A regenerative braking system for dc railway traction

GEC TRACTION

INTRODUCTION

Although there is much current interest in the development of the induction motor for railway traction applications, it is the dc motor which at the present time provides almost all of the world's electric traction motive power, and since the earliest days of electric traction a great deal of effort has been expended in devising methods of regenerative braking suitable for the dc motor on dc traction systems. However, until the application of semiconductor technology to railway traction began about 15 years ago, regenerative braking on the rapid-transit or commuter types of railway was rare compared to rheostatic braking and was seldom completely successful. Two features characteristic of those types of railway presented intractable problems:

sudden changes in the supply voltage required a fast response from the motor controller if surges of generated current were to be prevented;

and frequent gaps in the conductor rail required some quick means of temporarily diverting the generated current into a rheostat, to maintain braking effort and to prevent excessive generated voltages.

Both these problems have now been overcome by the application of solid-state power switching devices, and this paper presents one form of the solution, exemplified by equipment supplied to London Transport, Danish State Railways and Netherlands Railways.

An account of a simple braking system scheme is given by way of introduction, followed by a description of the modified scheme which makes possible an automatic change from a weakened, separately excited, field to a full series field mode of operation at the motor's base speed, and finally a description of the further modification which enables the blending of rheostatic and regenerative braking at times when the conductor rail (or overhead line) is not fully receptive to the returned energy.

SIMPLE BRAKING SCHEME

The most simple regenerative braking scheme employing a dc series motor and a thyristor controller (or chopper) is shown in Fig. 1. It works only at speeds below the motor's *base speed,* i.e. the speed (at a given motor current) at which the motor's generated voltage equals the line supply voltage. Below the base speed, the motor's mean generated voltage is less than the supply line voltage, and the chopper acts as a transformer, converting the low voltage, high current, motor energy into a relatively high voltage, low current, form which can then be returned to the conductor rail. The lower the speed, the higher the ratio of *on* to *off* times of the chopper (for any given braking current), so that the generated current, referred to the conductor rail voltage, falls approximately linearly from nearly full motor current at base speed to nil at some very low speed when the motor is almost short-circuited by the chopper.

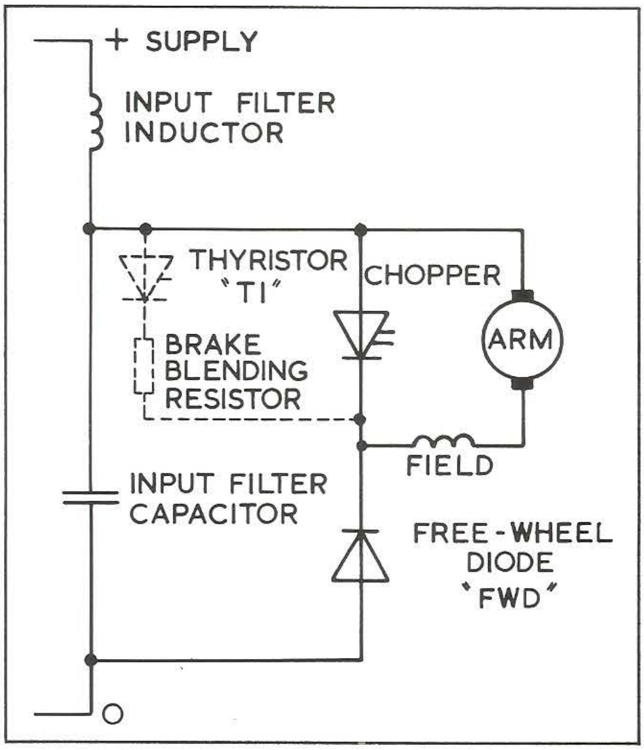

Figure 1 Simple braking scheme.

This transformation of energy has been called the *store and let fly* technique: while the chopper is on, current builds up in the armature and field and energy is stored in their inductances. When the chopper is turned off, the current, which continues to flow because of the inductive nature of the circuit, is transferred to diode FWD (see Fig. 1); in other words the motor's terminal voltage has been forced to increase to line supply voltage V by the addition of a voltage (equal to its inductance multiplied by the rate of fall of the current) to its rotational generated voltage E. Thus current flows via FWD and the motor into the conductor rail, transferrring the stored energy into the supply; this is the let fly process. A certain motor current ripple is essential to this technique, to provide the necessary voltage across the motor's inductance: this voltage, U, is shown in Fig. 2.

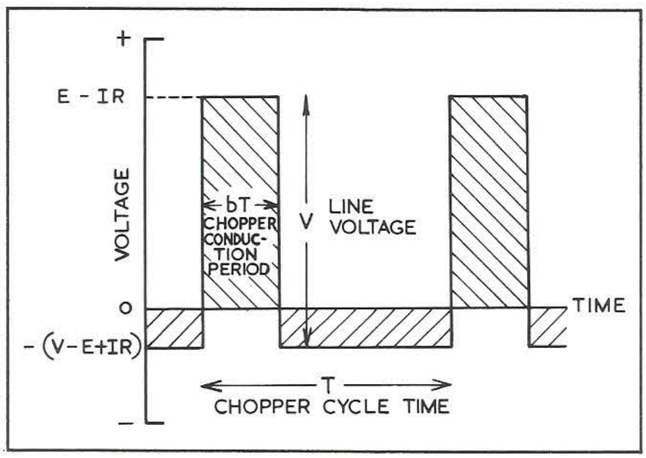

Figure 2 Voltage across motor inductance.

Control Characteristic

For any given speed n below the base speed an increase in generated current I (ie an increase in braking effort) results in a decrease in chopper conduction ratio b, as shown in Fig. 3. The chopper conduction ratio b is the ratio of its *on* time to its cycle time.

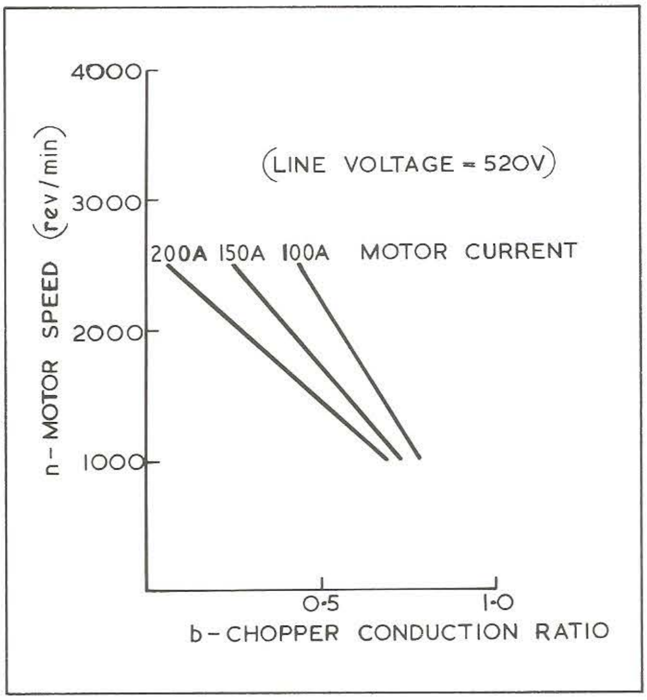

Figure 3

A simple explanation of this effect is possible, assuming that the chopper's cycle time T is short enough for the motor current ripple to be small. In the steady state:

$$\int U \, dt = 0 \qquad \ldots\ldots(1)$$

ie the areas above and below the axis of Fig. 2 must be equal, so that if the motor's resistance is R:

$$bT(E - IR) = (1 - b)\,T\,(V - E + IR) \qquad \ldots\ldots(2)$$

$$E = (1 - b)\,V + IR \qquad \ldots\ldots(3)$$

Equation 3 is plotted, with the chopper conduction ratio as parameter, by the dashed lines in figure 4. Now, the generated voltage is a function of speed and motor current. It is plotted with speed as parameter by the solid lines in figure 4, and can be represented approximately by:

$$E = knI \qquad \ldots\ldots(4)$$

where k is a constant for the particular motor.
Therefore

$$I = \frac{(1 - b)\,V}{(kn - R)} \qquad \ldots\ldots(5)$$

so illustrating the statement that the higher the motor current, the lower the chopper on-time.

This effect has been described by Wagner and Wolski.(1).

Referring to Fig. 4, the operating point at a motor speed of 3000 rev/min and a chopper conduction ratio of 0.5 is at A. To reduce the conduction ratio to 0.25 the operating point must move to B, an increase in current

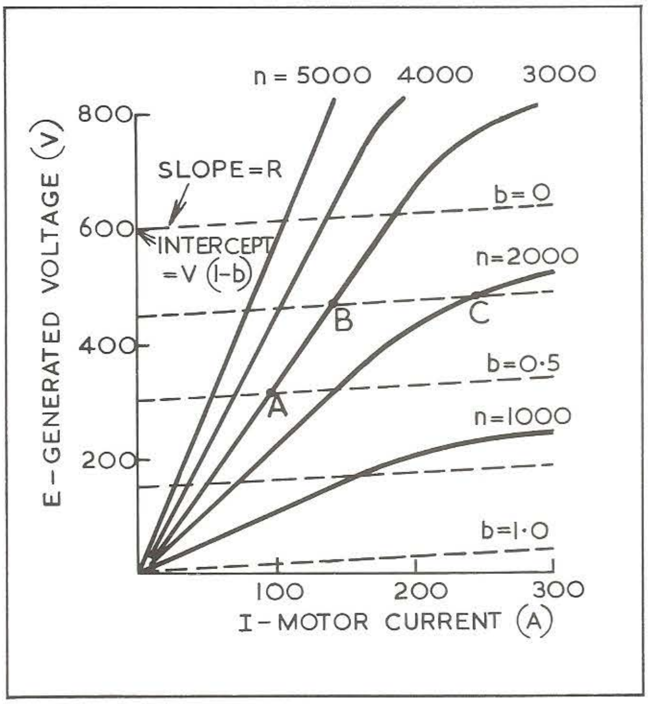

Figure 4

of about 50A. The operating regime is unstable in the sense that if there is no action by the control system a fall in speed results in a increased braking effort, bringing the speed down yet more rapidly. If the control system *sticks* at point B, so that the conduction ratio remains fixed at 0.25, by the time the speed has fallen by 1000 rev/min the current has risen by more than 100 A, and the operating point will be at point C and moving rapidly along the line b = 0.25 away from B.

Control system response

The control system, (as usual for a motor controller) increases the chopper conduction ratio in response to an increased current demand. To help explain the response of the system to a step increase in current demand, the voltage on the motor inductance has been re-drawn in Fig. 5 on the assumptions that speed is constant and that magnetic saturation can be neglected. The voltage during the chopper conduction period bT is therefore directly proportional to motor current I. The constant of proportionality, denoted by c in Fig. 5, ie (Kn — R). Fig. 5a represents the initial steady-state condition. In response to an increase in current demand, the control system increases the chopper conduction ratio; Fig. 5b. The motor current will not change immediately, but now that area A is larger than area B there is a net voltage applied to the motor inductance tending to increase the current. When I has increased to the new demanded level (see Fig. 5c), area A is yet larger, causing the current to continue to increase more rapidly. However, any further increase in current will mean that it exceeds the demanded level, and the control system will respond by reducing the chopper conduction ratio, as in Fig. 5d. The new steady state will be achieved when areas A and B are again equal, and it can be seen that since the amplitude of A is now larger than in Fig. 5a, its width must be smaller (the overall amplitude remains fixed at V), ie the chopper conduction ratio must be smaller.

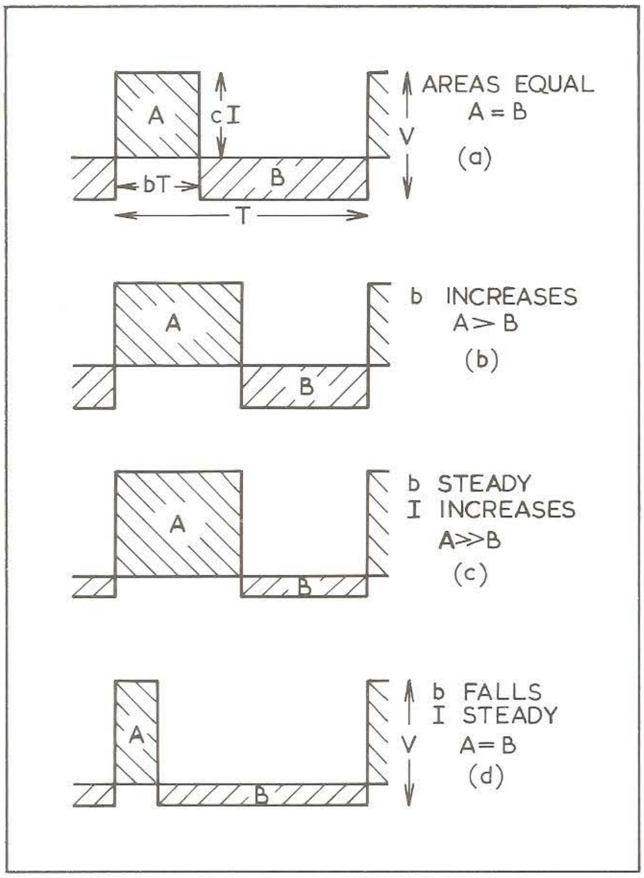

Figure 5 Voltage across motor inductance, illustrating control system response. (Same axes as Figure 2).

MODIFIED SCHEME WITH FIELD WEAKENING

From the foregoing it is clear that there is no stable operating point above the line b = 0 in Fig. 4, ie at speeds higher than the base speed the motor current would increase out of control of the chopper. There are two possibilities for extending the braking speed range: to insert resistance in the circuit or to weaken the field. Four possible resistor positions are shown in Fig. 6.

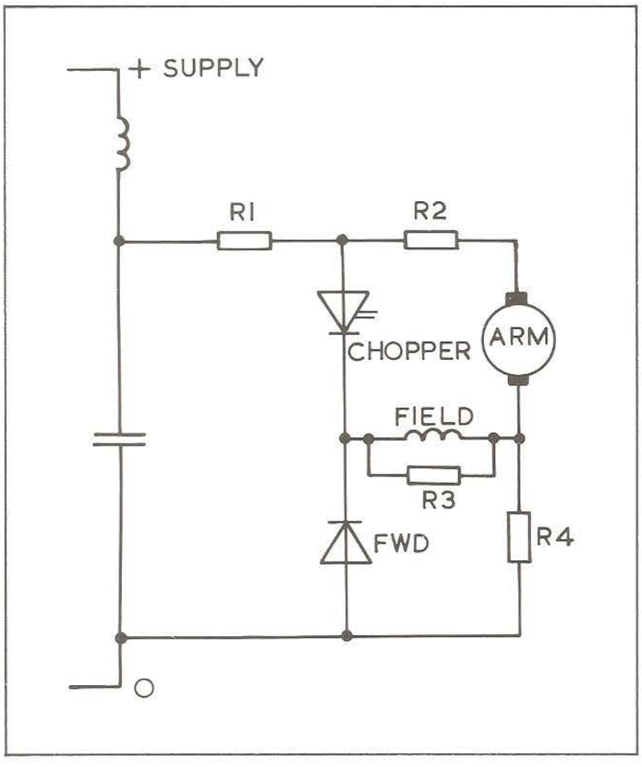

Figure 6

However, although manufacturers have produced equipment incorporating such resistors, the increasing emphasis placed on energy saving by railway administrations has meant that braking schemes using field weakening have been favoured over those using inserted resistance, and although some degree of field weakening is produced by resistors in positions R3 and R4 of Fig. 6, the preferred method of field weakening, which has the highest potential for regenerative efficiency, is by separate excitation of the motor field.

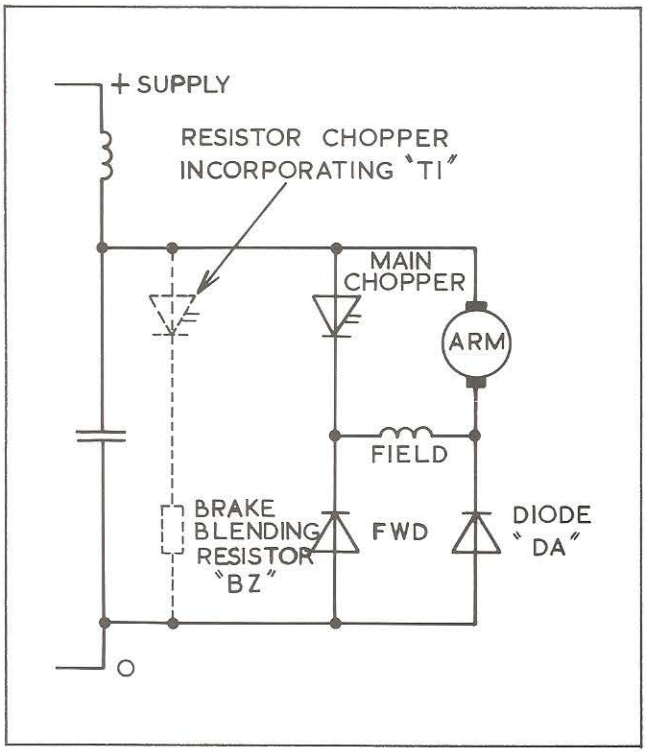

Figure 7 Field weakening.

The circuit shown in Fig. 7 is the same as the basic regenerative braking circuit for a series motor shown in Fig. 1 except for the introduction of the diode DA. It is the diode DA which, by allowing the armature current I_a to bypass the field as speeds higher than the base speed, brings about field weakening and ensures stable operation. An alternative way of describing the action is to note that when DA is conducting (it conducts the difference between armature and field currents) the voltage drop across DA is very small compared to the generated voltage, so that the chopper/FWD/field circuit and the armature circuit are practically independent. Thus the right hand (as drawn in Fig. 7) end of the field is effectively connected to the negative rail and the field may be considered to be separately excited, via the chopper, from the line supply, and not from the armature.

Separate excitation

The field strength may thus be controlled by the chopper independently of the armature, and weakened relative to the armature current as desired, subject only to limitations imposed by motor commutation. It is usually desirable to keep the product of field and armature currents constant, so as to maintain braking effort invariant of speed, and the field and armature currents, plotted against speed, will then form a set of "V" curves with apexes lying along the base speed curve appropriate to the line supply voltage, as in Fig. 8. The armature current is frequently curtailed as indicated to comply with either power or commutation limits of the motor.

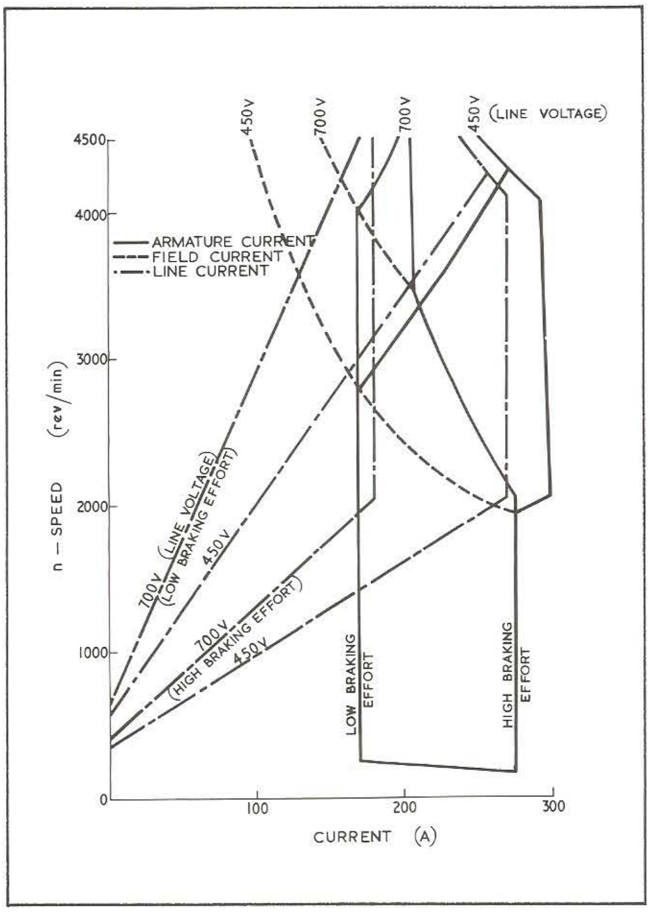

Figure 8

When DA is conducting,

$$I_f = \frac{bV}{R_f} \div \frac{V}{kn} \qquad \ldots\ldots(6)$$

where I_f and R_f are the field current and resistance respectively. Thus an increase in chopper conduction ratio results in an increase in braking effort, the opposite of the effect when DA is blocking. Equation (6) implies very low conduction ratios; braking at high speeds places a more severe constraint on chopper design than any other operational duty.

The regenerated line current at high speeds is almost equal to the armature current, since only a small current has to be diverted to feed the field. (The field current, which is less than armature current, is also referred to the low field voltage; referred to the conductor rail voltage it is even less). Below the base speed the regenerated current falls approximately linearly with speed as more and more current has to be diverted to the *store* function.

BLENDED REGENERATIVE AND RHEOSTATIC BRAKING

Blended rheostatic braking may easily be added to the simple regenerative scheme by means of the thyristor and resistor shown with dotted lines in Fig. 1. If at any time during the *let fly* period the line supply becomes unreceptive to the regenerated current, the thyristor can be fired, so that the current is diverted into the resistor and back to the armature without flowing through the line supply and diode FWD. The value of the resistor is chosen so that the voltage across it at maximum armature current is not greater than no-load line supply voltage, so that auxiliary machines connected to the line may continue to run unharmed. This is in contrast to conventional rheostatic braking, where the motor circuit is separated from the line supply, and the voltage is allowed at least to double in order to utilise the traction motor better.

The receptivity of the supply is gauged be measuring the conductor rail voltage, or more precisely the voltage across the capacitor on the motor side of the input filter. If the voltage on the capacitor tends to rise above no-load line voltage, the supply is deemed to be unreceptive and the resistor is switched in. (The resistor cannot discharge the capacitor because of diode FWD, but can only ensure that its voltage does not continue to rise).

At the end of the *let fly* period the main chopper takes over the current from the resistor, and at the end of the *store* period both the main chopper and the thyristor are turned off by the main chopper's commutation circuit.

Blending with field weakening

The system just described cannot be used directly with the field weakening scheme because the inductive nature of the field means that not all the generated current can be diverted into the resistor: a current (I_a — I_f) continues to flow into the conductor rail and back via the diode DA. The resistor must instead be connected across the whole circuit, as shown with dotted lines in Fig. 7, which then requires that the thyristor T1 be replaced by a chopper with its own means of commutation.

Integrated braking chopper

Fig. 9, diagram (a), shows in detail how the main and resistor choppers may be integrated so that each provides the other's commutation circuit, resulting in a flexible system of low cost. The operation of the chopper may be followed with the aid of the sequence of diagrams (b) to (f).

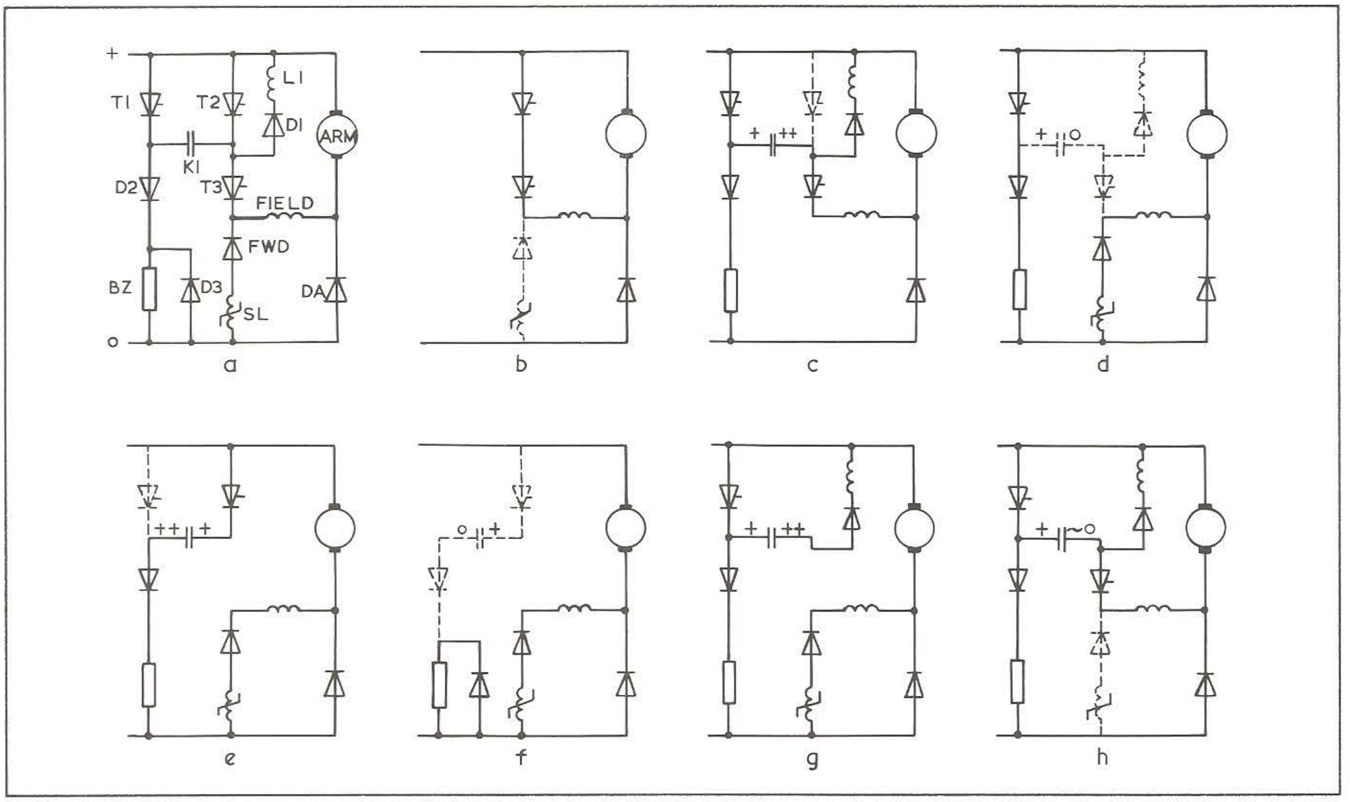

Figure 9

Sequential operation

Thyristors T2 and T3 are fired, see diagram (b), to start the *store* period. They conduct the field current, which builds up rapidly in the loop formed with the armature, while diode DA continues to conduct ($I_a - I_f$).

At the end of the *store* period thyristor T1 is fired to turn off T2: see diagram (c). To reduce the energy input to the field during the commutation process, the major part of the energy of capacitor K1 is recirculated by the resonant loop formed by diode D1 and inductor L1. The field current flows via T1, K1 and T3 until K1 is charged, ie until its right-hand plate (as drawn) reaches zero potential. This is depicted in diagram (d). Because of saturating inductor SL the capacitor overcharges slightly (its right-hand plate falls to a negative potential). When SL saturates, the field current is taken over by diode FWD, and T3 turns off. The excess capacitor voltage causes T3 to be reverse biassed, so securing its off-state.

Since the moment when T1 was fired the resistor BZ has been connected across the supply and consequently the braking energy has been dissipated rheostatically. At any time after T3 has turned off, regeneration to the supply may be commenced by firing T2, which reverses the charge on K1 and turns off T1 as shown in diagram (e).

The delay between T3 turning off and the firing of T2 is determined by the control system according to the line voltage and motor current monitored during the preceding period. If the line voltage is less than a certain value, there is no delay: T2 is fired immediately after T3 has turned off and the rheostatic component of braking is cut to a minimum. If on the other hand the line voltage rises above the set value, the delay is progressively increased (up to the maximum at which T2 firing coincides with the start of the next chopper cycle) over a certain range of line voltage. The purpose of this range of voltage is to encourage the several equipments in a multiple-unit train to share the regeneration. To enhance stability, the amplitude of the range is adjusted according to the regenerated current, being about 10% of no-load line voltage at maximum current, and more at lower currents.

For the remainder of the cycle the circuit is as shown in diagram (f); braking energy is returned directly to the conductor rail. The small inductance of BZ is accommodated by diode D3. The firing sequence then repeats.

Summary of sequence

In every chopper cycle, with a given motor current, the duration of the *store* mode, diagram (b), is determined by the speed (the lower the speed, the longer the mode lasts), and the relative durations of the *rheostatic* mode, diagram (d) and of the *regenerative* mode, diagram (f), are determined by the line voltage. The whole period is thus divided as shown in Fig. 10 between these three modes: the transitional commutation stages, Fig. 9 diagrams (c) and (e), are of relatively brief duration, although careful allowance must be made for them by the control system.

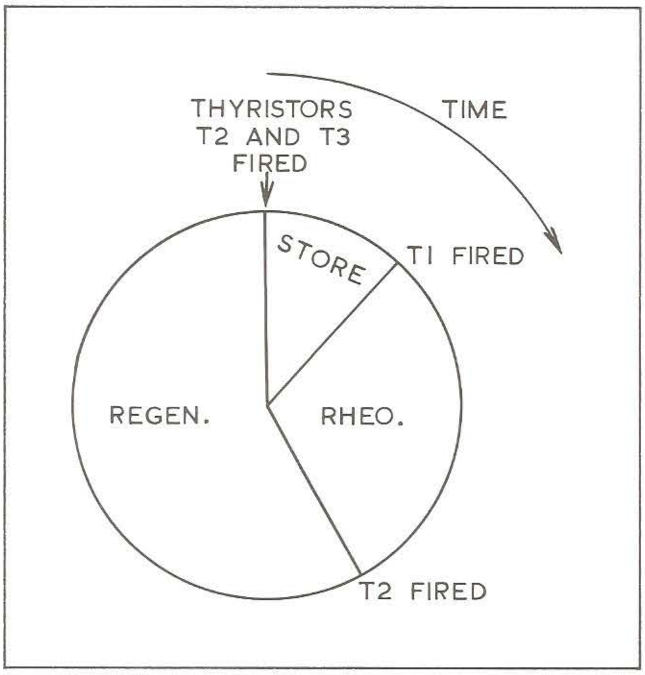

Figure 10

The switching between modes is not however apparent externally to the equipment because of the *averaging* effect of the input filter: the regenerated current in the conductor rail has very little ripple, because the presence of the input filter inductor ensures that it does not change appreciably over periods of the order of a single chopper cycle, and the excess of armature current over conductor rail current during the *regenerative* mode is absorbed by the filter capacitor. During the *rheostatic* mode, current flows from the capacitor, not only into the filter inductor but also into the braking resistor. There is a considerable voltage ripple on the filter capacitor due to this alternate storage and release of energy, but it means that the braking resistor current during the conduction period of T1, which as mentioned above has to be equal to the maximum possible motor current, is averaged over the whole chopper cycle, so that the effect is as though a braking resistor of higher value, appropriate (at the line voltage) to the portion of motor current that cannot be absorbed by the field circuit nor returned to the conductor rail, were connected steadily across the supply.

It is not possible with this system to reduce the duration of the *rheostatic* mode quite to zero even when the supply is fully receptive to regeneration, because a certain minimum conduction period of T1 is essential for the commutation of the chopper (Fig. 9), diagrams (c) and (e)). This relatively small degree of rheostatic braking is governed ultimately by the extent to which conductor rail voltage is permitted to rise above the no-load supply voltage, and by the characteristics of the thyristors: a minimum rheostatic *blend* of 6% is typical.

Since the supply is rarely completely receptive, this limitation is generally not an economic embarrassment, but should a further increase in regenerative efficiency be needed, diode D2 (figure 9, diagram (a)) may be replaced by a thyristor, which is not fired until it is necessary to reverse the charge on capacitor K1 as shown in diagram (e), or until the voltage monitor calls for rheostatic braking. The minimum rheostatic *blend* is then typically about 3%.

Changes in line voltage

The effect of a sudden fall in line voltage during braking is to cause the armature current to increase, but the increased current flows through diode DA, not through the field, so that the rotational generated voltage is not increased which together with the fast action of the chopper enables the surge in generated current to be controlled harmlessly.

Conductor rail gaps

The conduction period of T1 is controlled by an electronic servo system which normally adjusts it relatively slowly in response to changes of line voltage. However, if the train crosses a gap in the conductor rail, so that an open circuit is suddenly presented to the equipment, the filter capacitor voltage will rise sharply, at a rate governed by the capacitance, and on reaching a set value will cause thyristor T1 to be fired immediately, independently of the servo system. Thyristor T1 may be fired more than once per chopper cycle for this purpose, subject to certain brief *forbidden* periods to allow for correct commutation. A constraint is put on the value of the filter capacitance as a result of these *forbidden* periods.

When thus forced into the *rheostatic* mode, the system returns only slowly to regeneration at the other side of the rail gap. During a gap, the energy in the filter inductor is dissipated in a non-linear resistor connected across it, which prevents the line-side voltage from rising more than about 20% above normal.

Control System Stability

The frequency responses of both the T1 (or voltage) and the T2 (or current) servos have been designed after analysis of the stability of the complete system, including the motor and input filter. Simulation of the system gives some insight into the control problem, but generally it neglects the fact that the chopper controls the motor and the rheostatic blending by pulses and not truly continuously. For example, such simulation indicates that a proportional characteristic is sufficient for the voltage servo, whereas in practice it must be proportional plus integral, and also its reference voltage should be reduced in proportion to the regenerated current. The voltage servo acts on the line voltage monitored in preceding cycles and in effect predicts the voltage (and consequently the necessary blend of rheostatic braking) during the coming cycle.

The current servo used in braking above the base speed (and also in motoring) is also of proportional plus integral type, but of comparitively low gain (about unity) with adjustments to its gain at about 10 Hz and at above 200 Hz, to reduce conductor rail current ripple due to the interaction of chopper, motor and input filter at these frequencies (the lower corresponding to automatic train control signal frequencies, the upper to the chopper fundamental frequency). Too high a gain results in *limit cycle* operation with excessive current ripple, but acceptably small errors in achieved braking effort (about 5% of effort demanded) can be obtained with the low gain quoted, since the chopper control of the field excitation is direct.

For braking below the base speed, it is necessary to increase the gain by about 30 dB over the entire frequency range up to about 3kHz (at which frequency a noise limiting filter begins to have effect) since the chopper's control of the field excitation is then inverse. The gain must be greater than that of the chopper plus motor system without being so large that excessive current ripple is produced, and it is increased in proportion to motor speed (the 30 dB quoted above being at the base speed). Furthermore, since the motor's magnetisation characteristic and inductance are both functions of current, the gain must be adjusted according to the effort demanded; but the modification of gain at 10 Hz used in the low gain mode is not needed because the greatest possible regenerated current falls approximately linearly with speed as motor current is progressively diverted to the *store* function.

The complete control system is illustrated in Fig. 11. The transition between low and high speed gain modes is triggered by a detector fitted across diode DA. The trigger signal is modified by a low pass (15 Hz) filter, again to prevent *limit cycle* operation. The signal labelled "a" is the conduction ratio of the resistor chopper (ie of T1) and "b" is the conduction ratio of the main chopper (ie of T2).

It is necessary to match the servo characteristics most carefully to the particular motors and input filter used in each application. It is important that the chopper be capable of a sufficiently low minimum output. At high speeds the circuit stage shown in Fig. 9, diagram (b) is omitted; sufficient energy is transferred to the field from the commutating capacitor K1 alone during stage (c), without firing T2 at all. The energy transferred from the capacitor may be adjusted by delaying firing T3 and first recirculating some or most of the capacitor charge via inductor L1 as shown in diagram (g). When T3 is eventually fired (diagram (h)), a reduced amount of energy is transferred to the field. Circuit stages (g) and (h) replace (b) and (c) at the highest speeds.

CONCLUSIONS

A regenerative braking system for a dc series motor has been described in which both controllers (for the motor and for the blended rheostatic braking) are combined in a single thyristor chopper circuit at low cost. Advantage can be taken of the continually varying receptivity to regeneration of the line supply, with as low a rheostatic *blend* as is consistent with system stability, and gaps in the conductor rail can be negotiated without cessation of braking effort and with the application of acceptably small transient over-voltages to the train-borne auxiliaries.

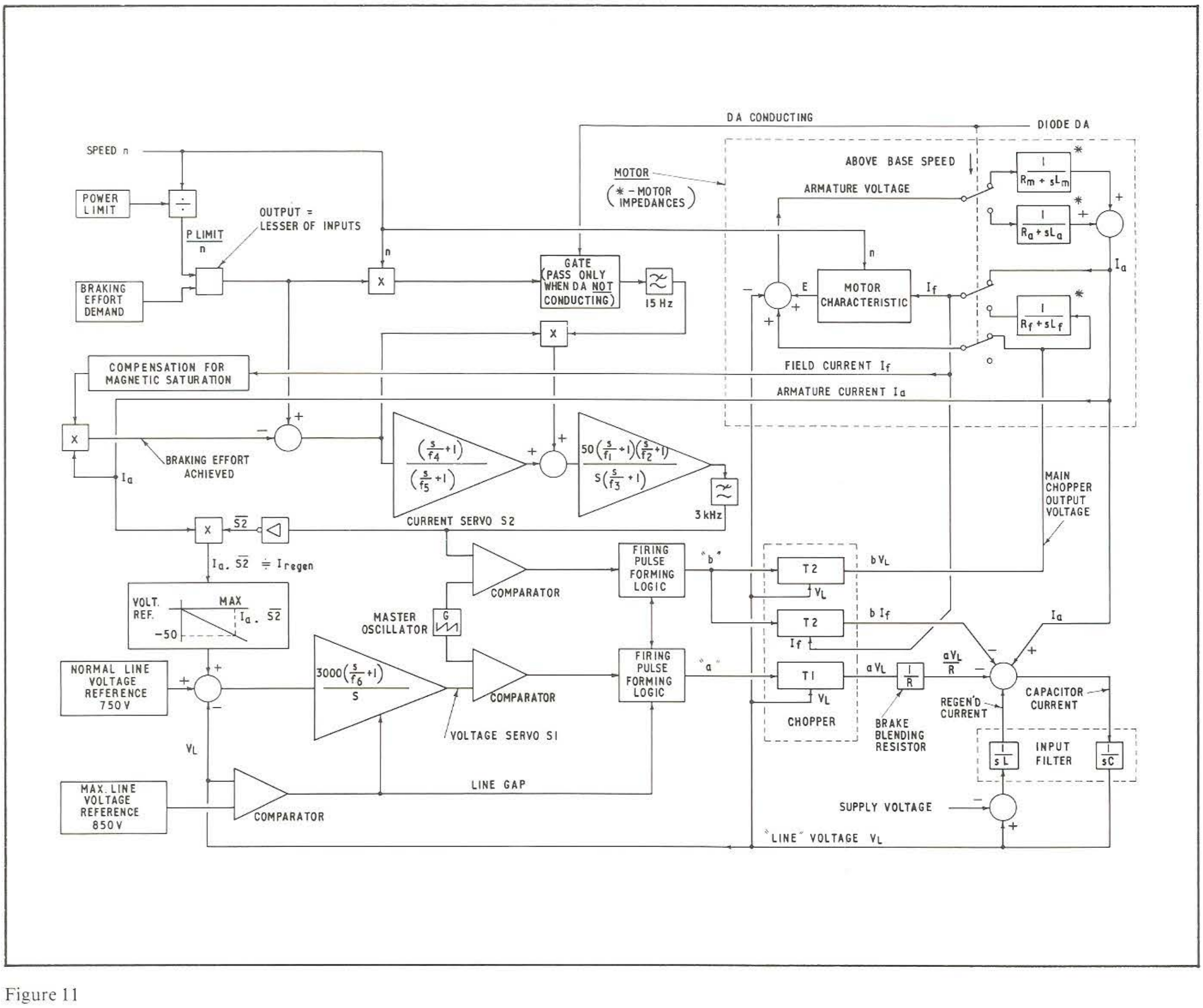

Figure 11

The system described also features an automatic change from weak-field operation, in which the motor is separately excited, above its base speed, to full series field operation below the base speed. This feature enables sudden changes in line voltage to be accommodated with little perturbation of braking effort, and it removes the need, usual with separate excitation schemes, for a large motor smoothing choke while retaining the control advantages of separate excitation of a high susceptance field at high speeds.

Reference

1. Wagner, R. and Wolski, A., 1964 "Batterie-Triebfahrzeuge mit Gleichstromsteuerung uber Silizium-Stromtore", *Elektrische Bahnen, Vol. 35, No. 10, p.p. 294-301.*

Zussammenfassung

Dieser Artikel befaßt sich mit einem Nutzbremssystem für mehrteilige Triebwagen erlautertam Beispiel von Ausrüstungen, die an die niederländische, dänische und britische Staatsbahn geliefert wurden. Das System basiert auf dem Einsatz eines herkömmlichen Gleichstrom-Reihenschußantriebsmotors und eines Thyristorstromstellers. Es wird für elektrifizierte Strecken mit 600/700 V und 1500V verwendet.

Es ist allgemein bekannt, daß zur Gewährleistung einer stabilen Rückgewinnung bei Drehzahlen über dem charakteristischen Vollfeldmotorwert entweder das Feld geschwächt oder Widerstand in den Stromkreis gegeben werden muß. Auf Energieeinsparung ausgerichtete Eisenbahngesellschaften haben sich meistens für eine Schwächung des Feldes entschieden, wo das höchste Potential zur Rückgewinnung liegt; bis jetzt wurde sie jedoch entweder auf herkömmliche Art (Schaltwiderstände parallel zum Feld) oder durch Einsatz eines fremderregten Motors realisiert.

Die Funktion des Stromkreises im hier beschriebenen System ändert sich automatisch vom fremderregten Schwachfeldmodus zum Vollfeld-Reihenschlußmodus, und zwar bei Erreichung der charakteristischen Motordrehzahl. Bei höheren Drehzahlen liefert der Zerhacker die erforderliche geschwächte Felderregung von der Gleichstrom-Fahrleitung bzw. der Stromschiene. Bei niedrigeren Drehzahlen funktioniert der Zerhacker wie üblich als Umformer, um die bei relativ niedriger Spannung erzeugte Motorenergie mit höherer Spannung zurückzuführen.

Die Alternierung dieser beiden Betriebsformen im gleichen Stromkreis, die außerdem ein automatisches Mischen von Widerstands- und Nutzbremsung ermöglichen kann, wenn die zurückgewonnene Energie nicht aufgenommen werden kann, war bisher noch nicht im Eisenbahnbereich zu finden. Dieses System führt zu einer stabilen, flexiblen Bremsausrüstung zu niedrigen Kosten bei hoher Leistungsfähigkeit.

Sumario

En este tópico se describe un sistema de frenado por recuperación para trenes de unidades multiples, ejemplificado por los equipos suministrados a los ferrocarriles de Holanda, Dinamarca, y del Reino Unido. El sistema está basado en la utilización de un motor de tracción normal, de c.c. en serie, junto con un interruptor rotatorio de tiristor, lo que ha sido utilizado en los ferrocarriles electrificados a 600/750 V y 1500 V.

Está bien conocido que para asegurar la regeneración estable a velocidades por encima de la caracteristica de pleno campo del motor es necesario debilitar el campo o, de otro modo, introducir resistencia en el circuito. Las administraciones ferroviarias conscientes de la energia han sido partidarias de la solución de debilitamiento del campo, que más possibilidades tiene para la recuperación, pero hasta ahora esto se ha llevado a cabo por los medios clásicos (resistencias conmutadas a través del campo), o mediante la utilización de un motor de excitación independiente.

En el sistema descrito por el tópico, el funcionamiento del circuito principal se cambia automáticamente del modo de campo debilitado de excitación independiente hacia el modo de pleno campo en serie, a la velocidad caracteristica del motor. Por encima de ésta velocidad el interruptor rotatorio hace alimentar la excitación debilitada necesaria con c.c. de la linea aérea o del tercer carril; a velocidades más bajas el interruptor rotatorio funciona como transformador en la forma acostumbrada y asi permitir el retorno de la potencia motriz generada a tensión relativamente baja hasta la linea de tensión más alta.

Hasta ahora todavia no habia sido utilizada en la tracción ferroviaria la alternancia de estos dos modos de operación dentro de un mismo circuito principal (que además puede facilitar la mezcla automática del frenado reostático y regenerativo para casos de encontrarse la linea no-receptora de la energia de retorno). Tiene por resultado un sistema de frenado estable y flexible, a bajo precio y de alto rendimiento.

Résumé

Le document décrit un système de freinage par récupération pour trains à unités multiples, illustré par l'équipement fourni aux chemins de fer de la Hollande, du Danemark et du Royaume-Uni. Le système est basé sur l'utilisation d'un moteur traditionnel en série à c.c. avec un écrêteur à thyristor et a été utilisé sur les lignes de chemin de fer électrifiées de 600/750V et 1 500V.

Il est bien connu que pour garantir une régénération stable à des vitesses supérieures aux caractéristiques du moteur à champ complet, il faut soit affaiblir le champ, soit introduire une résistance dans le circuit. Les services administratifs, conscients de la crise de l'énergie, out préféré la solution qui consiste à affaiblir le champ et qui offre la plus grande possibilité de régénération, mais jusqu'à présent ceci a été fait par des moyens traditionnels (résistances commutables sur le champ) ou par l'utilisation d'un moteur à excitation séparée.

Dans le système décrit ici, le circuit passe automatiquement d'un mode à excitation séparée à champ faible à un mode en série à champ complet, à la vitesse typique du moteur. Au-delà de cette vitesse, l'écrêteur fournit l'excitation voulue du champ faible par le câble aérien de c.c. ou par le 3e rail; à des vitesses plus basses, l'écrêteur agit normalement comme un transformateur, permettant à la puissance du moteur, produite à un voltage relativement faible, de retourner vers la ligne à un voltage plus élevé.

Le passage d'un mode à l'autre dans le même circuit (qui peut aussi fournir le mélange automatique d'un freinage par résistance et par régénération au cas où la ligne ne serait pas réceptive envers l'énergie de retour) n'a pas été appliqué jusqu'à présent à la traction des chemins de fer. Il en résulte un système de freinage souple, stable et très efficace à un prix intéressant.

Based on a paper by J.M. Whiting BSc(Eng) of GEC Traction. The paper was presented to the Conference on Electrical Variable-Speed Drives organised by the Institution of Electrical Engineers in association with the Institute of Physics in London, 25 - 27 September 1979

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