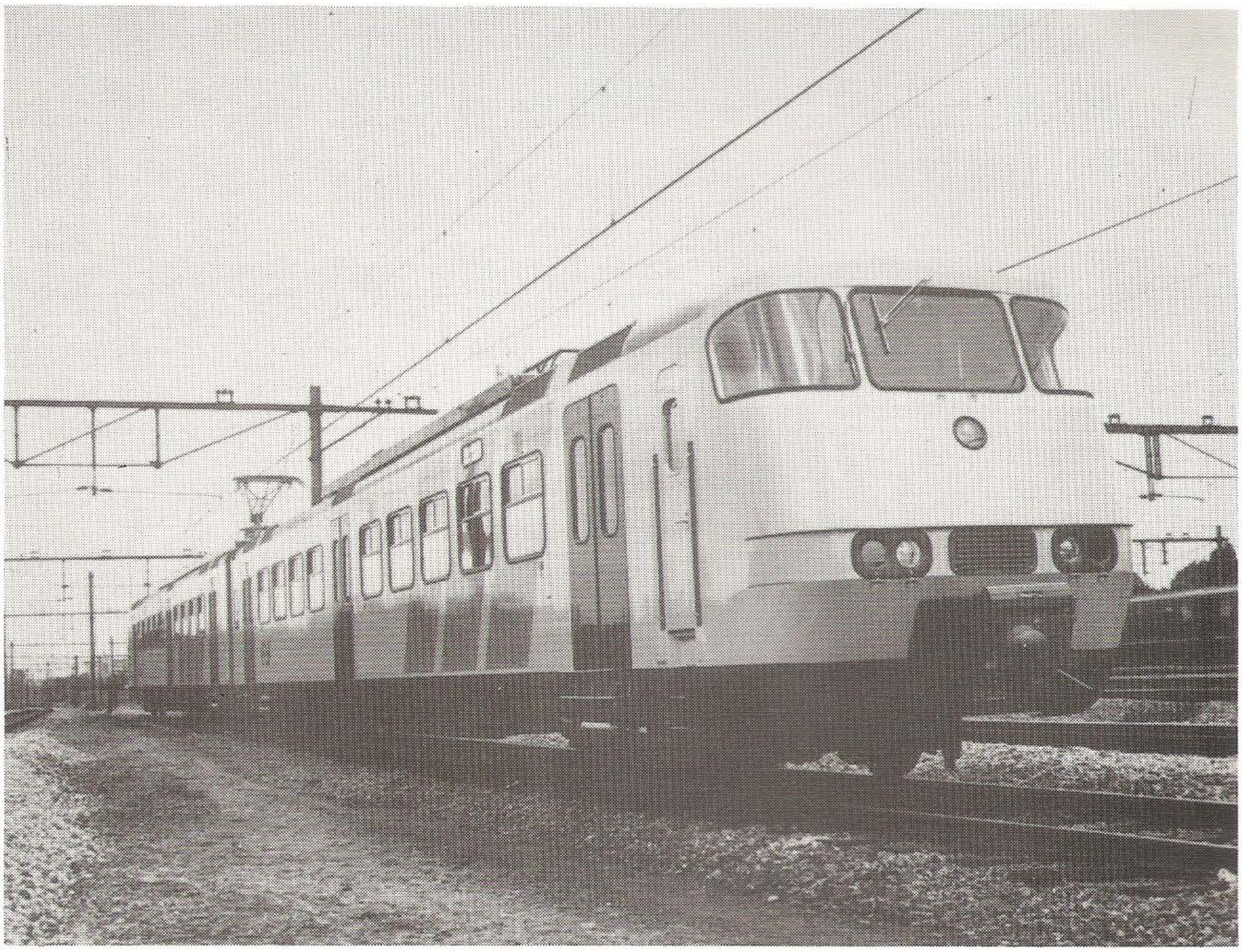
1500v choppers with rheostatic braking for Netherlands Railways

GEC Traction Limited

GEC TRACTION CHOPPER CONTROL FOR NETHERLANDS SPRINTER STOCK



The SPRINTER stock is a two-car train set intended primarily for providing a fast, frequent service on lines in Holland's western conurbations and in particular on a new line specially built to serve the growing town of Zoetermeer near the Hague. The specification calls for an interstation time of 92 seconds with 1500m between stops. To meet this duty, accelerating and braking rates of $1 m/s^2$ are required, irrespective of load, and all eight axles are motored. Braking is by blended disc and rheostatic brakes, with the rheostatic brake providing up to $0.7 m/s^2$ retardation.

In appearance as well as technical specification, SPRINTER makes a break from the ½-axles motored T and V stock now familiar throughout Holland. Sprinter is above all a rapid-transit stock and has 6 doors per car (instead of the V-stock's four) and other features which increase both the passenger capacity (294 per unit) and the rate of loading at stations.

SPRINTER has also been designed to meet an interurban stopping train duty, which requires a top speed of around 120 km/h (100 km/h would suffice for the rapid transit duty) and a relatively high standard of passenger comfort. For this duty, the SPRINTER train would leave the terminal station just after a fast inter-city train, and after stopping at every intermediate station, would arrive at the destination city just before the next inter-city express. Trains may consist of up to 3 units in multiple.

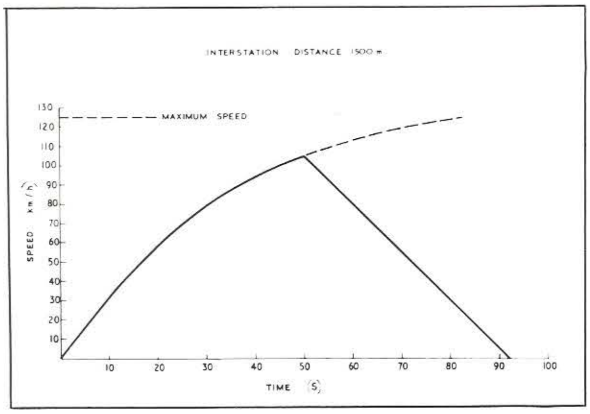
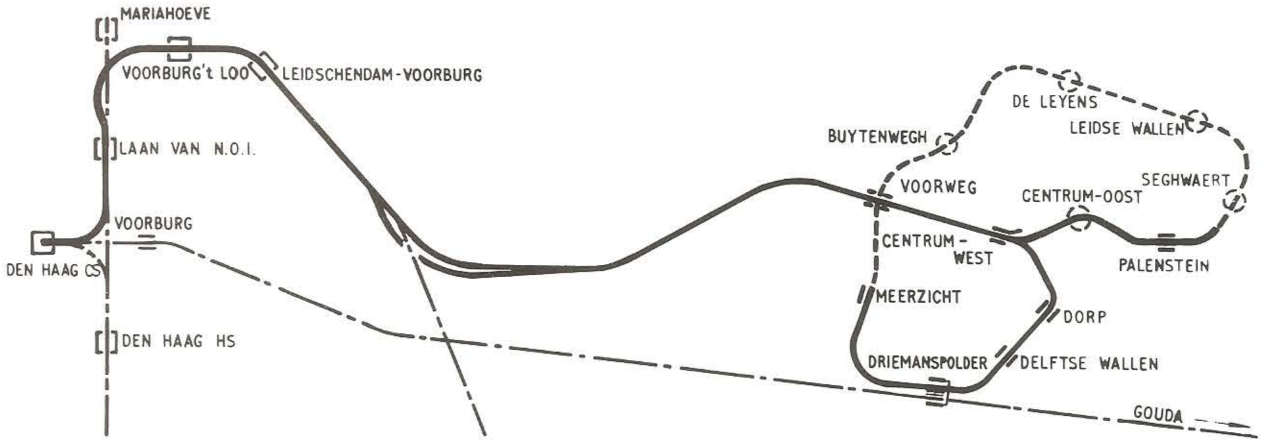


Figure 1 Speed/time curve for inter-station spacing of 1.500m.

The proto-series of SPRINTER consists of 15 units, of which two have chopper control equipment supplied by GEC Traction, while the remainder have conventional control equipment. The chopper equipment design follows logically from the programme of chopper development carried out jointly by GEC and Netherlands Railways on the test car "Jules" (a converted Postal car) since 1967.

The development began with a motoring-only chopper equipment, which led in 1970 to the supply of two GEC chopper equipments for the V6 stock. These equipments have since completed more than 1.3 million km in regular service, and



Route plan showing initial route for Sprinter trains and proposed extensions

are providing valuable information on long term reliability of the control electronics and the power components. The amount and frequency of routine checking has been progressively reduced as experience has grown.

Meanwhile, the Postal car was converted to a rheostatic braking scheme, and the experience gained through extensive trials led in turn to the supply of the GEC choppers with rheostatic braking for SPRINTER. More recently, the Postal car has been yet again converted, this time to a composite or blended regenerative-rheostatic braking system.

The SPRINTER equipment, like the V6 before it, is underframe mounted. The continuous improvement in thyristor performance during the last ten years has enabled the physical size of the SPRINTER choppers to be considerably reduced; it uses only 1/3 the number of main thyristors that the Postal car used, and yet has an accelerating current 1½ times greater. In addition, the power capacitors (i.e. the filter and commutating capacitors) can now be mounted as an integral part of the chopper equipment case.

SYSTEM TESTING

A thorough combined test of choppers and motors was carried out on the flywheel test facility at GEC's Preston works. The required 1500m duty cycle could be simulated and thermal performance of the chopper could be checked under controlled and repeatable conditions. In one test, the equipment was run at 160% of its continuous rating for 4 hours, and all choppers were checked at 115% of full load current as a routine test.

The stability of the control system and the correct functioning of the electronic logic were rigorously tested. Motor commutation was very good at all speeds in motoring and braking. The noise of the chopper was recorded and analysed (fig. 3); a new type of saturating choke has been

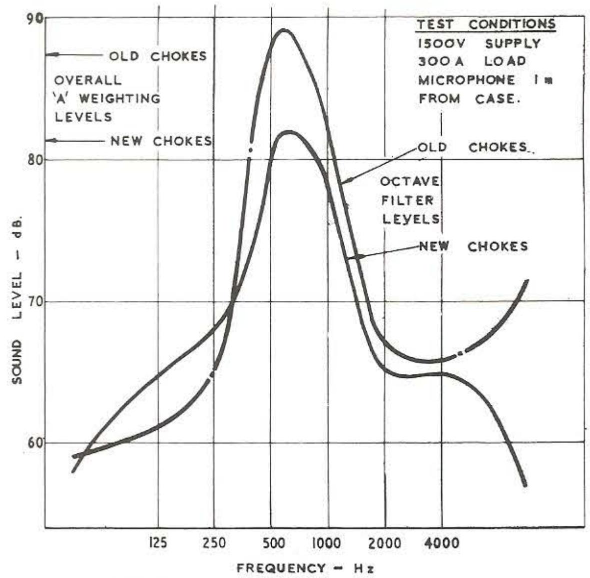


Figure 2 Sound level characteristics for a chopper equipment case.

used on SPRINTER which has led to a marked reduction in noise, as well as improved electrical efficiency, compared to previous designs.

Among the fault conditions simulated was 'lock-on' of the chopper when braking at high speed, to test the efficacy of the protection circuit (described later). The firing pulses to the turn-off thyristors were manually interrupted, and the ensuing rapid sequence of events was 'captured' on a high speed tape recorder for later play-back at slower speed on to an ultra-violet oscillograph for study. The test was repeated many times, without detriment to any of the equipment. The protection circuit controlled the armature current so quickly that no harm was done to the motors or choppers (or to the protection circuit itself) and when the braking contactors opened they had only to clear a small current.

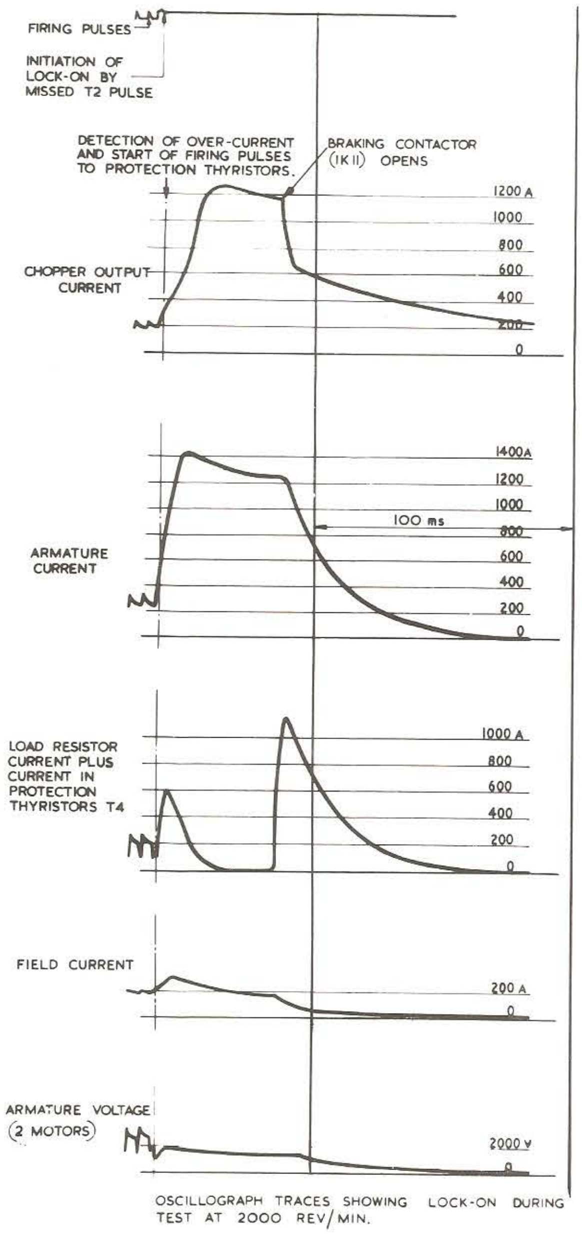


Figure 3 Osillographs showing the sequence following lock-on during tests at 2000 rev/min.

DESCRIPTION OF POWER CIRCUIT

The power circuit is shown in fig. 4, which is for one car of a two car unit. A single filter and single overvoltage protection circuit provide for two choppers, each of which feed two traction motors connected in permanent series. The motors operate always with a resistive field divert of 7%, which ensures that field current ripple is very small. The smoothing chokes 1L1, 1L2 keep the armature current ripple below 50%. Three stages of conventional field weakening are possible, and are used when the chopper is full on, i.e. when the main thyristors are switched on continuously. These notches correspond to the parallel weak field notches of the conventional units, but the series weak field notches can also be simulated (as can the shunt notch) as described below ('speed control').

The filter consists of the line choke 1L3 and the filter capacitor 1C17. The capacitor is in two parallel-connected halves mounted in the chopper equipment cases. The chopper cases are identical, but the thyristor firing pulses to them are in anti-phase, so as to lessen the filter duty.

The armature and field currents are individually monitored by the isolating transducers 1U1-1U4. These signals are taken to the main control electronics, where they are used to control the tractive or braking effort according to the demand. The other feedback signals from the power circuit are line voltage, digital over-temperature signals from the main thyristor strings, and signals which monitor the correct commutation of the choppers.

The braking overcurrent protection circuit consists of the thyristors T4 and T5. The armature current during braking is normally about 300A maximum but if it should exceed 400A, the thyristors T4 and T5 are fired, the effect being to reverse the voltage applied to the traction motor fields, thus forcing the currents to decay very quickly. At the same time, an electronic signal is given to open the braking contactors 1K11, 1K12, in order to clear the residual current.

The overvoltage protection circuit 1F19 consists of the thyristors T3 and the nonlinear resistor ('Metrosil') 1V3. The voltage on the filter capacitors is electronically monitored, and the thyristors are fired if the voltage exceeds 3700 volts. At this voltage the Metrosil takes a very large current (about 2.5 kA) and rapidly discharges the filter capacitors and protects the choppers and motors. The metrosil return current is not taken through the differential relay 1F1 negative coil, and so this relay trips the high speed circuit breaker 1F3 which finally clears the fault. The firing pulse generators for the overcurrent and overvoltage protection circuits are mounted on their respective equipment panels and are independent of the main electronics frame, which is in the cab. The electronics for the final amplification of the chopper firing pulses, including noise rejection and speed-up of the pulse leading edge, is also remote from the main frame, and is inside the chopper equipment cases, with separate power supplies.

The same type of thyristor is used in series pairs for T3, T4 and T5. These devices do not require heatsinks, and so the protection circuits are compact units which are mounted inside the main equipment case on the underframe.

The chopper is also protected by high speed fuses 1F21. These have a valuable secondary function of protecting the traction motors, by limiting the fault current, in the event of motor flashover. The filter itself also protects the motors by acting as a buffer to the worst voltage surges on the traction supply, and reduces the incidence of motor flashover considerably.

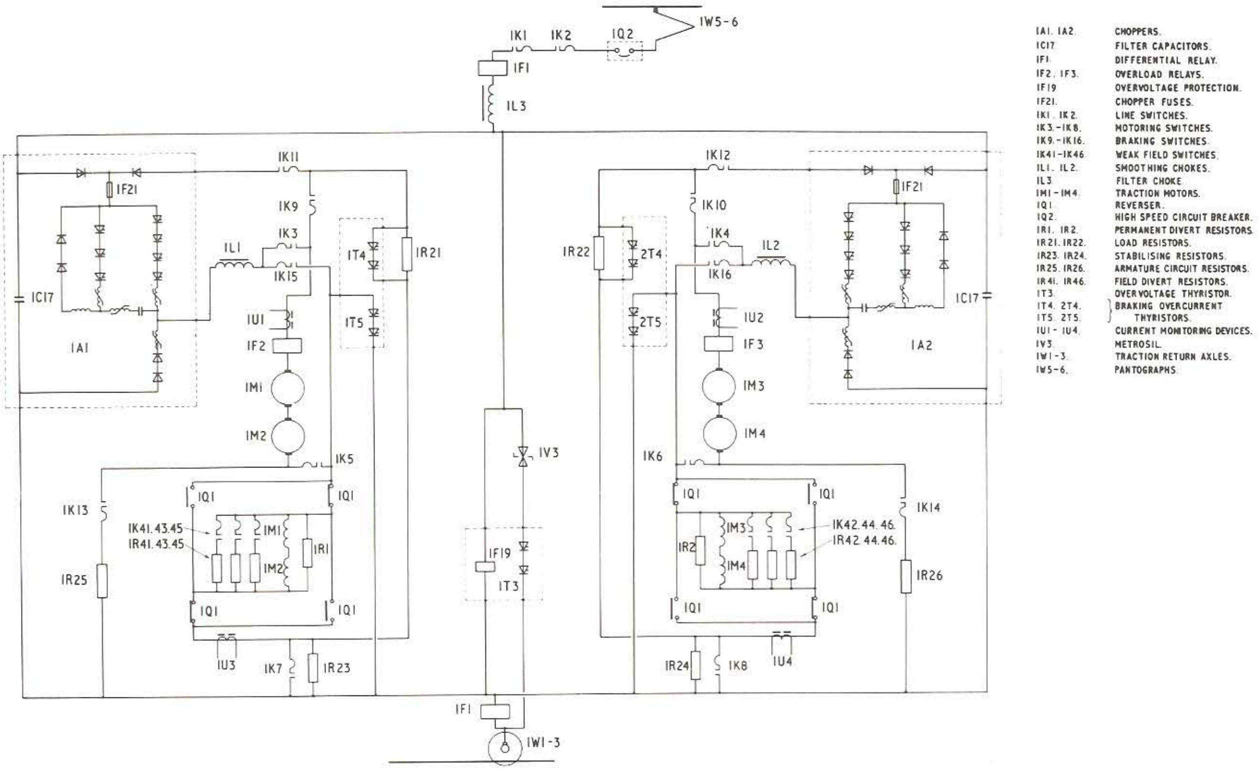


Figure 4 Simplified power schematic.

FILTER

Each SPRINTER chopper car has a low pass filter feeding two chopper groups,i.e. 4 motors.

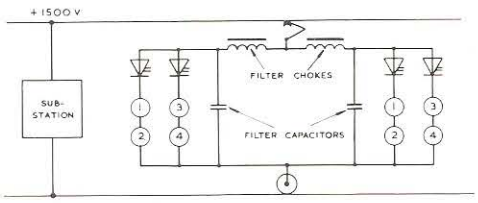


Figure 5 Filter circuit.

The filter is required to perform several distinct functions and the values of it's components are thereby constrained, so that the available choice of combinations of capacitance, inductance and the inductors's resistance, is strictly limited. The choice is further narrowed by considerations of space, weight and cost.

The functions that the SPRINTER filter, in common with any other chopper filter, must perform are:-

1 To present a certain minimum impedance (inductive) to the 50Hz and 75Hz ripple on the traction supply, so as not to interfere with signalling equipment operating at those frequencies.

2 To limit the line current ripple at the chopper operating frequency (and its harmonics) to a low value, also for signalling and telecommunications reasons.

3 To pass the d.c. line current to the chopper and motors with a low voltage drop, so that train performance is not appreciably effected.

4 To present a low-impedance (capacitive) source to the chopper, to allow it to draw square pulses of current.

It is the first of these 4 functions which generally determines the values of the filter components in practice.Currents at the mains frequency and its harmonics flow in the line to the chopper car. In practice, balanced conditions generally do not exist in the a c supply at the substation, and the rectified d c traction supply consequently includes ripple components at 50Hz, 100Hz, etc., as well as the normal 300Hz ripple due to 6-phase rectification. On the Nederlandse Spoorwegen 1500V system a component at 75Hz is also present. The chopper car presents a certain impedance to these a.c.components, due to its input filter, and consequently alternating currents flow in the line.

If the signalling system frequency is 50 or 75Hz, the amplitude of the alternating currents at those frequencies must be limited to prevent any possibility of interference with the signalling system. A minimum impedance at (say) 50Hz is specified by the signalling department. To meet this specification requires a certain minimum value of filter inductance because, although it is only the magnitude and not the phase of the alternating current which has to be limited, if the filter alone had a capacitive reactance the inductance of the overhead system would make the overall impedance fall to nearly zero at some definite distance from the substation;therefore the input impedance of the chopper car by itself must in practice always be inductive.

The input impedance of the chopper car is modified by the effective impedance of the motor groups appearing in parallel with the filter capacitor, and to arrive at the correct minimum filter inductance, for the chosen value of filter capacitance, requires a detailed analysis of the effect of chopper on-ratio on the filter input impedance. The possible minimum combinations of inductance and capacitance required are shown in fig. 6 (curve 1). Any inductance/-capacitance combination above curve 1 would fulfill the first function, but naturally considerations of cost, space and weight will mean that the chosen combination will lie as near to curve 1 as possible. The minimum combinations required by functions 2 and 4 are also shown in curves 2 & 4.

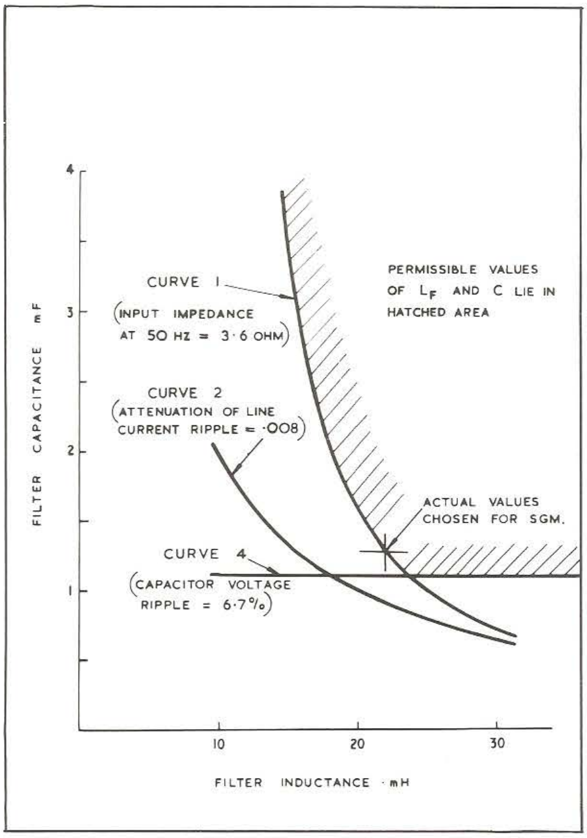


Figure 6 Filter inductance and capacitance.

The specification for the first function was given by NS, who were able to use the data gathered through tests on the Postal car and V6 stock choppers as a practical basis. A comprehensive series of measurements of chopper line current, were carried out on NS behalf by KEMA (the Netherlands Electrical Standards Institution) and measurements at the substations and track-side were also made by NS and the PTT. The SPRINTER specification for filter impedance was 0.6 ohm at 50Hz for 3 trainsets in multiple, i.e. 3.6 ohm for each filter.

The specification for the remaining functions were drawn up by GEC Traction on the basis of their experience. The specification for line current ripple was in terms of an attenuation FactorA.

$$A = (f_o / nf_c)^2$$

where f_o = resonant frequency of filter
f_c = chopping frequency
n = number of chopper groups per filter.

The factor A is the ratio of the line current ripple to the chopper current ripple. A value of .008 was chosen, so that

$$CL_F = \frac{1}{.008\ (2\pi nf_c)^2} = 20 \times 10^{-6}$$

The voltage drop due to the line choke is generally set at about 4% of line voltage at maximum line current. For SPRINTER, with maximum line current 560A a line choke resistance of 0.1 ohm was specified.

Finally, the fourth function was specified as a maximum voltage ripple on the capacitor of 6.7% (i.e. 200V), which requires a capacitance of 1.1mF.

The above figures for attenuation factor and voltage ripple are on the basis of a chopper frequency of 200Hz. If the chopper frequency is lower, these figures will be higher. In fact, the SPRINTER choppers use a frequency of 100Hz at starting, but the change to 200Hz is accomplished at a low on-ratio (and therefore low line current) and so the current and voltage ripples are less than the maxima produced at 200Hz, which occur at on-ratios of ¼ and ¾.

The transition from 100 to 200Hz is made as soon as possible during acceleration without producing any change in tractive effort. The control electronics adjusts the point of transition to compensate for changes in line voltage and accelerating current.

SPEED CONTROL

An advanced system of speed control is used (Fig 7) in which the driver has three options open to him:

- the 'economic' programme where the train will accelerate to the selected speed, and then coast until the driver makes the brake application for the next station;
- constant speed where the train will accelerate to the selected speed, and then will maintain this speed within 5km/h by motoring or braking automatically as required;
- manual control with the normal control handles.

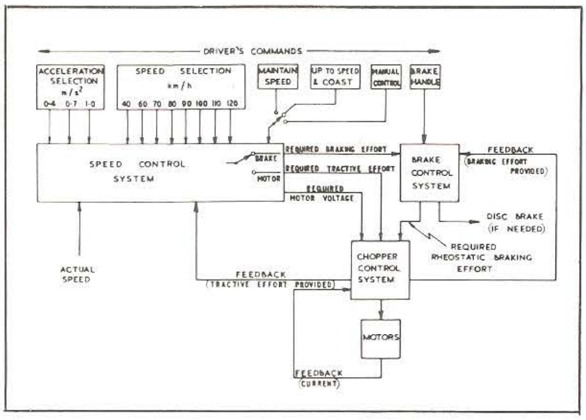


Figure 7 Schematic diagram of control system showing details of speed control feedback.

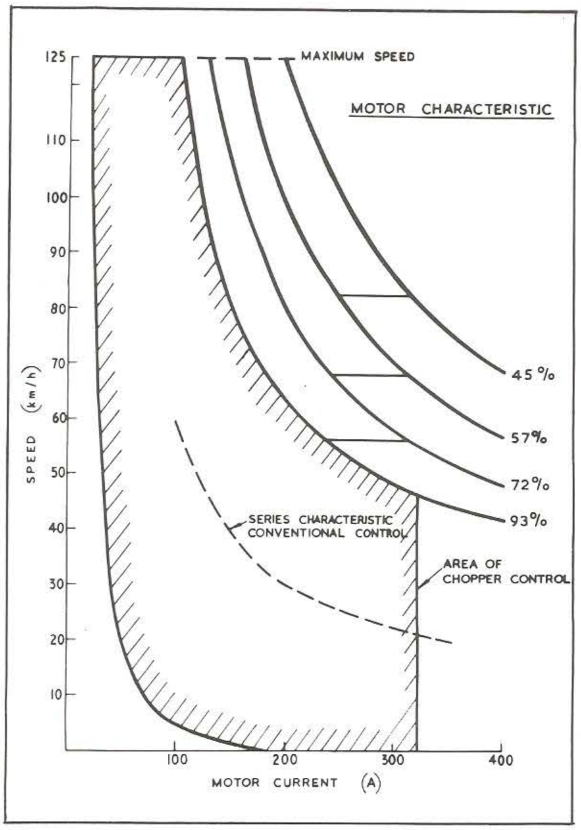


Figure 8 Motor characteristic slowing area of chopper control.

The driver has available, through push-buttons and switches, 3 acceleration rates and 8 speed selections, and on the brake handle, 7 stages of braking effort. Changes in acceleration or braking rates are automatically governed to less than 1m/s³ to increase passenger comfort.

The chopper's ability to control the motors efficiently at any point under their speed-current characteristic is a clear advantage in a system of this kind. Historically NS have used 3 or more stages of field weakening, in the "series" connection to increase the number of possible economic running notches below the full-voltage "parallel" notch. The chopper provides an infinite number of economic running "notches" (see Fig 8)and is thus able to match the required tractive effort exactly at any of the selected speeds. In conventionally-controlled SPRINTER units, the required motor voltage (and therefore the required tractive effort) can only be matched approximately, because of the limited number of available notches.

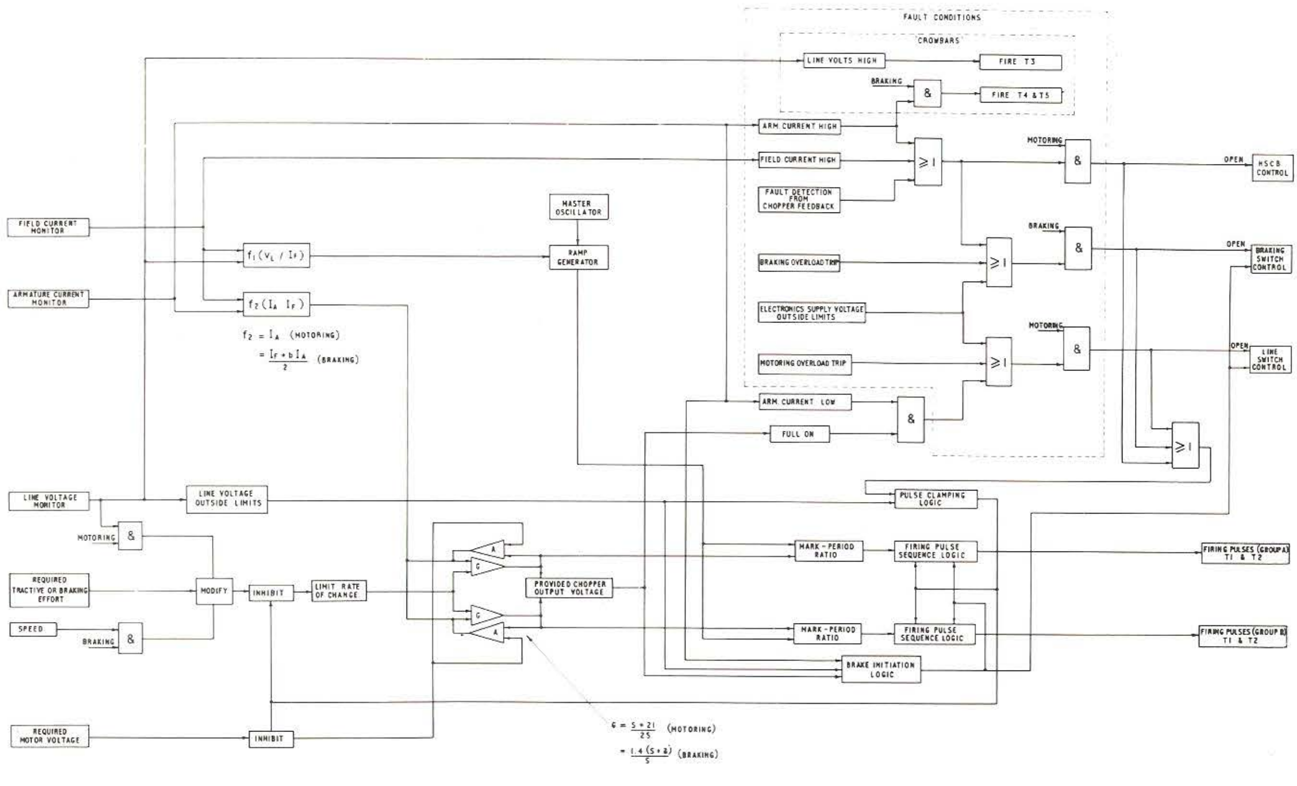


Figure 9 Electronics block diagram.

At the same time, there is no difficulty in making the chopper mimic a conventional trainset when required for multiple-unit operation, and indeed the SPRINTER chopper units, like the V6 stock choppers before them, will multiple with their conventional counterparts. Simulation of field weakening is provided by means of increasing the "required voltage" signal in the control electronics. Thus if the chopper unit is multipled with a conventional unit which is in series, 45% field, notch the "required motor voltage" signal will be equivalent to 50% of line voltage, plus an allowance for the field weakening. The chopper will respond with a mark-period ration greater than 50% (in fact about 67.5%)such that although the chopper unit's motors are still in full field, their tractive effort exactly matches the conventional unit's motors' effort. The chopper mark/period ratio is automatically compensated for changes in line voltage and train speed by means of the V_L/I_F function generator (see the electronics block diagram, Fig. 9).

The chopper output, i.e. the voltage applied to the motors, appears as in Fig.10. The main thyristors are conducting during the period t_1 and the auxiliary thyristors are conducting during the period t_2. For the remainder of the chopper cycle, all thyristors are off, and since motor current can circulate via the free-wheel diodes, the effective motor voltage during this latter period is nil.

The voltage during period t_1, is simply the line voltage, V_L

The voltage during the period t_2 is due to the commutating capacitor in the chopper discharging linearly from twice line voltage to nil. The current flowing in the capacitor is motor current, which is almost constant during the short time taken to discharge the capacitor (the length of t_2 has been exaggerated in Fig.13 for clarity). Therefore the average voltage during period t is V_L, and

$$t_2 = 2CV_L/I_F$$

where
C = capacitance
V_L = line voltage
I_F = motor current

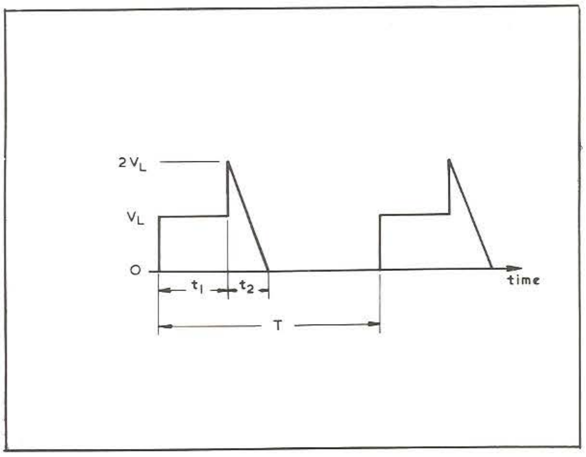


Figure 10 Chopper output voltage.

In practice the value of V_L is somewhat higher than line voltage due to over-charging of the capacitor because of various inductances in the chopper. The current I_F must be taken as the peak value of motor current allowing for current ripple in the motor circuit.

The average motor voltage over the whole cycle is

$$(V_L t_1 + V_L t_2)/T$$

and so the main thyristor on-time required for a per-unit motor voltage of U is

$$t_1 = U.T. - \frac{2CV_L}{I_F}$$

T and C are constants of the chopper, but both V_L and I_F are variable, and the function V_L/I_F must be computed before correct on time t_1 can be found for the required value of U. This is the purpose of the V_L/I_F function generator.

BRAKING CHARACTERISTICS

The armature and field currents necessary to produce a constant retardation are governed by the law

$$I_A.E_A = \text{constant}$$

where E_A = armature voltage
= function of I_F and I_A

In the SPRINTER stock, this law has been replaced by the formula

$$1.113\, I_A + I_F = \text{constant, C} \quad (1)$$

This formula is a good approximation to the true law over a certain range of speeds, provided that the constant C is carefully chosen and this is illustrated (in Fig.11) for the case of the highest electric braking rate (notch F5), for which C = 478.

The field and armature current are also constrained by the way in which, in the chopper braking circuit, some of the armature current is diverted to provide the field current during the chopper on-time. Thus I_A and I_F are related at any given speed by

$$I_F/I_A = \text{constant, W} \quad (2)$$

The combined action of equation (1), due to the electronic control system and equation (2), due to the configuration of the power circuit, produces unique values of I_F and I_A at any given speed and braking rate. The practical extreme values of W are 0.35 and 1.16 and lines with slopes of 0.35 and 1.16 are drawn on Fig.11, to define the practical range of operation. The true speed-current characteristic is shown in Fig.12 (drawn for C =478). This characteristic was originally predicted by a computer programme which analysed the braking circuit in stepwise fashion by breaking it down into the 5 modes discussed in the following section.

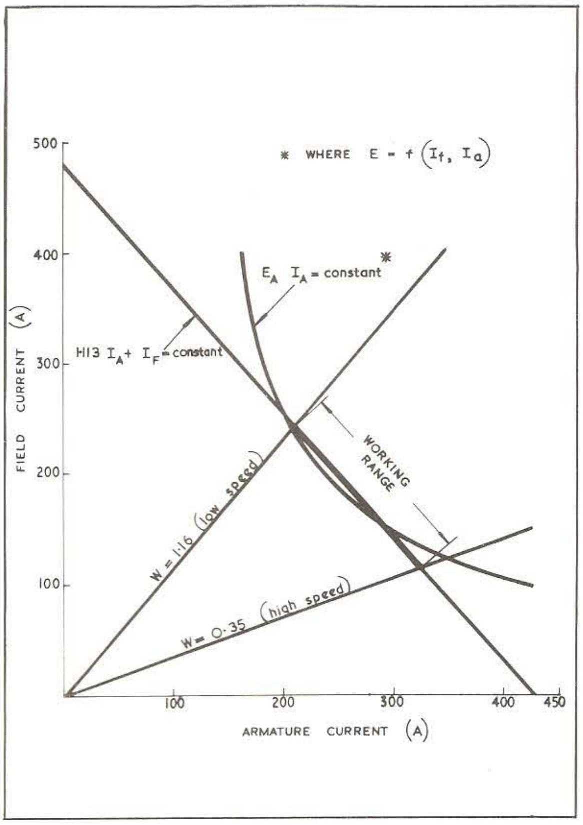


Figure 11 Braking characteristic.

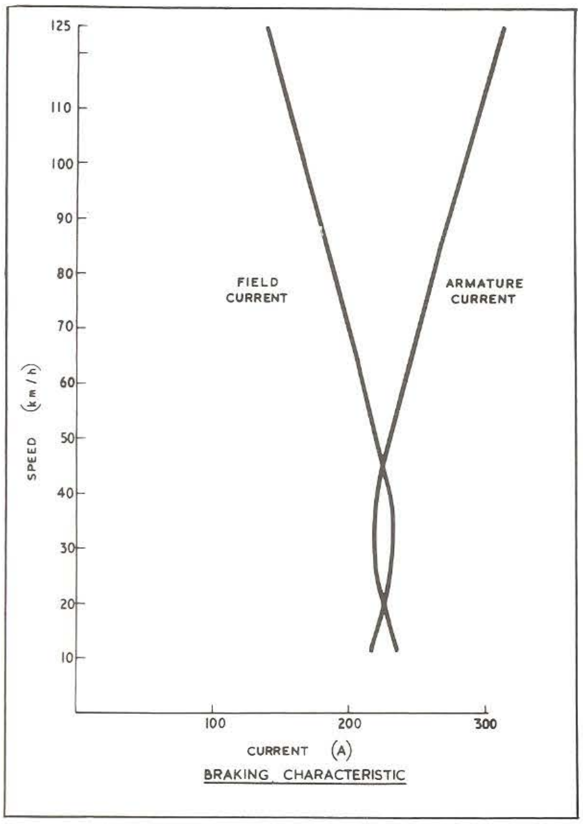


Figure 12 Braking speed-current characteristic.

OPERATION OF THE RHEOSTATIC BRAKING CIRCUIT

Referring to figure 13, it can be seen that the braking circuit goes through 5 different modes during each cycle of the chopper.

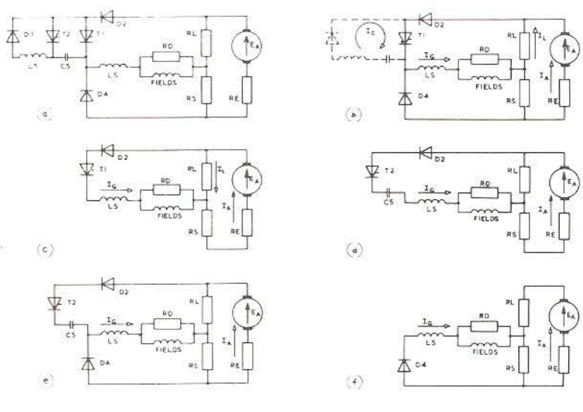


Figure 13 Sequence of circuit diagrams showing operation in rheostatic braking mode.

A simplified braking circuit schematic is shown at (a) and the parts of this which are active during each of the 5 modes are shown in diagrams (b) to (f).

In brief, the armature current rises during modes I, 2 and 3,and falls during modes 4 and 5. Its rate of rise and fall are governed by the train speed and its average value by the duration of modes I and 2, i.e. by the chopper on-ratio.

The cycle starts (diagram b, mode 1) when the main thyristor T1 is fired. The circuit formed by T1, D3, L5, and C5 at once comes into play and a current I_C flows until the charge on the capacitor C5 (which did have its left-hand plate positive with respect to its right, see description of diagram (e) below) is reversed. The diode D3 then blocks and is inactive until the next cycle.

Meanwhile in mode 1 in the main braking circuit, T1 is also conducting the armature current I_A. It has been assumed in diagram (b) that I_A is less than the smoothing choke current I_G; this will generally be the case except at the highest speed. The freewheel diode D4 is therefore called upon to conduct the difference current I_G-I_A. The voltage between D2 anode and D4 anode is thus very small (a few volts only) so that external armature voltage is approximately I_A.RE (say 150 volts). The armature current rapidly rises as it flows through the effective short-circuit formed by the chopper, while I_G decays slowly.

As soon as the armature current I_A becomes greater than $I_G \frac{RL}{RL+RS}$, the freewheel diode D4 blocks and the next mode (mode 2) is entered (diagram c). The current in RL now quickly changes to its normal direction and builds up (it is I_A-I_G), so that the voltage across the smoothing choke and fields rises to several hundred volts. Therefore I_G begins to increase and although it always lags behind I_A, the difference between the two and thus the load resistor voltage, tends to become constant at about 600 volts.

The third mode (diagram d) begins when the thyristor T2 is fired and connects the commutating capacitor C5 in circuit. The main thyristor T1 is extinguished and a step increase in voltage is applied to the left-hand end of the smoothing choke LS. Most of this step increase in voltage is taken by the choke and not the fields, which are shunted by RD.

As the capacitor discharges, the voltage across the smoothing choke plus field eventually becomes negative and when it equals - I_A.RS the freewheel diode D4 starts to conduct again. The circuit is then in the fourth mode (diagram e). The capacitor continues to discharge, but now at a decreasing rate because current can now flow in D4. Thus the capacitor current falls from I_G to nil when D4 current rises from nil to I_G. This requires that load current should rise again from $I_A - I_G$ to I_A and that stabilising resistor (RS) current should rise from I_A to $I_A + I_G$. At the finish of mode 4, the voltage across the capacitor C5 is relatively high (about 1800V). It is inverted by the chopper at the start of the next cycle and used in mode 3 to provide reverse-bias voltage for the main thyristor. In practice, mode 4 does not end immediately when capacitor current becomes nil as, due to inductance in the chopper, the capacitor current tends to reverse and its charge to increase further, until diode D2 blocks.

The cycle is completed by mode 5, (diagram f). The armature and field circuits are now separate, apart from stabilising resistor RS which carries $I_A + I_G$. Both I_A and I_G decay during this mode, I_G mainly because of the relatively high voltage (about 140V) across RS.

The above account has assumed that I_A is less than I_G at the start of the cycle. At speeds greater than about 75 km/h, however, I_A is always greater than I_G and the cycle begins with mode 2 (diagram c) immediately. The figures quoted are for the highest braking rate of 0.7 m/sec^2.

No reference has yet been made to the actual field current I_F because the long time constant of the fields with their resistive shunt RD ensures that I_F will be almost constant and so will play no direct role in determining the duration of each mode. It is the smoothing choke current I_G which is the effective field current so far as the remainder of the circuit is concerned and the difference between I_F and I_G which may exist at any time due to the ripple on I_G flows forwards or backwards through RD without very much effect on the remainder of the circuit, although of course the average field current is thereby weakened.

ELECTRONIC SYSTEMS

The electronic systems on SPRINTER come under three main headings:-

1 The main control electronics which are in the form of plug-in modules mounted in a frame in the bulkhead of the driver's cab.

2 The thyristor firing-pulse amplifiers and associated electronics, which are mounted in the chopper equipment cases on the underframe.

3 Auxiliary electronics (the voltage and current monitoring devices and the over-voltage and overcurrent protection circuit electronics), which are mounted in the central equipment case on the underframe.

The chopper equipment has been designed to have a working life of 25 years, and the electronic systems therefore have to work reliably and without deterioration for the same period.

The practice of GEC Traction over many years in meeting the stringent requirements for traction electronic systems has been applied to SPRINTER.

1 by using only components of guaranteed quality, either to a military specification or to the new BS.9000 series of specifications;

2 by eliminating as far as possible components of high failure rate. For example, no potentiometers are used on SPRINTER, and all adjustments and calibrations have been pre-set during routine test, using metal film resistors. Reed relays are less reliable than solid state components, but where it is necessary to use them in the interface between the electronic equipment and the 110 volt contactor control gear their reliability is increased as much as possible by using only reeds with contacts rated for highly inductive loads and by running the relay coils well within their ratings;

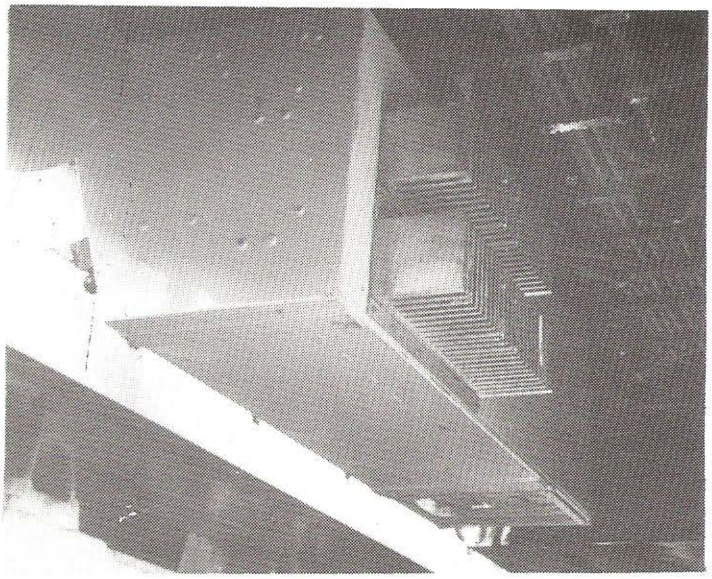
3 by derating all electronic components considerably with respect to their published ratings. A derating factor of 2 is general, and is also applied to the power semiconductors in the chopper, with respect to parameters such as thyristor turn-off time and rate-of rise of voltage withstand. The electronic operating temperature range is -20°C to +70°C;

4 by protecting the electronic system from the effects of externally produced electrical noise or voltage surges. This has been achieved by a number of means. First, by providing buffering between the 110 volt supply and the 15-0-15 volt electronic supply by a filter and inverter. Second, by providing complete electrical isolation between all electronic systems and the remainder of the train board electrical equipment. Third, by using twin-twisted and screened cable to carry electronic signals to avoid interference from the power and 110 volt circuits, and by arranging for the proper earthing of the screens of these cables at a "star point". Fourth, by designing noise immunity into the electronic circuits.

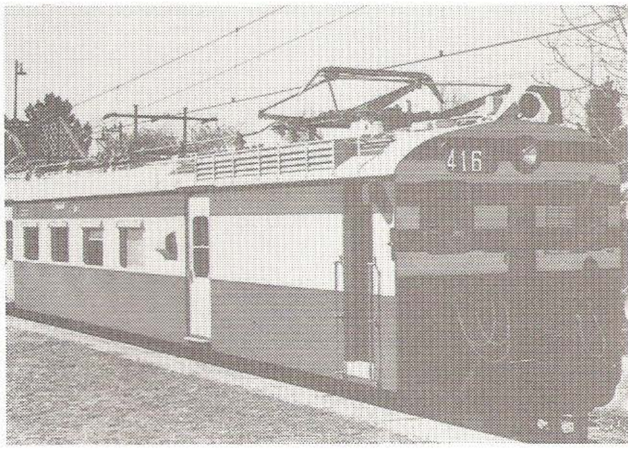
Experience in recent years with equipments in several countries has shown that the problem of achieving reliability under the harsh traction conditions has been effectively solved. The control electronics on the V6 stock has had only 4 failures in 1 million kilometres of service operation.

DATA

Motors	8 x 165 kW (continuous) accelerating 273 kW maximum in braking
Max. Speed	125 km/h
Max. Acceleration	$1 m/s^2$
Max. Retardation	$1 m/s^2$
Max. Jerk Rate	$1 m/s^3$
Time to 120 km/h	72s.
Nominal Line Voltage	1500 volts
Working range of voltage	1000 to 2000 volts
Max. Line Current (Chopper Units)	1120A.
Max. Line Current (Conventional Units)	C.1300A.
Normal Laden Weight	129 t.
Main Thyristors (per 2 motors)	4 x 1200 v, 22 μs turn-off time
Auxiliary Thyristors (per 2 motors)	3 x 1600 v, 50 μs turn-off time
Protection Thyristors Overvoltage (per 4 motors)	2 x 2100 v, converter grade
Overcurrent Protection (per 2 motors)	2 x 2100 v, converter grade, two strings.
Commutating diodes	2 x 2200 v, 4 μs recovery time
Freewheel diodes	2 x 4400 v.
Motoring diode	1 x 4400 v.
Braking diode	1 x 4400v.



For further details about:



MOTORING ONLY CHOPPERS
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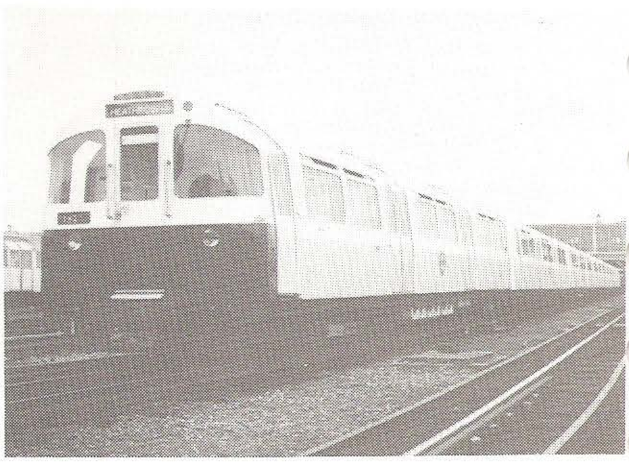
3000v system
see Publication GET / MU 3.

REGENERATIVE / RHEOSTATIC BRAKING CHOPPERS
as supplied to London Transport
600v 4th rail system
see Publication GET / MU4



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GEC Traction Limited

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