eighty-two teeth in the gear, and for the passenger locomotives there are twenty-nine teeth in the pinion and seventy-one teeth in the gear. Both gears and pinions are made of high-carbon oil-treated stock, having an elastic limit of 85,000 pounds per square inch.

The gear cases are made of sheet steel with rim and sides securely riveted together. The supporting brackets extend over the rim of the case and are securely riveted to the rim and sides. The magnet frame is made of cast steel and, except in size, differs but little in general appearance from standard box frame railway motors.

The front of the motor is carried on the truck through an improved spring suspension. The design is such that both the downward and upward thrust is taken through springs. This form of suspension largely reduces the shock on the motor in passing over switches, crossings or other rough places in the track. The spring gears, and to a less extent the motor suspension, relieves the teeth of the gears of "hammer blows," and equalizes the load on the pinion and gear teeth at each end of the motor.

The brush-holder design is of standard construction. The holders are supported and protected from the ground through mica insulated studs.

In service the motors have operated with most excellent results. The commutators take on a bright, smooth polish, with no indications of etching at the edges of the segments. The effect of the spring gears and spring suspension is to make the motors run with unusual quietness. There is no noticeable gear noise while the locomotives are in motion. The absence of vibration is also noticeable. This is quite a marked contrast to heavy twin geared motors when operating without spring gears and spring nose suspension. The motors run at a comparatively low temperature in service, the capacity of the motors being sufficient to handle heavier trains than originally contemplated.

THE CONTROL EQUIPMENT, WITH REGENERATIVE ELECTRIC BRAKING FEATURE, ON THE LOCOMOTIVES OF THE CHICAGO, MILWAUKEE & ST. PAUL RAILWAY

By R. Stearns

Railway Equipment Department, General Electric Company

The author describes the control features of the St. Paul locomotives in great detail. The article is profusely illustrated which greatly helps an understanding of the text. Special attention is paid to the regenerative control.—Editor.

The engineer of a single 282-ton St. Paul electric locomotive has an enormous concentration of power at his command. The ease, efficiency, reliability and safety with which this power is made to serve the purpose of the engineer, while he maintains his train schedule involving wide variations in locomotive speeds, up and down grade, over the rugged profile of the Rocky Mountains, depends in a large measure upon the motor control equipment.

Owing to the great power needed in this exacting transcontinental service, the control design, both mechanically and electrically, includes many interesting departures. Particularly owing to the economic and safety requirements of definite speed regulation by electrical means down grades, the novel feature of regenerative electric braking has been provided in addition to the air brakes.

COLLECTION OF CURRENT

The system of current collection, which must be capable of handling unusually heavy currents at high speeds, has the distinctive feature of using two parallel adjacent copper conductors supported alternately and independently, by loop hangers from the same messenger wire. A continuously flexible contact surface, for the most part of double area, is thus obtained. In addition, each pantograph is equipped with two sliding contacts. Ordinarily, therefore, there are four points of contact between the collector and the trolley wires. With this very flexible combination a single pantograph, (and there are two on all locomotives for emergencies) can easily collect the heavy currents obtaining in the St. Paul service. Sparking is entirely eliminated. The current required for a single locomotive at the continuous rating of the motors is 840 amperes. In the passenger service, speeds up to 60 m.p.h. and over are attained.

Figs. 8 and 9 are characteristic curves based on 3000 volts line showing the amperes per motor obtained, at different locomotive speeds, in the freight and passenger service respectively. The current input through the collector as required by the eight traction motors is four times the ampere per motor reading as indicated.

The engineer controls the operation of his pantographs by means of an air valve. To raise the pantograph, air from the main reservoir is admitted to a pair of cylinders. The pistons of these cylinders energize powerful springs which in turn raise the collector and at the same time regulate the pressure against the trolley wire. The raising springs are energized at all times while the collector is in use, by maintaining air pressure in the cylinders. To lower the pantograph, air is exhausted from the cylinders, thus de-energizing the springs. The pantograph will then drop to its minimum collapsed height. The range of action of the trolley is between 17 feet and 25 feet above the rail.

As air is necessary to raise the pantographs, an auxiliary trolley pole with swivel base is supplied to collect current for the air compressor whenever the locomotive is first put into service. Fifty pounds is the minimum operating air pressure.

Fig. 1 shows one of the St. Paul locomotives equipped with two pantograph trolleys and also the auxiliary pole trolley used for starting purposes. It may be noted that the locomotive has two cabs. The pantographs installed on these cabs are connected by a bus line, so the duplex electrical equipments can be supplied from either trolley.

3000-VOLT PROTECTIVE APPARATUS

When 3000 volts was chosen as the desirable line potential for transmitting the great energy required by the locomotives of this extensive railway system, a further innovation was introduced into the design of the control equipment. It was appreciated from experience that, provided the protective devices in the main trolley circuit are reliable, short circuits clear themselves more quickly with high than with low voltages, and there is less attendant damage. The design of the main emergency switches and fuses was considered of great importance and these devices were accordingly mounted in a single high tension compartment of ample dimensions. Figs. 2 and 3 show this compartment.

The trolley lead starting from the pantograph trolley first enters the high tension compartment and is divided into two circuits,—main and auxiliary. A combination switch and fuse shown at the left in Fig. 3 is in the main circuit. An identical combination switch and fuse (except that a lower capacity fuse is used) is shown at the right of the picture. From the main switch and fuse, the main power lead goes directly to the controlling apparatus of the traction motors.

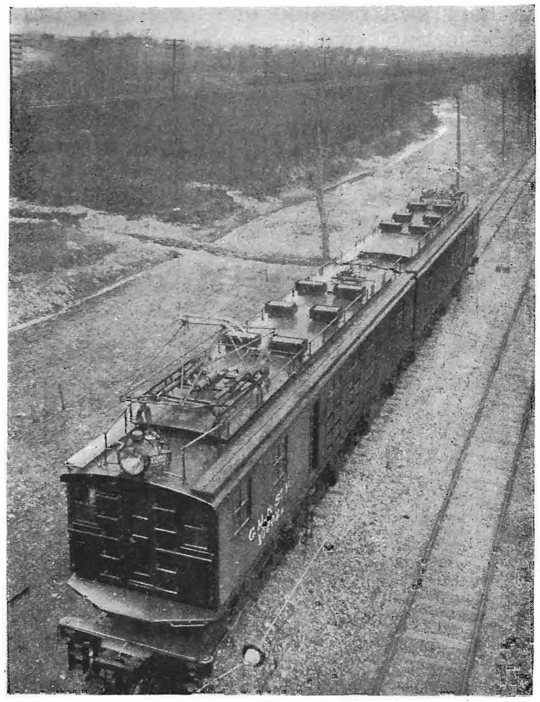

Fig. 1. St. Paul Locomotive Showing Twin Shoe Sliding Pantograph Trolley and Auxiliary Pole Trolley

The auxiliary lead passes to the four disconnecting switches shown at the top of the compartment and from there separate supply leads run to the motor generator set, air compressor and cab heater.

The compartment is made of sheet steel strongly reinforced with angle and channel irons and is thoroughly lined with insulation. A great saving in space has been effected by using for each combination switch and fuse a single arc chute containing two stationary contacts to which the incoming and outgoing leads are attached. The feature which combines the functions of switch and fuse consists in a cradle pivoted at one end carrying, on high voltage insulators, the supports for a copper ribbon fuse. These supports also carry spring contacts which complete the function of a switch. When the cradle is raised or lowered by a handle external to the compartment, the pair of spring contacts engages with the two stationary contacts and in this way closes or opens the switch. When the switch is closed the fuse is in circuit and automatically protects the circuit against overload.

The high tension compartment is equipped with three doors; one each for the main and auxiliary switches and one for the separate disconnecting switches. These doors are interlocked with the external operating handles so that no conducting parts can be approached without first opening its circuit by dropping the switch cradle. When either switch cradle is dropped it will be noted its fuse is entirely disconnected from the circuit.

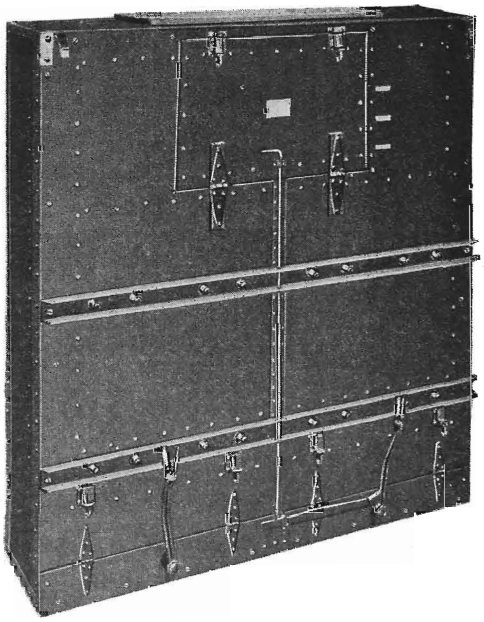

Fig. 2. 3000-volt Switch and Fuse Compartment

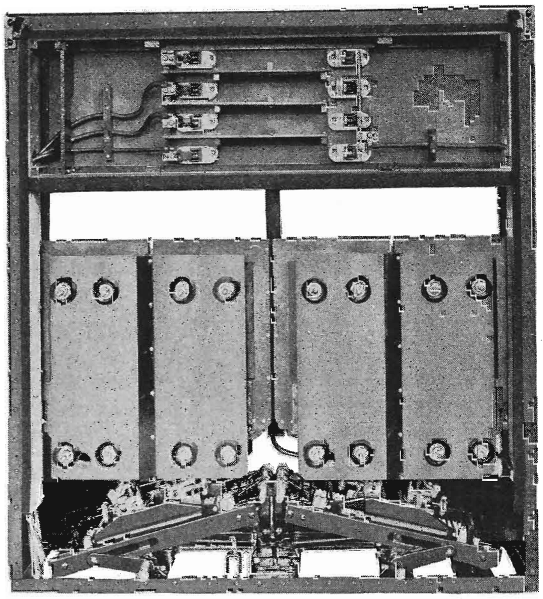

Fig. 3. 3000-volt Switch and Fuse Compartment with Sheet Steel Front Removed Showing Arc Chutes and Contact Mechanism

In addition to the protective apparatus in the high tension compartment, a 3000-volt aluminum cell lightning arrester is tapped into the main lead near the collectors. The lightning arrester, installed in a grounded sheet iron box, is mounted on the back of the high tension compartment.

3000-VOLT CONTACTOR COMPARTMENT

Aside from the apparatus already mentioned, the 3000-volt equipment of a locomotive consists of eight traction motors; two air compressor motors; two cab heaters; two driving motors for the motor generator sets; and the control equipment for all these devices. Since all this 3000-volt equipment is in duplicate, the following description will cover only that portion located in one of the two cabs which is entirely independent in operation. This controlling apparatus is grouped in a sheet iron compartment located near the center of the cab. Allowing for aisles on either side, the space occupied by this compartment, extends from the floor to the roof of the cab.

The complete set of rheostats used in regulating the current in the four traction motors is assembled at the bottom of the compartment along the floor of the cab. Each rheostat is mounted upon 3000-volt insulators as shown in Fig. 4. The rheostat is of the cast grid type shaped to effectively meet the space limitations of locomotive service. The remaining controlling apparatus is located in four groups directly above the rheostats. The rheostats are separated from the equipment groups above by a partition. The bottom of the rheostat compartment is open, and complete ventilation of the rheostats is obtained through six chimneys leading up to ventilators at the top of the cab. The control groups are installed between the chimneys. An idea of the space occupied by all this part of the equipment may be obtained by reference to Fig. 1 which shows clearly the location of each chimney.

Fig. 5 shows the groups of control equipment as they are located with respect to each other in the cab. Upon the supports of Group 1 are mounted the high voltage disconnecting switches and starting sets of the motor generator set and compressor, also the heater disconnecting switch, a portion of the rheostat and tap field contactors and the translating relays between motor running and regenerative braking connections.

Group 2 shows the rheostat contactors.

Group 3 contains the overload relay and a set of line contactors, governed by it. This apparatus protects automatically against careless operation on the part of the engineer while the fuse in the high tension compartment is final protection against short circuit.

The function of the contactors in Group 4, which are assembled along and actuated by a compressed air driven cam shaft, is to series parallel the traction motors in order to obtain two efficient continuous running speeds. The two handles which may be seen at the end of this switch in the foreground of Fig. 5 also provide for cutting out a pair of motors when one of them is damaged. With one pair of motors cut out the other pair of motors can be controlled either in single or multiple unit locomotive operation.

By removing the side covers of the control compartment, the switch groups can be made very accessible from the main aisles of the locomotive. The aisle down the center of the compartment between the groups provides for easy inspection in front. Fig. 6 is an end view of the contactor groups looking along this center aisle.

The circuit connections of the main power system supplying the traction motors are shown in Fig. 7. The relative location of

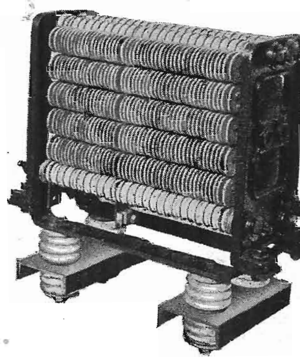

Fig. 4. Resistor Mounted on 3000-volt Insulators

the overload relay tripping coils, line contactors, rheostats, rheostat contactors, series parallel contactors, field shunts with their contactors and reverser, are indicated. This wiring diagram shows the complete progression, in schematic form, of the different circuits necessary to motor operation only. It may be noted that the motors of each half unit are connected in two series pairs. The master controller provides for operating these pairs in series through sixteen rheostat

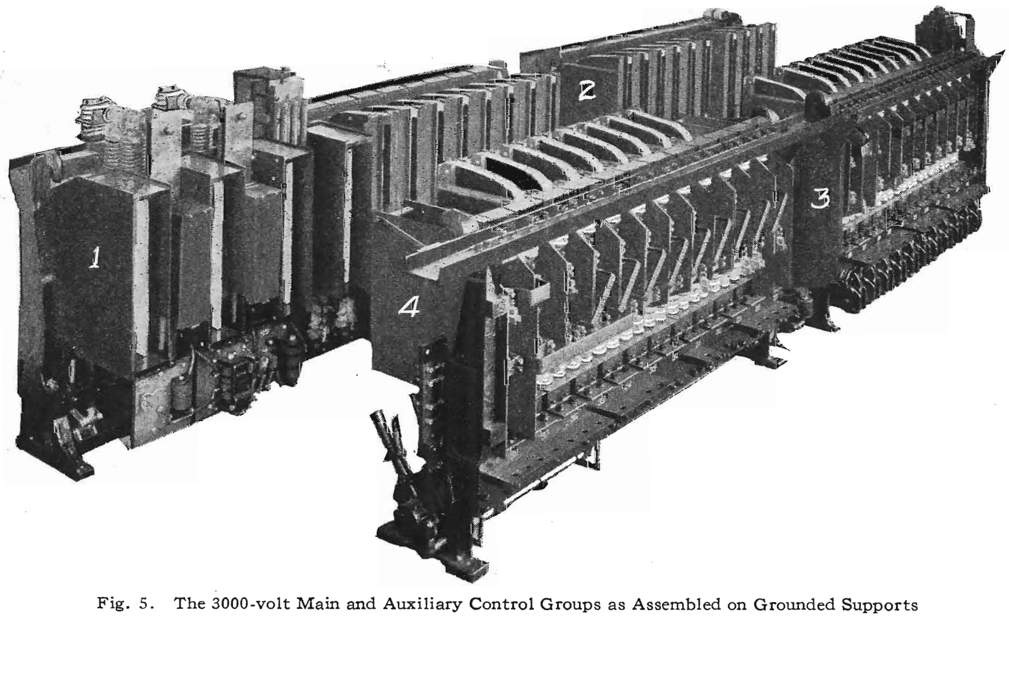

Fig. 5. The 3000-volt Main and Auxiliary Control Groups as Assembled on Grounded Supports

points, and a seventeenth full series running point; then through eleven rheostat points in parallel and a twelfth full parallel point. An additional parallel point with the fields of the traction motors shunted is provided on both the freight and passenger locomotives for efficient higher speed running.

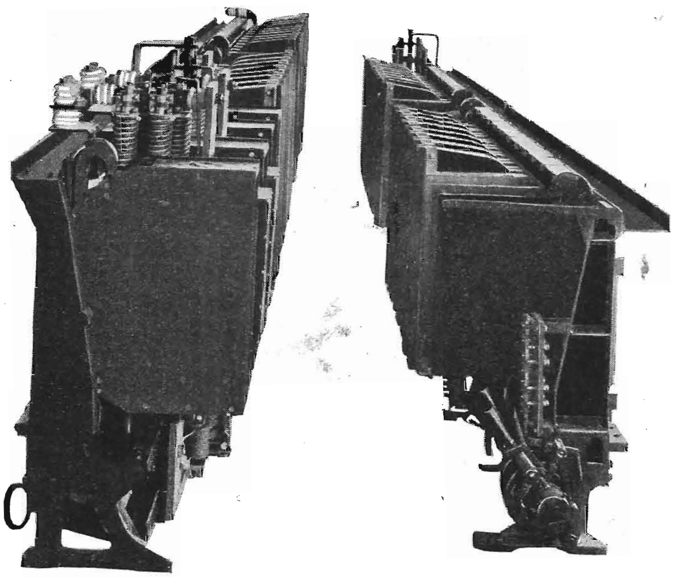

Fig. 6. End View of 3000-volt Equipment and Supports

Due to the large number of rheostatic steps provided to vary the voltage at the traction motor terminals during acceleration, and due to the extremely flexible drive between motors and drivers, the acceleration of a St. Paul locomotive is very smooth. Dynamometer car tests indicate that practically constant and continuous drawbar pull can be obtained. Experience in starting unusually heavy trains in the abnormally severe service of the past winter indicates that a very smooth acceleration is obtained at all times, permitting the locomotive to work close to the slipping point of the wheels, fulfilling completely the requirements of this severe Rocky Mountain service. Characteristic curves showing all the rheostat points of the freight and passenger locomotives, based on a constant potential of 3000 volts, are shown in Figs. 8 and 9 respectively. The curves made in dash lines show the transfer steps made while the series parallel switch passes from one position to another. This transfer can be effected without appreciable decrease in torque and any jerking of the train is absolutely eliminated by the method of transfer employed.

LOW VOLTAGE EQUIPMENT

Practically all the equipment not as yet described is more closely related with the master control circuits leading to the engineer's position and is therefore designed for low voltage—125 volts or less.

While the reverser switches the fields of the 3000-volt traction motors, it is necessary to insulate for low voltage only, since the fields are maintained on the grounded side of the armatures at all times. A view of the reverser is shown in Fig. 10. The same type air motor which drives the series parallel switch is used to operate the reverser. By means of a cam shaft and a set of powerful spring contacts driven from the former, through rocker arms as shown, a very positive wiping contact is obtained. The reverser is completely enclosed in a sheet iron box and is located outside, and adjacent to the high tension compartment of the high voltage control apparatus.

The shunts and similar apparatus associated with the motor fields are designed for low voltage.

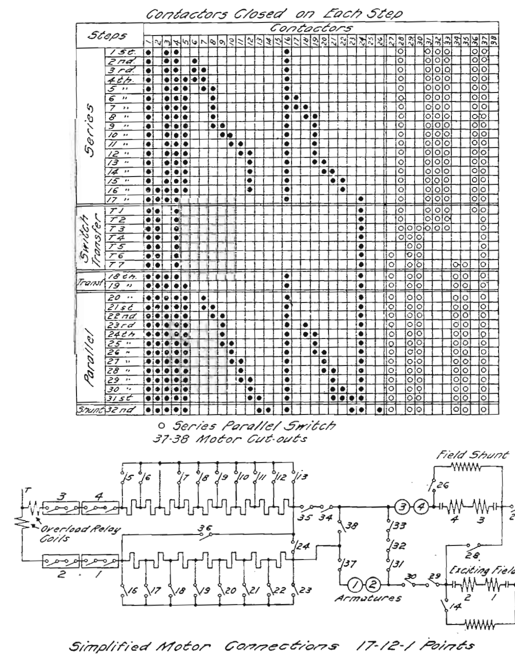

Fig. 7. Simplified Connections of Control with C-116 Controller, Motor Operation Only

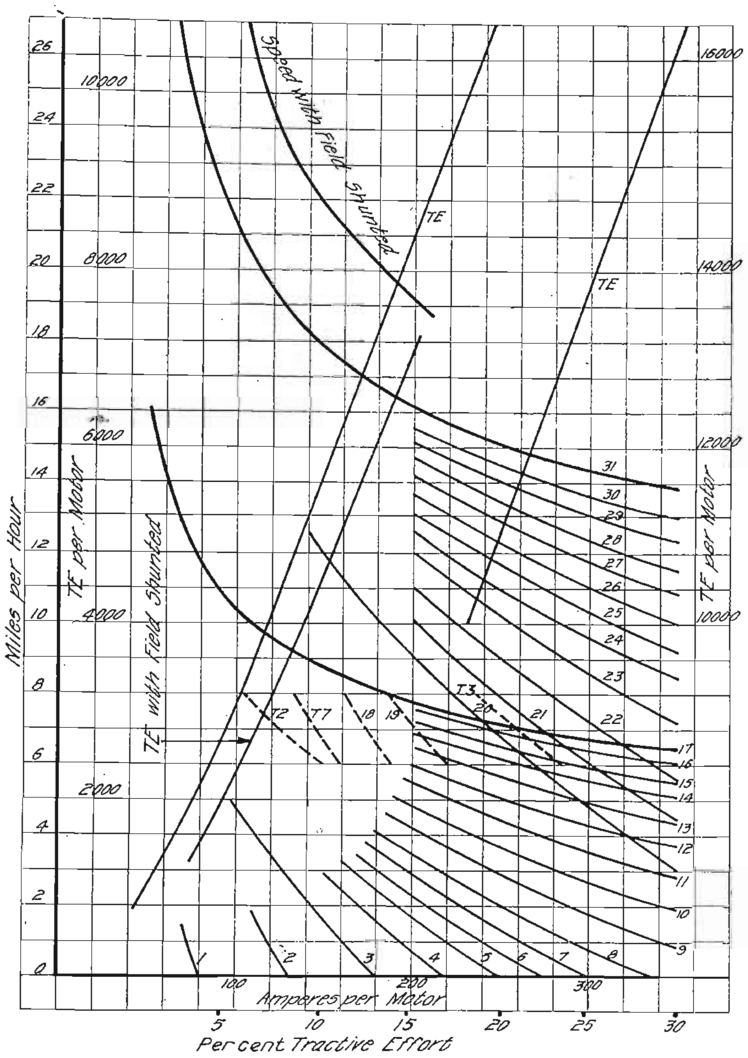

Fig. 8. Motor Operation in Freight Service

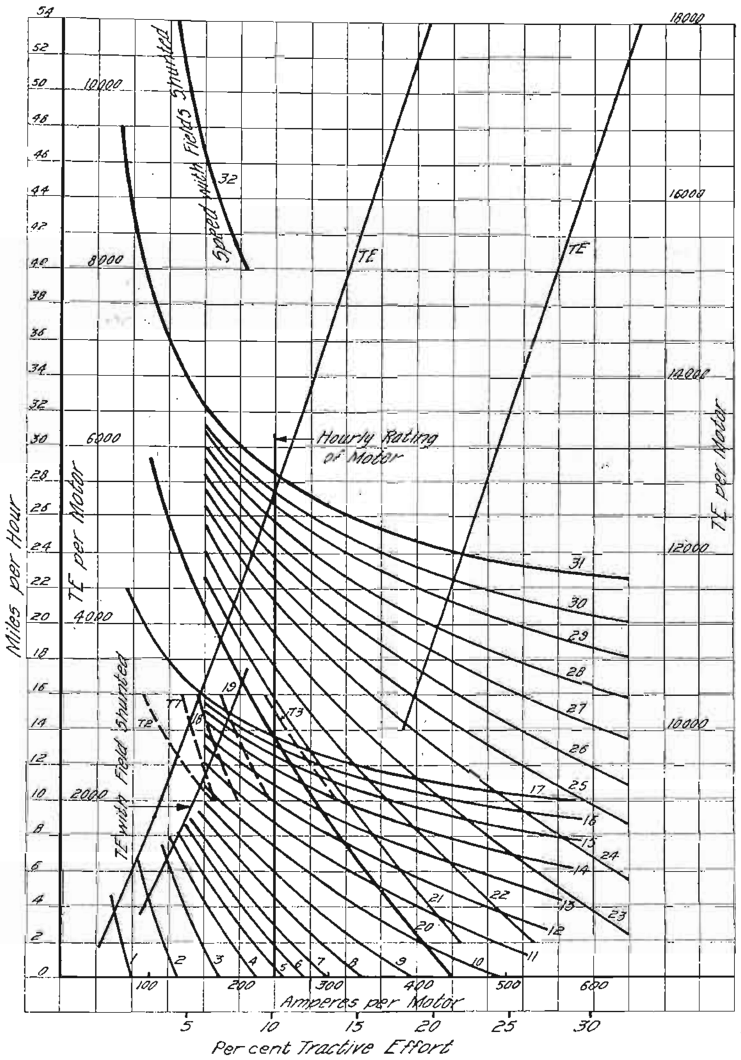

Fig. 9. Motor Operation in Passenger Service

Typical Speed Tractive-Effort Curves at 3000 Volts Line for Each Point with C-116 Controller and 8 GE-253, 1500/3000-volt Motors

MOTOR GENERATOR SET

A motor generator set driven by a motor directly connected to the 3000-volt trolley supply is used for auxiliary purposes. Referring to Fig. 11, this set consists of a direct connected fan, the driving motor, an exciter and a small 125-volt generator. The fan is used for ventilating the traction motors, thereby materially increasing their continuous capacity. The 3000-volt switching apparatus of the driving motor is located in the control compartment as already described. The exciter is used during electric braking, to super-excite the traction motor fields, and, while not thus employed in passenger service, to re-charge the storage batteries required to light the trailing passenger coaches. The generator supplies power for the master control circuits, cablights, headlight and other low voltage auxiliaries.

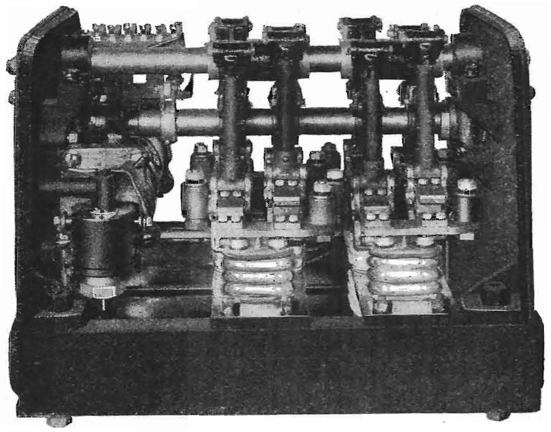

Fig. 10. Reverser

REGENERATIVE ELECTRIC BRAKING

Regenerative electric braking is a feature of the control equipment on the St. Paul locomotives. This feature adds very materially to the safety of operation by supplying a second braking system in addition to the air brakes. It provides increased economy of operation by reducing wheel, track and brake shoe wear. It permits faster speeds down grades, due to the better ability of definitely controlling the locomotive which is difficult at best with the air brakes. It also adds materially to the comfort of the passengers, due to smoother operation down grades. All this is attained by very simple and reliable additions to the equipment required for motor running.

As the head-waters of the Missouri, falling down hill, turn waterwheels direct-connected to electric generators, thereby supplying electric power for hauling any St. Paul locomotive with its train up a grade, so do those locomotives which descend grades, by rolling down hill, revolve their motors in turn as generators and similarly deliver power to any other ascending locomotive. In this way a conservation of energy is effected in that a portion of the power required for raising the locomotives to the top of the divide is later returned in the descent.

With the simple direct current motor adopted for these locomotives, operation as motors or generators depends upon whether the voltage of the trolley system at the locomotive is above or below the voltage at the motor terminals. When the locomotive is motoring the voltage at the motor terminals is lower than the trolley potential and power flows into the locomotive. When the locomotive descends a grade, and is braking, the engineer, through his controlling means, effects an increase in the voltage across the motor terminals so that power flows from the locomotive into the transmission system. The generation of this returned energy reacts on the locomotive so as to cause retardation

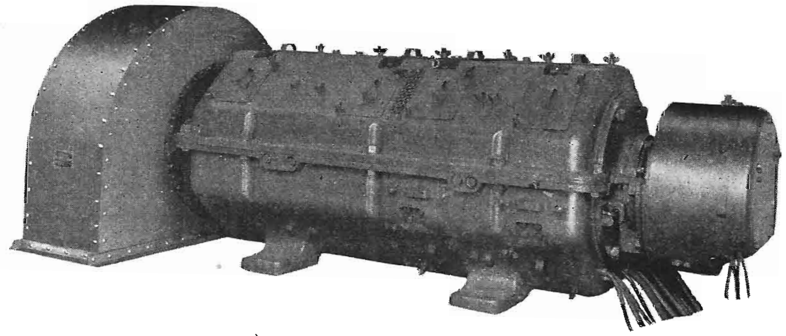

Fig. 11. Auxiliary Motor-generator Set

or braking besides effecting an economy by returning power to the line. The means for raising the voltage level of the motors, thereby returning power to the line in electric braking, rests in the use of the exciter before mentioned, so connected as to super-excite the traction motor fields when braking. Fig. 12 is a simplified diagram of these connections.

The series direct current motor has been found to be particularly well suited to traction service because of its inherent characteristic which automatically adjusts torque for change in grade. That is, to any particular speed and voltage there always corresponds one definite value of torque and current. With a decrease in speed there is an automatic increase in tractive effort, and with an increase in speed there is an attendant decrease in tractive effort.

With the connections as shown in Fig. 12, by properly proportioning the design of the

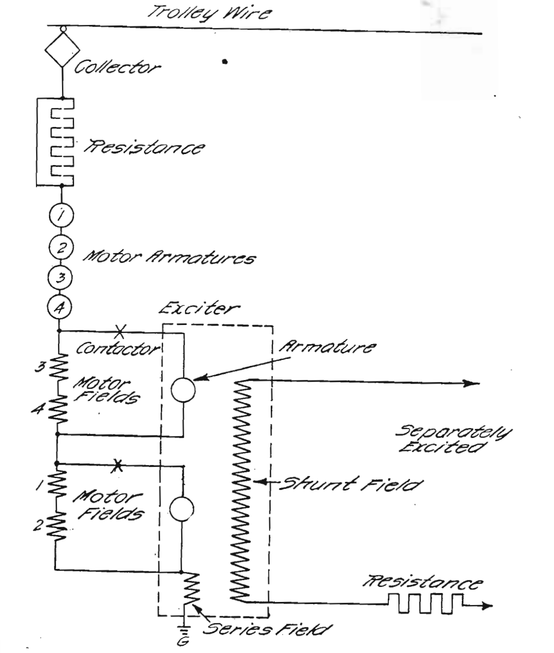

Fig. 12. Simplified Connections for Regenerative Electric Braking Showing Four Traction Motors and Exciter

exciter for its service in super-exciting the traction motor fields, the stable characteristic is inherent in the braking connection as in the motor connection. As the generator function is a reversal of the motor function, the traction motors in this case, provide in regeneration, that, with an increase in speed, there is an increase in braking effort and with a decrease in speed, there is a decrease in braking effort. The fact that a stable characteristic is closely maintained during regenerative braking, is one of the greatest contributing elements to the success of electric brak-

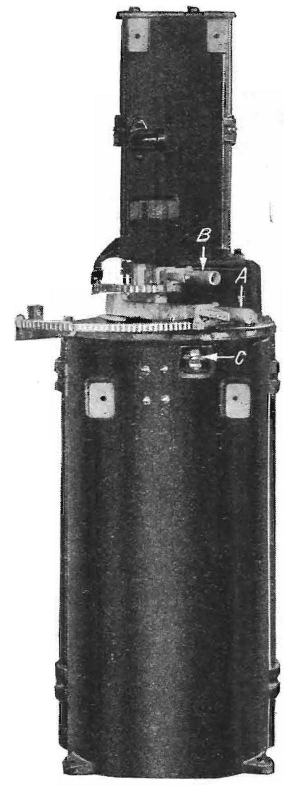

Fig. 13. Master Controllers Showing Operating Handles

ing in this service. This stable characteristic permits operation down grades at constant speeds with little regulating effort on the part of the engineer, except as changes in grade or curves occur, which require large variations in the intensity of the braking.

So far as the engineer is concerned there is nothing mysterious about the electric braking. In motor running he varies his tractive effort by changing the resistance in series with his traction motors thereby limiting the amount of power to be expended in his motors. In braking, he merely changes the resistance in the shunt field of his exciter thereby regulating the increment of voltage above the line and the power returned which reacts as his braking effort.

Fig. 13 shows the combined master controllers which the engineer uses for controlling his locomotive or locomotives if two or more are connected together. The large lower controller is necessary for motor operation. The small controller inverted upon the motor controller is used solely for the added regenerative braking feature. A combination of 3 handles, A, B and C is required. "A" is used to regulate the torque and speed, during motor running, through the rheostat points and the full running points with no external resistance in circuit and provides for changing the motor groupings between series and parallel; "B" is the braking handle which the engineer uses for varying the intensity of the retarding torque which may be accomplished with the motors running either in full series or full parallel; "C" is the handle for regulating the forward or backward movement of the locomotive and is called the reverse lever.

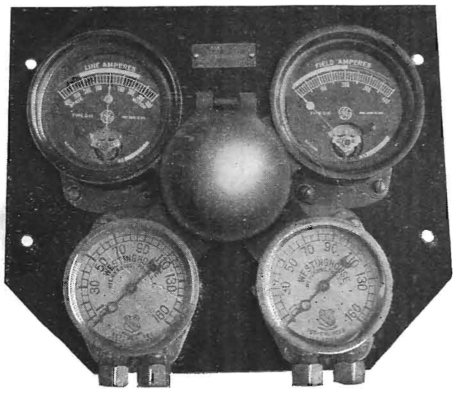

Fig. 14. Illuminated Gauge and Ammeter Panel which is Located in Front of the Engineer

Fig. 14 shows the illuminated ammeter and gauge panel which is located directly in front of the engineer to assist in operating both his electric and air brake systems. The pointer of the line ammeter, during motor operation, moves to the right as

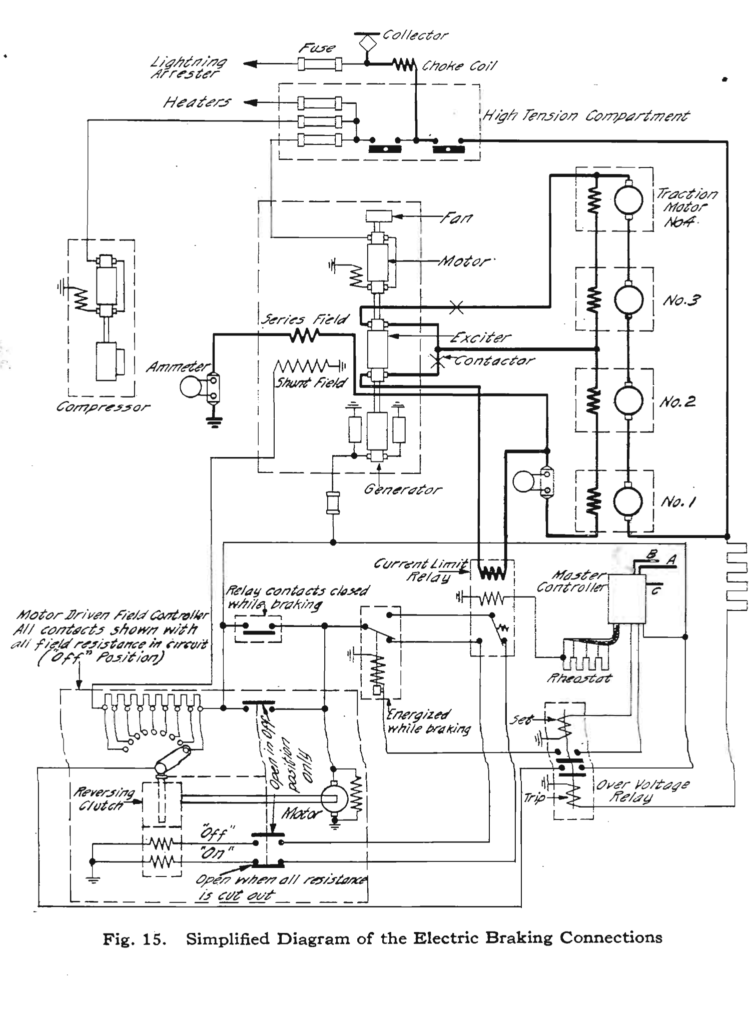

Fig. 15. Simplified Diagram of the Electric Braking Connections

indicated when showing the amount of current taken from the line. The engineer accelerates his locomotive by watching this ammeter. When the pointer of the ammeter moves to the left, the amount of current returned while braking is indicated. While braking, the engineer also watches his field ammeter which measures the current in the traction motor fields, at that time being super-excited. Red marks are located on the ammeter scales to show when the continuous capacity of the motor is being exceeded. Use of these meters provides, both in motor running and braking, for the most efficient operation of the locomotive.

Fig. 15 is a simplified diagram of the electric braking connections showing master controller, relays, field rheostat, exciter and the traction motors.

Fig. 16 shows the exciter field resistor with its controller. This device is regulated from the "B" or braking handle of the master controller. To assist in multiple unit operation, so the different sets of motors will properly divide their load, a current limit relay is used in the system of connections between the master controller and the exciter field controller to fix the setting of the latter.

In conclusion it may be said that, after ten months operation, including the severest winter season in a number of years, the electrical equipment on the St. Paul locomotives has satisfactorily fulfilled the requirements. Ease of operation is emphasized by the fact that the steam engineers could be given electric locomotives with but a few days instruction and that, from the first, electric locomotives were pooled with the steam so an engineer would not know, until called, whether he was to take out a steam or an electric locomotive. Reliability is evidenced by the fact that even, during the inauguration of this electrification, which took place in winter, heavy freight movements were maintained on the electrified zone of the St. Paul, while elsewhere in this mountainous region steam locomotives were tied up.

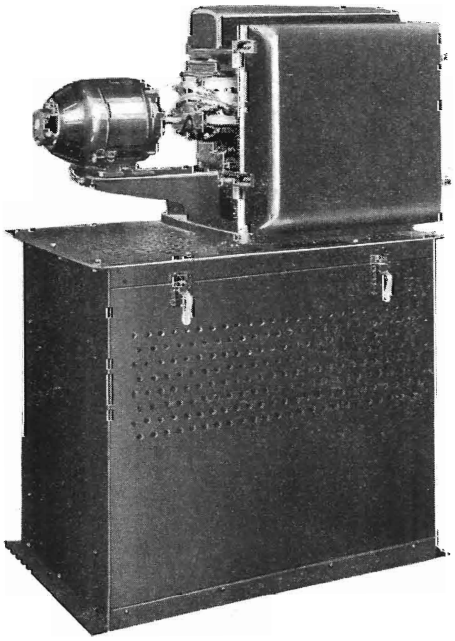

Fig. 16. Exciter Field Rheostat with Controller