaching the front end, which is closed, is forced to return through the axial ducts and into the discharge case, where it is dissipated as before.

The air for the exterior path is delivered from the receiving chamber encircling the armature (see Fig. 8) through special nozzles which distribute it over the external surface of the winding. It then passes over the remainder of the armature surface and field surfaces and out through the brush-holder yoke openings.

The separate blower can be designed with greater efficiency than the direct connected fan and in addition permits the use of a temperature control, which governs the starting and stopping of the blower within selected

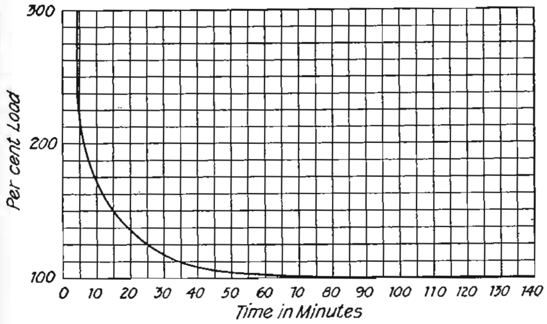

Fig. 9. Time to Increase Temperature of M.C.F. 8-1000-514 1500 Volts 60 Degrees C. without Blower

temperature limits of the generator. The curve in Fig. 9 gives the time that the generators can carry given loads for a final temperature of 80 to 85 deg. C. with a room temperature of 20 to 25 deg. C. The temperature control follows this curve very closely and does not start the blower until the machines have reached the above temperature, which is entirely safe for this class of insulation. The saving effected by this combination amounts to approximately 500 kw-hr. daily for each 2000-kw. set and a proportionate amount for the 1500-kw. set.

Efficiency

The curves given in Fig. 10 show the efficiency of a 2000-kw. set, first fitted with

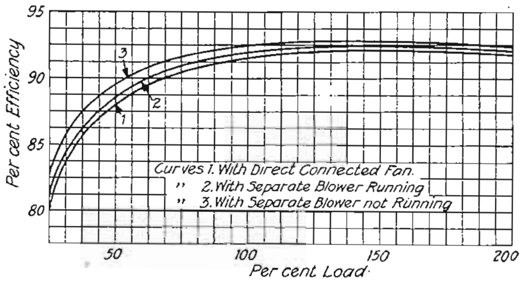

Fig. 10. Curves Showing Efficiencies of Motor-generator Set Under the Conditions Named

direct connected double fan; second, with separate blower, blower running; third, with separate blower, blower not running.

It should be noted that the efficiencies take into account all the determinate losses from the motor terminals to the generator terminals, including those of the exciters.

Reversed and Parallel Operation of D-c. Generators

An interesting feature in connection with the operation of these sets is that the regenerative operation of the locomotives requires the d-c. generators to motor. This motoring is performed with no change in the field windings. A d-c. machine connected as an accumulative compound generator, when reversed in operation, becomes a differential compound motor which, if operated from a source of constant potential, has a rising speed characteristic with increasing load. The speed being fixed by the synchronous motors acting as generators there is a slight tendency for the load to build up, but the excitation of the motors on the locomotive may be controlled to hold any load desired. In actual service there has been no tendency to unequal division of load between machines in parallel or unstability between the substations and locomotives under any condition of generator or motor action of the direct-current generators.