

REGENERATIVE ELECTRIC BRAKING

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After first noting some of the previous uses of regenerative control in railway work, the author passes on to show the difficulties which have been encountered in designing regenerative control apparatus for the standard direct-current series railway motor. The advent of the commutating pole motor has removed many of these difficulties. The operation of regenerative control on the 3000-volt direct-current locomotives of the Chicago, Milwaukee & St. Paul Railway is then dealt with. A table showing the amount of energy returned to the line for various train weights, grades and speeds is given and the article is concluded by a summary of the advantages derived by the use of regenerative control.—EDITOR.

The successful regeneration of power by electric locomotives when descending grades has been the dream of inventors and engineers ever since the initial trip of the first electric car at Richmond, Va. in 1887.

A great many different combinations of fields, armatures, motors and control have been proposed to accomplish this purpose, and several schemes have been tried out with such indifferent success that, until recently, very little has been heard of this method of operation. It has been the common opinion that a commercial system of regeneration of electric power could not be produced with the well-known standard direct-current series motor, owing to the series characteristics of

on the locomotives, such as the Great Northern Railroad's three-phase installation at the Cascade Tunnel, the Italian State Railways in Italy, and more recently, the split-phase electrification of the Norfolk & Western Railroad at Bluefield, West Virginia.

The three-phase induction motor characteristics are such that it lends itself very readily to this method of control as it is only necessary to operate the motor slightly above the synchronous speed to cause it to work as a generator; but it has the serious inherent disadvantage that electric braking cannot be obtained at any other speed.

The Great Northern Railroad has used regenerative electric braking in connection with its 115-ton, three-phase locomotives through the Cascade Tunnel on a 1.7 per cent grade ever since this electrification was completed in 1909, with very gratifying results from an operating stand-point, as regards brake shoe wear, wheel troubles and ease of control, etc. Passenger and freight trains up to 2500 tons are taken through the tunnel safely and easily without the use of the air brakes and the railroad officials have been so greatly impressed with the desirability of this method of braking that they would not consider any other method of operation. *Fig. 1 shows the general characteristics of these locomotives when motoring and regenerating.

The Norfolk & Western Railroad also reports very satisfactory results with electric braking with their split-phase system; full descriptions of this electrification have been given in the technical press.

Very few attempts have been made to develop electric braking control for the commutator a-c. railway motor, such as is used on some of the first single-phase electrifications, so that electric braking is only used commercially at the present time with the direct-current and three-phase or split-phase systems.

* For a complete description of this electrification see paper before the A.I.E.E. by Dr. Cary T. Hutchinson, Vol. 28, 1909.

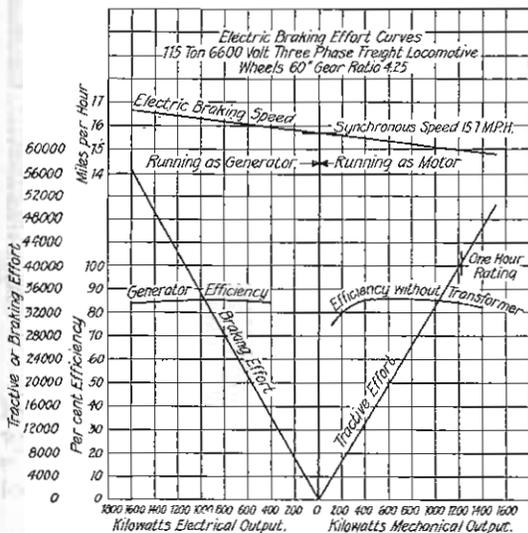


Fig. 1. Curves Showing Braking Effort and Speeds of Three-phase Locomotive

these machines and the operating difficulties caused by the great and rapid fluctuations in trolley voltage.

There have been several very successful installations of regenerative electric braking in connection with the three-phase or split-phase electrifications using induction motors

General interest was greatly revived in regenerative electric braking by the announcement that the officials of the Chicago, Milwaukee & St. Paul Railroad had adopted the 3000-volt direct-current system with the regenerative braking feature for their extensive electrification across the Rocky Mountains through Montana and Idaho, a distance of 440 miles. This decision was made after a careful study of the merits of the different systems, one of the requirements being that electric braking must be provided

without doubt marks one of the greatest advances in steam railroad electrification work in the last few years.

At first glance it would not seem very difficult to devise a system of control, motor connections, etc., such that series wound direct-current motors could be made to act as generators; but until recently the additional cost and complication of motors and control were so great and operation so difficult and unreliable that regeneration had never come into commercial use, although a great

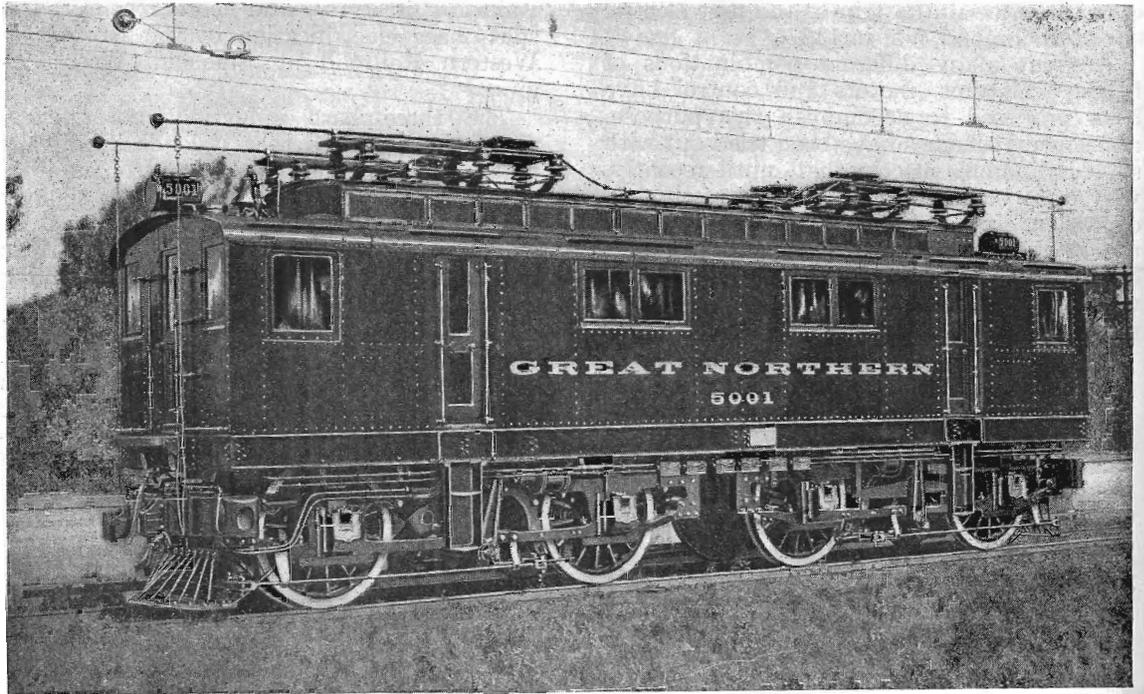


Fig. 2. Three-phase Locomotive Used for Electric Braking

as part of the locomotive equipment. This interest increased as the electrification approached completion and the tests on the locomotive indicated that the equipment more than met the expectations of the designers. Operation in actual service for a period of ten months over the very irregular profile shown on page 957, on 226 miles of line has proved that the complete system is an unqualified success, electric braking with passenger and freight trains at all speeds being successful in every way.

This is the first time that electric braking has been used on large locomotives equipped with standard direct-current series motors operating over heavy mountain grades, and

many systems have been proposed. Most of the schemes suggested involved special motor with special combinations of shunt and series field windings and a complicated control equipment.

One of the fundamental causes of failure was due to neglect to take into account the great and rapid changes in trolley voltage encountered in regular railroad work, with the result that the motors could not take care of the extreme overloads caused by a sudden decrease in trolley voltage. It is evident that if the motors acting as generators are generating a certain voltage and held at constant speed by the train, which cannot quickly change its speed, a rapid decrease in the

trolley voltage, due to line drop caused by the acceleration of another train in the immediate vicinity, would cause a very bad overload and probably lead to the flashing over of the motors, if some means were not provided to take care of such a condition. The few early trials of electric braking were made before the advent of the commutating pole railway motor with its rugged construction and great overload commutating capacity. The commutating pole motor automatically becomes a very excellent generator and its use has contributed greatly to the very successful results obtained.

A scheme of regenerative electric braking control was developed a short time before the Chicago, Milwaukee & St. Paul Railway decided to go ahead with their electrification, such that a standard series direct-current commutating

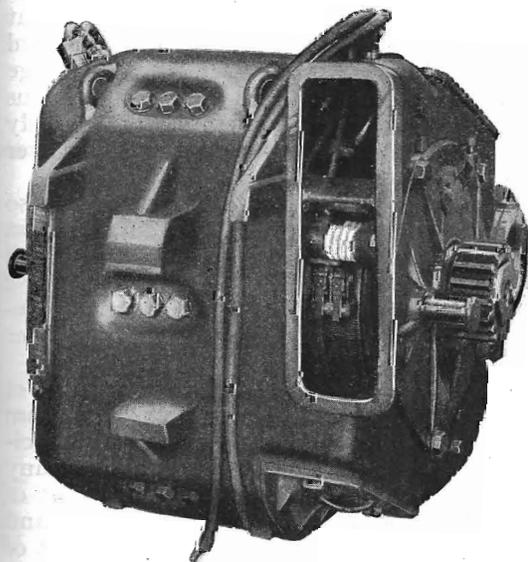


Fig. 4. 1500/3000-volt Series Direct-Current Railway Motor Which will Function as Motor, or as Generator for Electric Braking

pole railway motor could be simply and easily caused to act as a generator when driven by the weight of the locomotive and train on down grades, without adding to the weight of the motor or changing its fields or connections.

The additional equipment for regeneration is very slight, consisting simply of a small generator, electric braking controller and a small amount of control apparatus to make the few connections required. The small generator is used to excite the motor fields

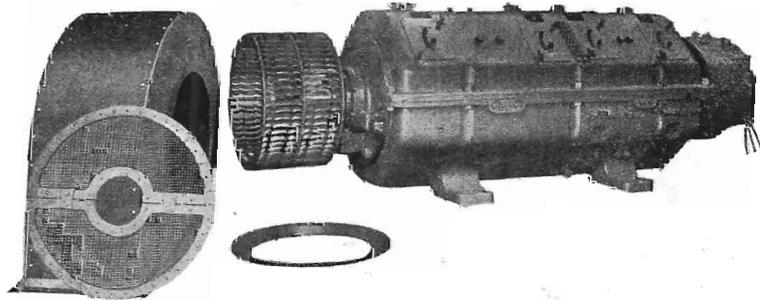


Fig. 5. Motor-generator Set Used to Supply Excitation for the Railway Motor Fields when Regenerating and Power for Control, Headlights, Blower, etc.

and forms part of the motor-generator control set which furnishes power for operation of the control, headlights and blower. (Fig. 5). The control and manipulation of the locomotive is accomplished by a small braking controller similar to and placed immediately above, the main master controller used to control the locomotive. (Fig. 6). These controllers are suitably interlocked so that the possibility of the engineer making mistakes is entirely eliminated. The control is so designed that the motors can be connected in series or parallel, giving two high efficient running points, and the same flexibility is obtained when operating as generators for electric braking as when running as motors. The controllers are interlocked so that electric braking can only be applied when the motors are connected in series or parallel. This scheme of control with the great variation in voltage obtainable as generators gives a very wide range in possible operating speed.

The sequence of operations of the controllers is so self evident in combination with the ammeters in the main locomotive and motor circuits, that the regular steam locomotive engineers have no difficulty in operating the locomotive without special training under all the severe conditions encountered in moving heavy trains over mountain grades.

The regular operation of the locomotive as a straight locomotive is not interfered with in any way, but electric braking is immediately available at any time either to slow down the train at curves or stops, or to hold the train on the heavy grades. If

the speed of the train on any grade reaches a higher point than desired before braking is applied, electric braking can be applied very slightly and gradually brought up to the point required to slow down the train and hold it at the desired speed. This is a dis-

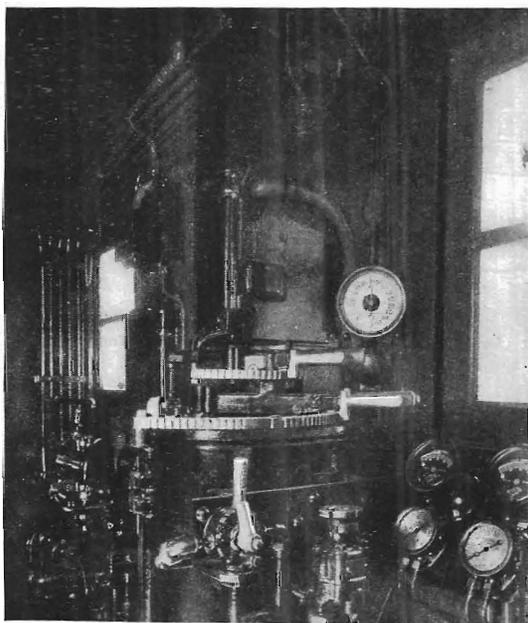


Fig. 6, Electric Braking Controller and Main Master Controller on Locomotive

tinct advantage and is only possible with direct-current electric braking.

The regeneration control is entirely automatic and the braking effort is held constant for any definite setting of the braking controller, being entirely independent of the change in trolley voltage, distance from substations or nearest locomotive, change in grades, etc. The wide latitude in braking speeds is shown in Fig. 7 and 8 which indicate very clearly the great flexibility of this type of braking. Trains can be taken down the grades at practically any speed desired by using the proper series or parallel connection of the motors.

It is evident that the motors acting as generators must generate a gradually increasing or decreasing voltage as the locomotive leaves or approaches a substation if the braking effort is held constant and the train is held at constant speed. The control takes care of this automatically, without attention, while giving practically constant speed braking. A locomotive or locomotives descending

a grade with a train act exactly the same as a portable substation on wheels moving between the substations, but electrically and physically connected to the substation buses. The substation generators fix the voltage and the locomotive must generate this voltage plus the voltage drop due to current returning to the station busbars. If power is fed into another locomotive the generated voltage is dependent upon the drop in voltage due to load taken from the substations by the locomotives not regenerating. It is possible for one train descending the grade to take a lighter train up the other side of the mountain with all the power passing through the substation busbars, but without power being supplied from the substation. In this case the generating apparatus simply floats on the line and determines the trolley voltage.

A locomotive equipped with electric braking can take a heavier train down a grade than it can pull up the same grade, due to the fact that the friction of the train has to be overcome when ascending the grade but assists the locomotive in holding the train on the down grade. It has always been necessary to figure on a larger motor for braking than would ordinarily be used, due to the fact that it would be used continuously, but the internal ventilated type of motor used on high voltage d-c. locomotives has such a high continuous capacity that it can be operated continuously at the normal locomotive rating without over heating.

The advantages of electric braking are so many that it is difficult to pick out the most important; but as the saving in power is self evident it is usually the one given the first consideration, although there are other benefits, which in the end may prove of greater value.

The saving in power is undoubtedly one of the most important benefits obtained from electric braking and reaches a very appreciable figure, if the profile consists of many grades above one per cent. The amount of power returned depends upon the length and the steepness of the grade, and the weight of the train. If the grade is steep and short a large amount of energy would be returned for but a short time, so that the actual value of the returned power would not be very great. If the grade is a long one, power is returned for a much longer period, and may be an appreciable percentage of the total power required to operate the road.

Calculations and actual demonstration indicate that there will be a saving of at least

15 per cent of the total power demand with a profile as usually encountered in mountain divisions, if the power conditions are such that all the returned power can be utilized.

A train descending a two per cent grade will return nearly 60 per cent of the power required to haul it up the same grade besides the attendant advantages as regards operation, safety and decreased wear on wheels, brake shoes and track. The fact that a 2500-ton trailing train descending a two per cent grade at seventeen miles per hour will return 3000 kw. or 4000 h.p. to the trolley gives a good idea of the amount of power made available for the operation of other trains on the system which was absolutely thrown away in heating the brakeshoes and wheels with the old method of braking. If this grade is seventeen miles in length, 3000 kw-hr. would be available at the locomotive with a value of \$21.60 at 0.8 cent per kilowatt hour, assuming 10 per cent loss in transmission to the nearest trains or substations.

It is interesting to note the amount of power which would be returned to the overhead conductor by freight and passenger

directly proportional to the speed and weight of train and the energy returned for any speed and train weight can be calculated from data in the table.

Weight Train Including Locomotive Tons	Grade Per Cent	Speed m.p.h.	Kilowatts Returned to Trolley	Power in Killo watt hours if Grade is 20 miles long
1100	.7	40	600	300
1100	1.	35	930	530
1100	1.5	30	1360	900
1100	2.	30	1920	1280
3000	.7	25	1030	820
3000	1.	20	1450	1450
3000	1.5	20	2500	2500
3000	2.	17	3000	3500

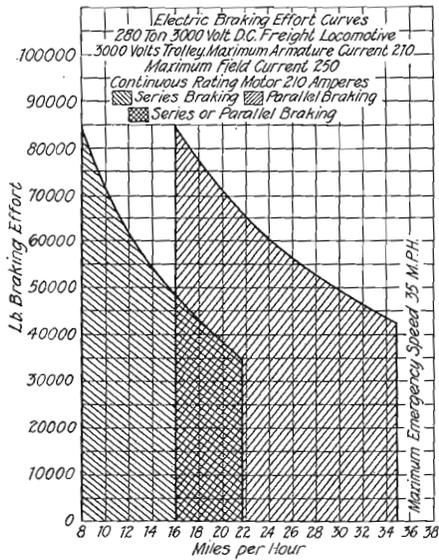


Fig. 7. Electric Braking Effort Curves of 3000-volt D-c. Freight Locomotive Showing Wide Range in Braking Speeds

trains usually moved over mountain divisions when descending different grades. The number of kilowatts and kilowatt-hours returned to trolley under certain conditions will be found in the following table. The kilowatts regenerated on any grade are

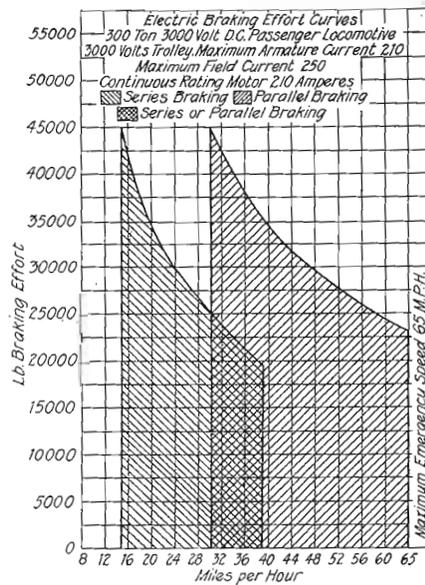


Fig. 8. Electric Braking Effort Curves of 3000-volt D-c. Passenger Locomotive Showing Wide Range in Braking Speeds

Electric braking has many advantages in addition to the saving of power, one of the most important being the great increase in ease and safety of operation in taking a long heavy freight or passenger train down a mountain grade. With regular air brake braking it is necessary to repeatedly recharge the auxiliaries; and all the braking is dependent upon the air pumps upon the locomotive. With electric braking but very little air is required, as it is only necessary to keep the train line charged while the locomotive does the braking. Under these conditions the air brakes on the cars are always in condition

and the brake shoes and wheels are cool and not red hot or worn out, due to excessive use on a long grade, with the result that in case of emergency the air brakes are instantly available at maximum efficiency, giving a duplicate braking system.



Fig. 9. Freight Train Using Electric Braking Descending 2 per cent Grade on East Slope of Rocky Mountains. Chicago, Milwaukee & St. Paul Railway Electrification

With electric braking the entire train is bunched against the locomotives and the braking effort is absolutely uniform and constant as there is not the surging back and forth in speed encountered with air braking, which results in decreased wear and tear on brake equipment and greatly increases the comfort of passengers. There is also an entire absence of noise due to grinding of brake shoes and wheels, which is especially disagreeable on heavy passenger trains.

The operation of heavy trains on long steep grades has long been the dread of all railroad operators on account of trouble with brake rigging, hot and worn out brake shoes, broken wheels, trouble with air compressors, etc., which are entirely eliminated by electric braking. The saving in maintenance due to the elimination of these troubles can only be obtained by actual demonstration over a period of time, but it should amount to an appreciable item in addition to the increased safety to passengers and train crews.

It is a well established fact that track rails wear very fast on steep grades with standard

air braking if the traffic is very heavy, and it has been proved that this wear is greatly reduced and is practically the same as on the up-grades if regenerative electric braking is used. The experience of the Italian State Railways in this respect indicates that this saving may be one of the most important advantages of this type of braking; but operation in this country has not yet been extensive enough to show the actual saving.

It is evident that if regeneration is used, all of the apparatus on the locomotives and in the substations, etc., must be capable of operating inverted. Not only must the motors on the locomotives act as generators, but the generating equipment in the sub-stations must invert, and if motor-generator sets are used, the direct-current generators must operate as motors and the synchronous motors as generators. They must be capable of doing this instantly and as often as required without affecting reliability or successful operation in any way.

All of the apparatus in the locomotives and substations for the Milwaukee electrification have been designed to meet these severe conditions and successful operation for over almost a year has demonstrated that they have more than met the requirements of actual service and the railroad company.

SUMMARY

The advantages of regenerative electric braking may be stated as follows:

- Saving of approximately 15 per cent of total power required.
- Elimination of brake shoe and wheel wear and brake rigging troubles with material reduction in maintenance charges.
- Removal of difficulties encountered in operation of long heavy freight and passenger trains on long grades due to inherent operating characteristics of air brakes.
- Reduction in wear of track on grades and severe curves.
- Increased safety to passenger and train crews due to duplicate braking systems.
- Increased comfort to passengers and reduced wear on equipment due to constant speed on grades and uniform braking when slowing down for curves and stops.
- Elimination of grinding and noise of brake shoes and wheels on heavy grades.