Suburban rail transport

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1. Introduction

During the last decade there has been a major expansion of suburban and urban railways. More than thirty new railway systems have been commissioned, eleven are currently under construction and twenty-five are in the planning stage. In addition a large number of existing suburban railways have been modernised with new fleets of vehicles and major expenditure on civil engineering, electrification and train control systems. The following details describe some of the improved vehicles and electrical systems on dc railways and consider the problems of compatibility that have emerged and how the traction industry has evolved to solve them.

2. The railway system

2.1 A modern dc suburban railway is a complex electrical system comprising several interacting subsystems — power supply, traction control, signalling and telecommunications. On a new railway these are usually specified simultaneously but, during modernisation of an existing system it is not uncommon to find, for example modern thyristor choppers operating with 1920s signalling systems or 1940s mercury arc rectifiers. New systems and modernised systems thus present different challenges to the engineer. On a new railway he may be faced with designing part of the electrical system when the specification for another part has not even been written and on an existing railway he may have to ensure compatibility with a variety of fixed equipment of uncertain age and characteristics.

2.2 The technology associated with traction equipment supplied to the new railways has in general evolved during the last decade. Simultaneously, and usually in isolation from traction propulsion manufacturers, those companies supplying equipment for signalling and power supply were also developing new systems. These developments usually did not meet each other until they were supplied to the same customer and this has resulted in major engineering problems of compatability rather than of individual system design.

Examples of the problems that can occur:

(a) To obtain a power supply contract a supplier may design for minimum cost. This can cause problems not only for the traction supplier due to high prospective fault currents but also to other railway contractors and the electricity supply authority due to waveform distortion.

(b) Signalling systems developed by American, French, Japanese or UK companies have differing levels of immunity to conducted and radiated interference. They may have to operate with rolling stock propulsion equipment supplies by other companies whose equipment characteristics were not envisaged at the time of signalling system development.

2.3 On railways in Europe, Japan and the USA it is usual for all system suppliers to be indigenous but in other countries this is often not so. On some projects consultants endeavour to specify systems so that compatability problems should not occur. However, in an increasing number of cases the railway authority looks to one of the contractors for system integration and this burden frequently falls on the car builder as the largest single supplier. A current example of this is Seoul where, for lines 3 and 4 of the Metro system the company is contractually responsible for all the interface engineering between the power supply, signalling systems, systems provided by Seoul Metropolitan Subway Corporation and the rolling stock.

2.4 The introduction of modern propulsion or other new equipment onto existing railways poses different problems. While only one element may be changing the other systems may, over different parts of a route, have different operating characteristics. The fact that there are differences will be known to the railway authority's engineers but the magnitude of them may not be known until the advent of new equipment necessitates their measurement.

3. Power supply

3.1 One of the first considerations in a large project is the layout of sub-stations and feeding arrangements. This, however, is dependent on the operating philosophy (eg, what level of supply redundancy is required), provision for future extension of the system and the type of vehicles to be operated.

Experience on various railways has shown that the power demands of lightweight regenerative chopper trains can be less than 60 percent of the demands of heavier vehicles with resistance control. Computer programs have been developed that enable a full train service to be simulated over a route to investigate alternative locations and ratings of substations and configurations of feeders. The same suite of programs can be used to simulate failure conditions, for example the loss of an ac supply feeder or of a complete substation, to calculate the loadings on the remaining equipment or to predict the maximum train service that can be safely operated.

3.2 Heavily loaded subways are, inevitably, in city areas where EHV supplies may not be available and where space and wayleaves for substations and feeders are difficult to negotiate and expensive. From the electricity authority's viewpoint it may be convenient to supply a railway from a variety of local HV feeders. This raises a the problems of voltage fluctuation and harmonics but has benefits of supply integrity.

3.3 On a dc freight line or an inter-city passenger railway it is relatively easy to predict feed point load fluctuations. Each substation supplies only one or two trains in each direction and their load changes are predictable and slow.

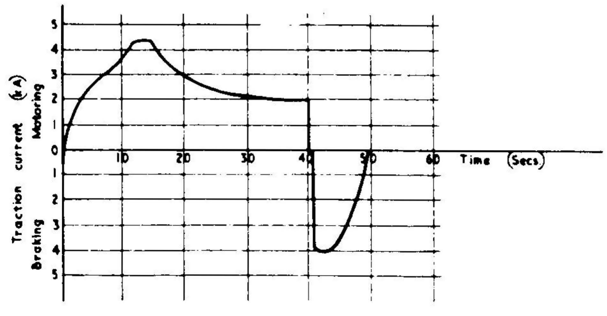

Fig 1 Typical traction current profile (Seoul stations 319-318, all out)

On a mass transit line the situation is very different. Up to ten trains may affect the load on a particular substation and these can change from full motoring to full regeneration in a few seconds (Fig 1). On one hand it is possible, but not likely, that all ten trains start simultaneously or, alternatively, all brake simultaneously. On the other hand, it is possible that at any time, equal numbers are braking and accelerating. Load fluctuation is thus a statistical problem and computer simulations take this into account.

+ Presented at the SAIEE Electrical Transport Session of the Annual Transportation Convention in 1983 held at Milner Park, Johannesburg on 27th July, 1983.

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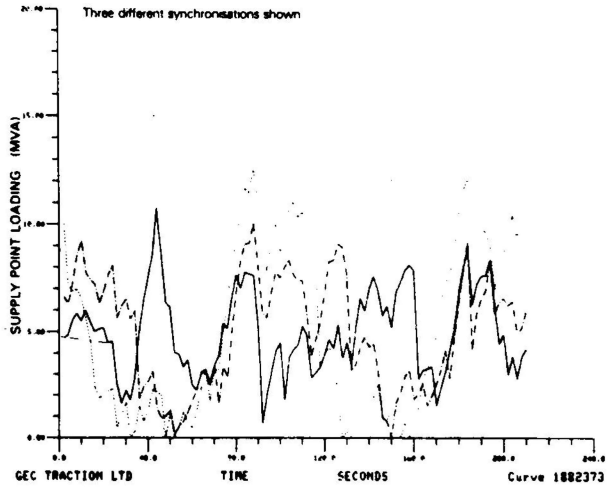

Fig 2 Seoul line 4 6 car trains 3.5 min Headway Yongsan Feeder Variation of supply point loading

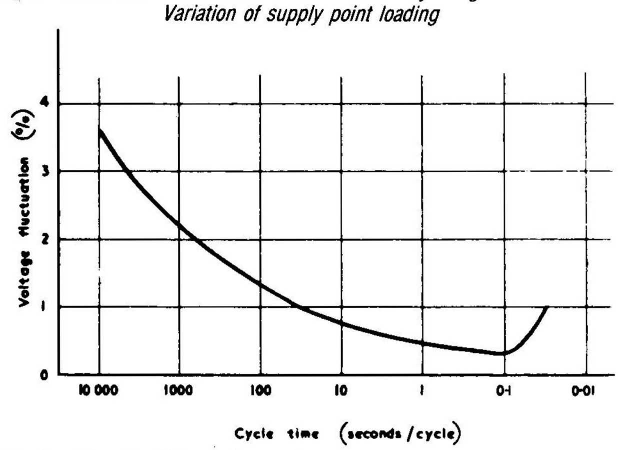

Fig 3 Allowable Voltage Fluctuation

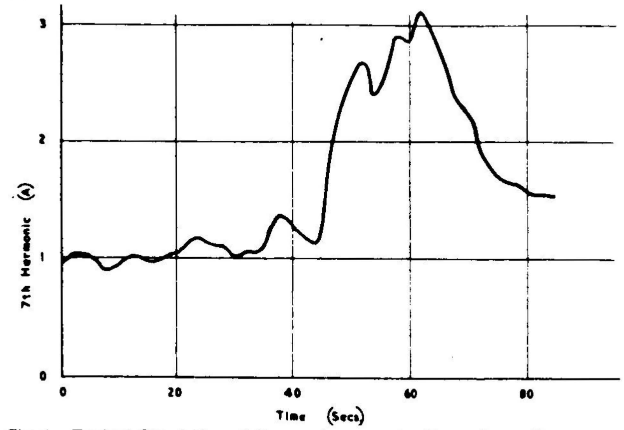

Fig 4 Typical Simulation of Harmonic currents (Hong Kong Mass Transit Railway Substation No. 3 120 Sec Headways)

Rather than considering the load for a hypothetical worst case or an arbitrary synchronisation between up and down lines, the actual load currents are simulated for minor variations in timetable (and in particular for different layover times at the end of a track) and average and peak values of ac feeder loads are calculated. It has been found that this technique, although expensive on computer time, gives a more realistic simulation of a real operating railway than does a single computer run (Fig 2).

3.4 There is no clear international standard of what constitutes an acceptable voltage fluctuation for a waveform of the shape typical of traction loads. An IEC standard specified the fluctuation acceptable for step loads (Fig 3) and from a comparison of the Fourier analysis of this and the substation waveform it is possible to say whether a particular load is likely to be a problem, but all comparison of this type can only be indicative.

3.5 Harmonic voltage distortion is a more tangible problem. In the UK the Electricity Council's Chief Engineer's Recommendation G5/3 lays down specific limits and rectifier simulation programs can predict the harmonic distortion with a good degree of accuracy (Fig 4). As a result of these predictions the decision can be taken on whether 6-pulse, 12-pulse or 24-pulse rectifiers are necessary to meet the distortion limits. For most heavily loaded urban systems fed from 33 kV suppliers 12 or 24-pulse rectifiers are likely to be necessary.

3.6 Co-ordination of system protection has to take into account seven different levels of protective device (Fig 5):

(i) Supply authority breaker
(ii) Incoming substation breakers
(iii) Rectifier ac breaker
(iv) Rectifier dc breaker
(v) Feeder breaker
(vi) Train roof fuse
(vii) Train line switch group

The rectifier ac and dc breakers are provided to cover the eventuality of substation equipment faults and isolation requirements. The main overload protection features are carried on the track feeder breakers. These breakers usually incorporate both direct acting trips for rapid circuit disconnection in the event of major faults and a time graded trip feature for longer term lower level faults (Fig 6).

The advent of regenerative chopper trains has made the detection of major faults by substation breakers more difficult since the substation is no longer the only source of power. In particular the problems of a number of regenerating trains all operating under closed loop current control feeding a vehicle fault and the effects on the rate of rise of fault currents by the chopper input filters have led to a review of vehicle protection. On a number of systems the continued use of line breaker protection with resistance insertion to limit fault currents is perfectly satisfactory. On some

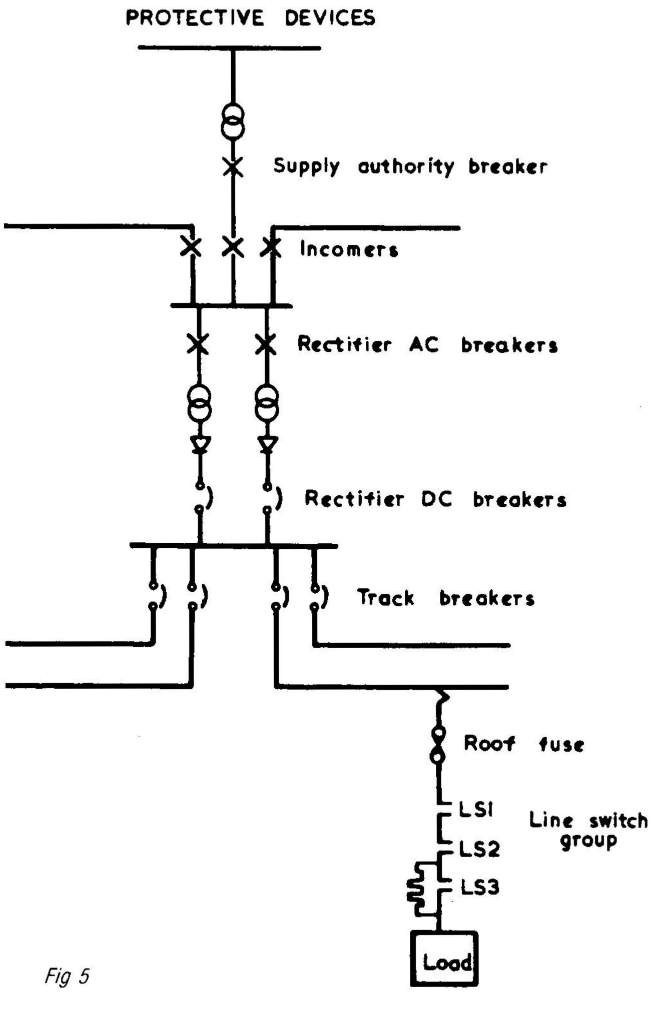

Fig 5

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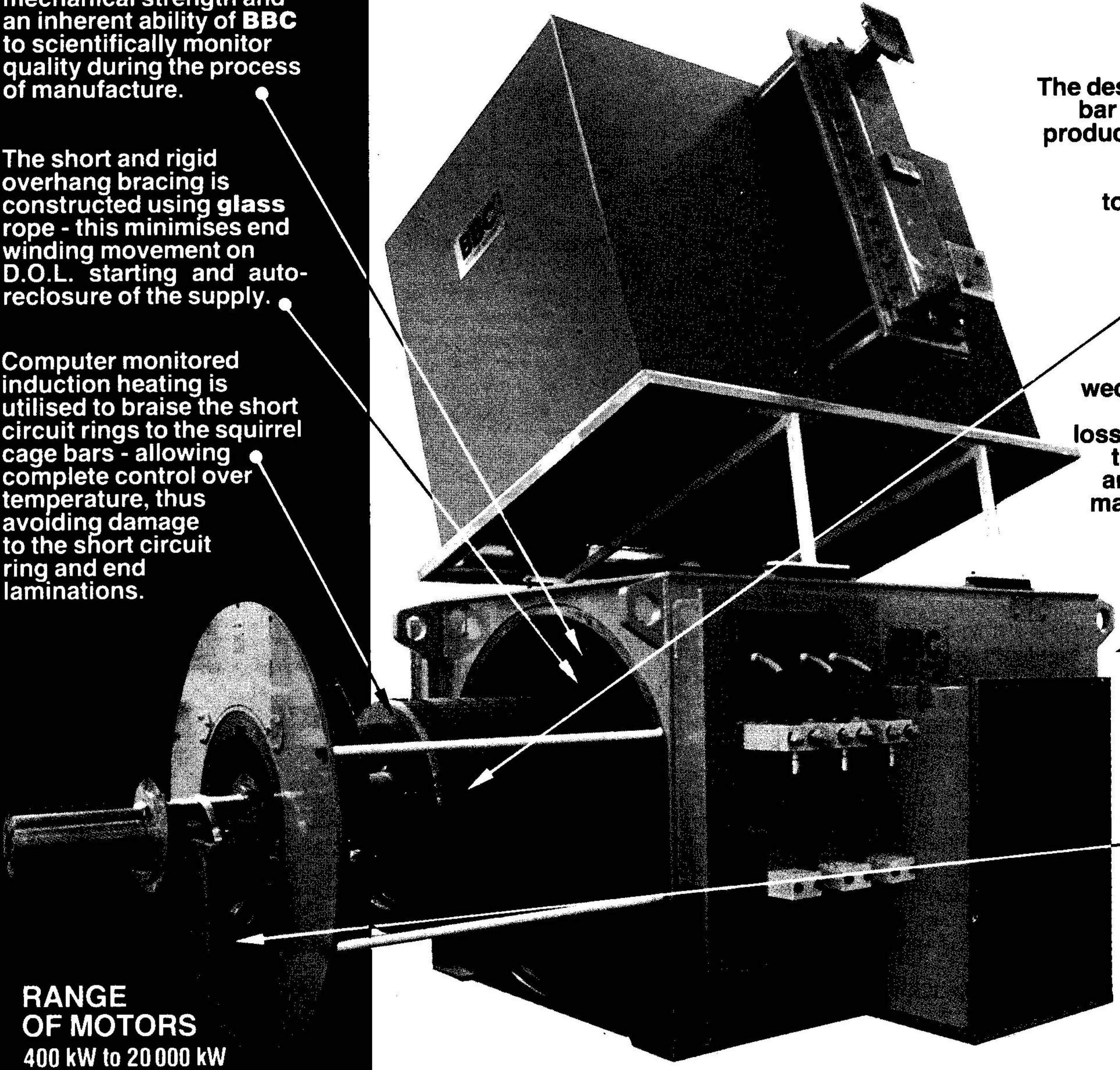

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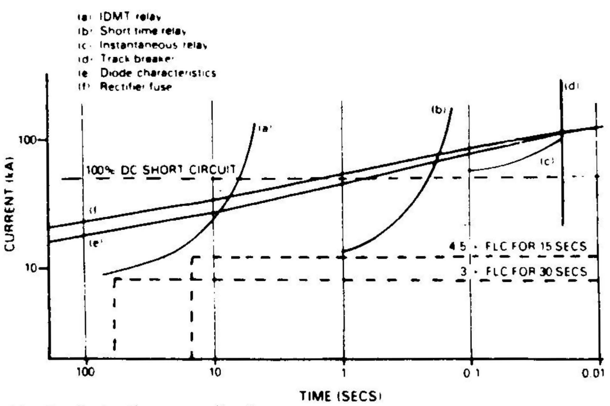

Fig 6 Protection co-ordination curve

rapid transit systems, however, it has become necessary to fit either roof fuses or vehicle HSCBs. The choice of an HSCB, roof fuse or line switches can only be carried out as part of a full power systems study. To ensure correct co-ordination at all points of a highly loaded system with other trains that may be motoring or regenerating is a problem that would be difficult to solve without modern computer techniques.

3.7 The electrical characteristics of a dc railway are dominated by the design of the substations and, in turn, the output characteristic of the substations is determined to a large extent by the design of the transformers. The regulation, maximum short-circuit current, harmonics in the ac supply and the dc ripple current can all be controlled by the transformer design.

The regulation of a substation is of great importance to the operation of the railway — all units need to have the same regulation or the load will not be shared equally. If the regulation is too steep the train will not be supplied with sufficient voltages on the high overloads and train performance will suffer. Raising the voltage at the high-load end will, of course, give a high voltage at no load, stressing the insulation or even exceeding the voltage capability of some components, so that this in itself is not a solution.

Low regulation is achieved by reducing the impedance of the transformer. A low impedance transformer will give rise to high short-circuit currents, which may not be acceptable to the convertor or to the dc switchgear. The essence of a good design is therefore the compromise between the conflicting requirements of regulation and short-circuit currents.

Advanced designs of transformers using coupled secondaries allow low regulation over the normal load range while limiting short-circuit currents.

Fig 7 shows typical regulation down to short-circuit for three alternative transformer designs, each having the same regulation over the normal working range. The choice of connection is then made taking into account the following:

(i) The number of phases required for ac harmonic considerations;
(ii) DC ripple currents limits for track signalling considerations;
(iii) Whether fully coupled secondaries on 12-pulse units are necessary in order to achieve the correct short-circuit-to-regulation relationship.

It should be noted that if double secondary units are specified the balance between both secondaries on all counts must be very close, ie, same voltage, same leakage reactance, same copper loss, or the load taken by each secondary will not be the same.

3.8 In rural and suburban electrifications it has been common practice to earth the system at each substation and for the tracks to be effectively earthed to structures and through the track fastenings. In high density urban systems the situation becomes more complex. Many modern signalling systems will only work with unearthed track and steps have to be taken to prevent stray currents from the railway causing corrosion of civil engineering structures and adjacent services. Certain railways have solved this problem by insulating the track and running the power system 'earth-free'. In other applications solid connections have been made to all structural metalwork which have been brought to the negative panel in the substation. Apart from solving the corrosion problem

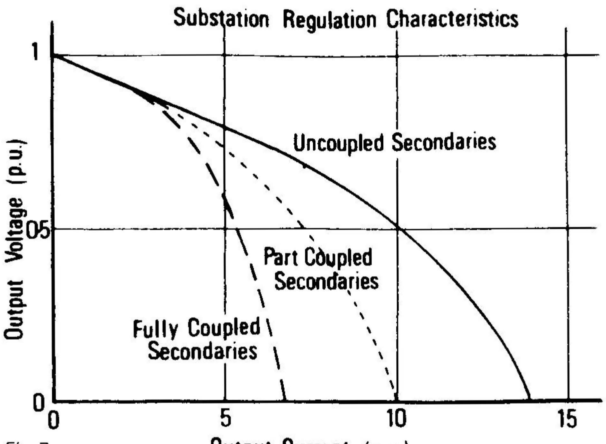

Fig 7

the earthing system has to take account of the requirements of signalling systems, touch voltages and the need to provide a fault current path compatible with the substation protection. there is thus no unique earthing scheme applicable to all railways, and each application requires separate consideration.

The system that was adopted in Hong Kong for example was to bond all the civil engineering metalwork to a return conductor and to use drainage diodes to return stray currents to the rectifier (Fig 8).

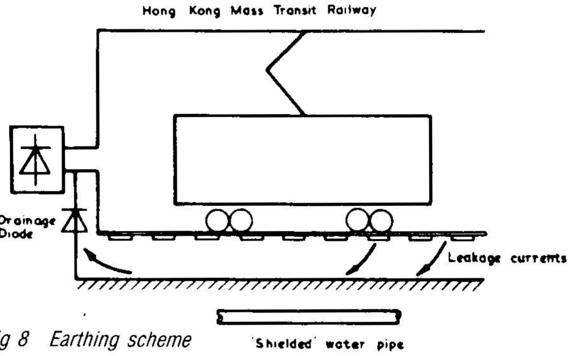

Fig 8 Earthing scheme

4. Vehicle equipment

4.1 The majority of vehicle propulsion equipments in current large scale production have evolved over the past decade and current design problems with both switch resistor and thyristor control schemes are associated with producing them at lower cost for a very competitive market together with reduced energy consumption.

The major innovations have been:

(a) Increased power/mass ratios
(b) The consolidation and general acceptance of thyristor chopper equipment
(c) The increasing use of microprocessor techniques
(d) The emergence of three-phase drives

4.2 On the initial Hong Kong trains, which have all axles motored and are in two-car sets, each car was fitted with a camshaft equipment, while on the second contract there is only a single camshaft controlling eight traction motors on a pair of cars as shown in Fig 9. The power mass ratio of the electrical equipment improved by 8 percent. The use of one control equipment to supply eight motors is also used on thyristor chopper equipments.

4.3 The lasting impact of the oil crisis of 1973 can be seen in the specifications for new stock for railway administrations the world over. The rationale in favour of choppers, pre-1973, was often based on superior reliability and availability compared to conventional equipment, whereas now it is their energy-saving features that have assumed the greater importance. It has also become the norm to specify regenerative braking to save energy.

4.4 The use of regenerative braking has two major design implications: firstly it affects the motor specification. During regeneration the motor voltage is necessarily limited to line voltage, which cannot be allowed to rise by more than about 20 percent above

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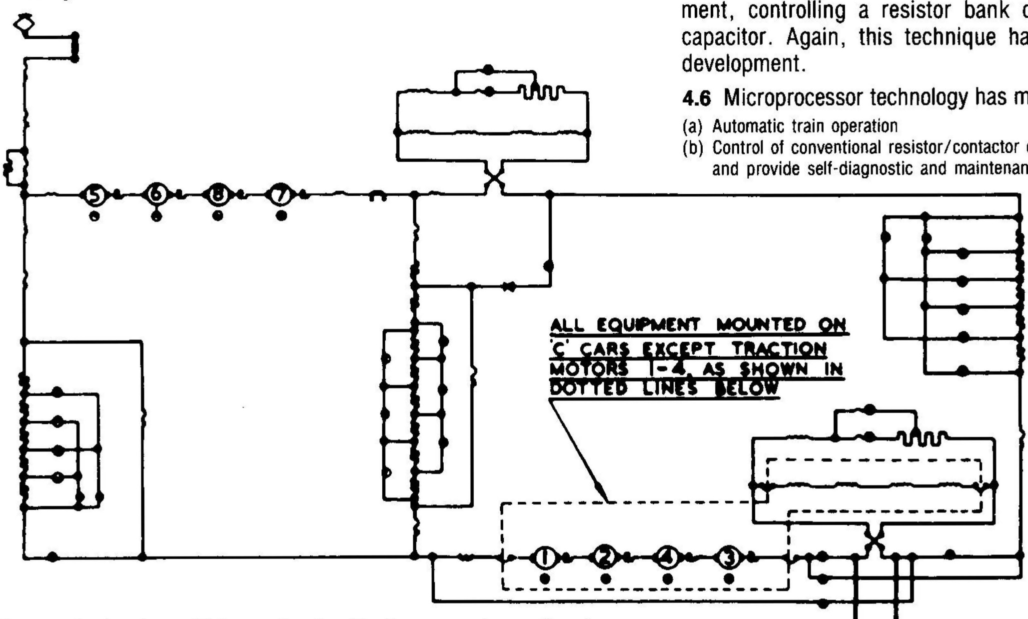

Fig 9 Power circuit Hong Kong (TWE) cars

the nominal value. (This contrast with the normal practice in rheostatic (dynamic) braking, in which the motor voltage is permitted to rise to above twice the nominal line voltage.) Thus, for regenerative braking, double the armature current is required to obtain the same braking effort. As a compromise a resistance bank can be connected in series with the armature so that at maximum speed the motor voltage can exceed the line voltage. The choice therefore is between a larger, costlier traction motor on the one hand and a reduction in regenerated energy on the other. While it is the railway administration which must make this choice, comprehensive data on energy consumption through a suite of computer programs such as those developed by the company are available to evaluate train performance.

4.5 A second side-effect is that braking effort is dependent upon the line supply. If the supply system (the overhead wire or third rail) does not have a load able to absorb at least as much energy as is being generated by the train, the electric braking effort will not be available. (What happens in practice is that the line voltage begins to rise, in response to which the chopper control electronics reduces the current it is asking the equipment to generate, and thus the braking effort will fall.) This shortfall in braking effort can be made up by the train's air brake system, but it is preferable for the electric brake to be independent of the line supply. An extreme case of 'non-receptivity' occurs during pantograph bounce. when that happens, the chopper output voltage rises too quickly for the air brakes to respond before it becomes necessary to switch the electric brake off altogether. The result is a jerk felt by the passengers. One remedy is to fit a second chopper to the equipment, controlling a resistor bank connected across the filter capacitor. Again, this technique has reached a high state of development.

4.6 Microprocessor technology has made an impact in four areas:

(a) Automatic train operation
(b) Control of conventional resistor/contactor equipment to optimise performance and provide self-diagnostic and maintenance facilities
(c) The control of electronic systems
(d) The provision of maintenance equipment that is portable and allows rapid identification of problems, particularly on electronic equipment, when the maintenance fitter may have little knowledge of the equipment being tested.

4.7 The automatic train operation (ATO) equipment supplied for the renovated Glasgow underground is shown in block diagram form in Fig 10. The system uses two unpowered track beacons positioned before each station shop with additional beacons for speed restrictions. The train has a transmitter/receiver and microprocessor control unit. The equipment provides for accurate stopping to maximise train length for a given platform length and to optimise energy consumption. Braking routines for different approach speeds and recordings taken during service trials are shown in Fig 11.

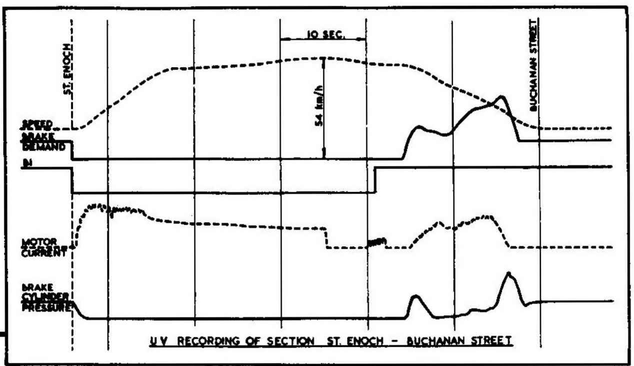

Fig 11 Automatic train control braking profiles

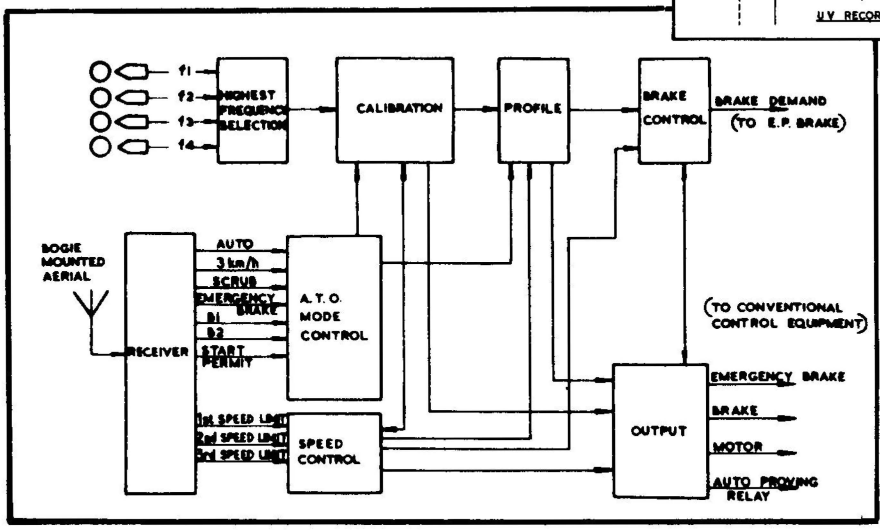

Fig 10

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4.8 The company has recently delivered two microprocessor controlled locomotives to the South African Transport Services. These locomotives have four dc motors that can be connected in series or series/parallel by electropneumatic contactors. In either combination, starting resistors are initially connected in circuit with the motors and are progressively cut-out by the opening and closing of various contactors in a predetermined sequence.

The control system was designed from the outset to include comprehensive test facilities. On initial switch-on the microprocessor carries out a self-check program. This checks that all the peripheral interface modules (ie, all the modules which interface the microprocessor system to the rest of the electronics) and the program memory can be addressed by the microprocessor and that no data corruption is taking place. Only when this program is completed satisfactorily can the microprocessor enter the main program. Control signals from the driver's master controller are fed to the logic where they are first checked for validity and, if correct, output signals are then generated to directly operate the various contactors. The state of each contactor is checked by monitoring auxiliary contacts to check each step in the contactor sequence. Any fault detected is stored by the microprocessor and can be displayed as a 16-bit alphanumeric message on a simple display unit when connected to the microprocessor system.

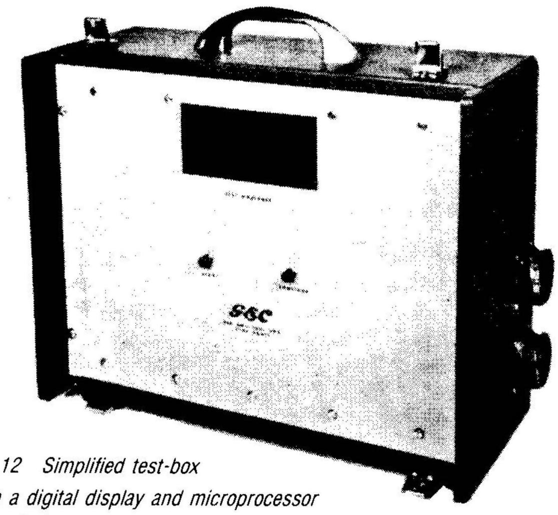

Fig 12 Simplified test-box with a digital display and microprocessor controlled

4.9 Fig 12 shows a microprocessor controlled test box recently supplied to British Railways for testing the control electronics on multiple unit trains. No electronic knowledge is required by the user who has one pushbutton switch to start the test procedure. A two-digit display advances as the tests are carried out sequentially. Whenever a faulty response is detected by the microprocessor, it signals the operator by sounding an alarm and halting at the test failed. The operator then consults the handbook provided, which indicates the component that requires changing.

4.10 During the past decade there has been increasing development of three-phase drives for suburban transport. The application range from magnetically levitated people movers using linear motors such as is being installed at Birmingham Airport in England, the UTDC vehicles developed in Canada using transistor inverters, tramcars together with rapid transit and suburban vehicles.

At the present stage of development three-phase drives have three major problems. They are cost, mass and complexity. The cost of a three-phase equipment is between 20 percent and 50 percent more than for alternative drive using dc motors. It is likely that by using gate turn off (GTO) thyristors the costs will reduce (but these cost reductions will also apply to dc chopper equipment). It is likely that three-phase drives will, in the forseeable future, always be more expensive than drives using dc motors but as the difference in price reduces, the benefits of not having to maintain a dc machine will compensate for the additional cost.

5. Signalling and train control systems

5.1 Traditionally dc railways have used ac track relays for detecting the presence of a train. These have sometimes worked at mains frequency but more usually at a special signalling frequency generated by rotary machines. More modern schemes have used audio frequencies generated by electronic oscillators or by electromechanical reed vibrators. In some systems these are pure tones in others they are modulated to give a greater degree of security. Other track circuits use electronically generated pulses to detect trains.

Train control frequencies are also present on the track. In the simplest design these are unmodulated tones transmitted towards the train. If the train passes a stop signal the tone is cut off and the brakes are automatically applied. More complex systems 'overlay' a modulated train control signal over the rails that can contain speed reference information and, in some systems this is the time division multiplexed with the track circuit frequency.

5.2 Apart from continuous audio frequency tones, modulated tones and pulses, train control systems sometimes use very low frequency (VLF) radio to interrogate track beacons. Radio communications systems are encountered from VLF to UHF and trackside cables can contain a wide variety of signals — dc mains frequency, telephone base-band, carrier systems, etc. Co-ordination of these signals with power supply and chopper frequencies can be a major exercise. (The increasing use of fibre optics that are totally immune to electrical interference is heartily welcomed by railway engineers.)

5.3 There are three basic mechanisms by which a traction system can interfere with a signalling system:

- Conductive coupling
- Magnetic coupling
- Electric coupling

- *Conductive coupling* occurs when two circuits share a common conductor. A voltage is generated in the disturbed circuit by current flowing in the disturbing circuit through the common impedance. This type of coupling can occur in all electric railways in which the running rails are used both to complete the traction return circuit and also as conductors in local track circuits.
- *Magnetic coupling* occurs between circuits formed by long parallel isolated circuit. In general these inductive effects caused by parallel exposure are more significant in telephone and line side control circuits than in rail based track circuits.

Inductive interference can also occur in train borne cab signalling detectors due to the flow of disturbing currents in the running rails. In this situation a mutually induced voltage, proportional to the rate of change of disturbing current, will appear at the terminals of the detector coil.

With chopper equipment another source of inductive interference is associated with under car chokes. Direct magnetic coupling, due to the local field of the chokes, may be experienced in short track circuits and local loops. This effect is normally associated with the external field of the unshielded input choke, armature circuit chokes and the commutation circuit choke and has been particularly troublesome in earlier designs of low power, audio frequency, jointless track circuits used in the USA. However, since the effects were recognised, chopper designs have been produced to minimise the external radiated field and this trouble should now be in the past.

It is the relatively high frequency current found in the chopper's commutation circuit which is one of the main interference sources. A major recent advance has been the application of toroidal construction to commutation chokes, which improves their 'Q' factor as well as reduces their external field. A feature of the company's chopper design is that the resonant frequency of the commutation is much lower than that in many schemes. This is possibly because the peak resonant current does not need to be two or three times the motor current, as is required by other schemes. The operation of the circuit only requires that the commutation resonant frequency be somewhat higher than the chopper frequency itself. This feature combines with the toroidal construction of the commutation choke to reduce power losses, noise and the stray magnetic field to low values.

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● *Electric field effects* are manifested by capacitive coupling, usually between parts of the chopper circuit and the car body. Capacitive charging and discharging currents will flow in local earth circuits, every time the output voltage of the chopper circuit changes in a 'step' fashion. The energy levels involved in such couplings are small and, to date, had not been a significant problem.

5.4 Of the above forms of interference, conducted interference is the most significant on modern systems. There are four basic mechanisms that have to be considered when designing a train for a railway system:

(i) The chopper frequency, or one of its harmonics, can directly interfere with the track circuits.
(ii) The train can present such a low ac impedance to the substation ripple voltage that the ripple currents in the traction system interfere with the track circuits.
(iii) The beat frequency between the chopper frequency, or one of its harmonics, and a substation ripple frequency could coincide with the track circuit frequency. If de-modulated by a circuit non-linearity the beat frequency could influence track circuits. Similarly beating between two choppers of different frequencies could cause frequencies to which track circuits are susceptible.
(iv) The input filter could 'ring' at a signalling frequency when excited by a line voltage step.

5.5 Modern thyristor chopper systems usually operate in the range 200 to 400 Hz. Pairs of choppers can be interlaced to double the frequency seen on the track and thus generate fundamental ripple in the octave 400 to 800 Hz. However, these are not the only frequencies present as an analysis of chopper waveforms shows there are harmonics up to several kHz. The substation rectifiers produce multiples of the power system frequency and both chopper and the power system frequency can vary by a small amount. A signalling system using audio frequency track circuits and automatic train control commands frequently uses several discrete frequencies. These are usually in the range 500 to 5 000 Hz. It is not unusual for the chopper designer to be restricted to only one or two frequencies within the possible octave of operation. This is shown in Fig 13 for the Seoul subway.

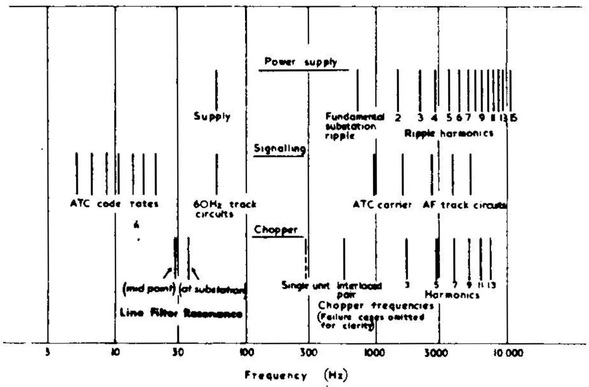

Fig 13 Allocation of frequency spectrum - Seoul Subway

5.6 Many older railways systems use vane relays for track circuit train detection. In theory these respond only to the power circuit frequency at the correct phase. However, tests have shown that a nominal 50 Hz relay responds over the range 40 to 60 Hz and, if the local 'phase reference' supply is distorted or if any saturation occurs in signalling components, the track relay can show significant responses at multiples and sub-multiples of the mains frequency. A typical response curve is shown in Fig 14. The problem of the train's impedance to substation ripple voltages can be looked at in two ways. If a new design of chopper train is being introduced into a system on which conventional trains have been operating satisfactorily then the input impedance of the chopper train can be compared with that of the conventional trains. On the other hand on new systems the estimation of ripple currents has to be considered from first principles.

A conventional train presents its lowest impedance to the line when the motors are connected in series/parallel in weak fields and are working hard (and thus saturated). The inductance of the fields is effectively shunted by the field divert circuits and the predominant inductance is thus in the armature. When carrying a high current the armature inductance is unlikely to be greater than 2 mH per motor. (Test bed results are sometimes misleadingly high as they are frequently taken at low machine loadings.) Thus the total parallel inductance of a train could be around 0,5 mH.

When designing choppers for existing rail networks it is good policy to include an input filter to give an input impedance no less than that presented to the line by conventional trains. However, this practice is not universally accepted and several manufacturers produce choppers with relatively low input impedances. These are adequate if the trains are to be used only on modern signalling systems with audio frequency track circuits, but if the trains have to run on older systems with mains frequency track circuits, very low input impedances can degrade the level of safety.

5.7 A chopper waveform consists of a sequence of harmonics of the fundamental ripple frequency. This sequence of frequencies is attenuated by the characteristic of the input filter. The filter normally takes the form of a series-parallel L-C filter. This had a classical second order characteristic as shown in Fig 16. Under normal conditions the filter is under-damped, with a damping ratio of around 0,2, but this depends on the chopper loading.

5.8 The substation output is not smooth dc but includes harmonic current ripple depending on the pulse-number of the substation and the degree of substation filtering. Certain administrations specify the use of a dc choke on a substation and others specify shunt harmonic traps. Thus the ripple on the substation output can vary by almost an order of magnitude depending on the filtering provided. There is no 'standard' and each case has to be separately considered. If there is a current generated by a chopper harmonic differing by the mains frequency from a supply system harmonic then the resulting difference frequency could affect the signalling system. However, just because there are voltages of the right frequency does not mean there will be signalling interference. The ac impedance of the system must be sufficiently low for each of the two harmonic voltages to generate sufficient current and there must be a non-linearity to de-modulate the 50 or 60 Hz beat frequency. Fig 14 shows a typical beat frequency

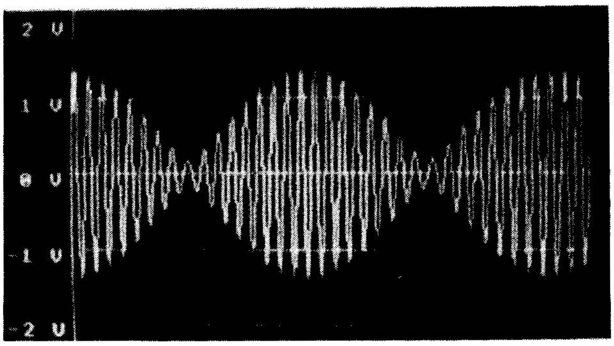

Fig 14 Beat frequency (simulation)

product by a third harmonic power system frequency of 108 Hz and an amplitude of 0,78 V and a fourth harmonic chopper frequency of 1 132 Hz with an amplitude of 0,6 V. If the above waveform were to pass through a piece of signalling equipment, such as an impedance bond, it could suffer non-linear distortion as shown in Fig 15 and the power frequency component could conceivably affect a vane relay. This possibility is taken into account when considering the introduction of choppers onto existing railway systems.

5.9 The chopper input line filter is specified to smooth out the chopper ripple. As a second order filter it has a resonant frequency given by the expression.

$$f = \frac{1}{2\ LC}$$

During initial switch-on the filter is heavily damped by a 10 ohm resistor but, during normal operation, resistive damping cannot be considered as it would incur very large losses. Normally the line filter is not excited into resonance and so no voltages or cur-

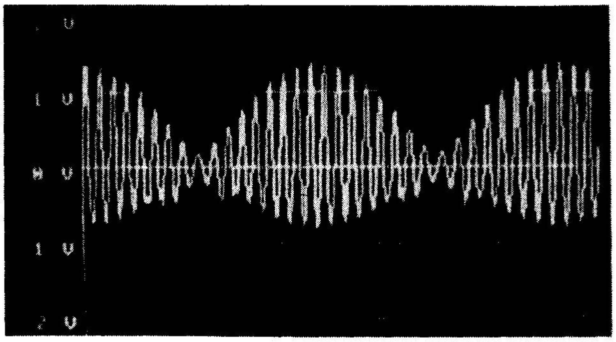

Fig 15 Demodulation caused by non-linearity

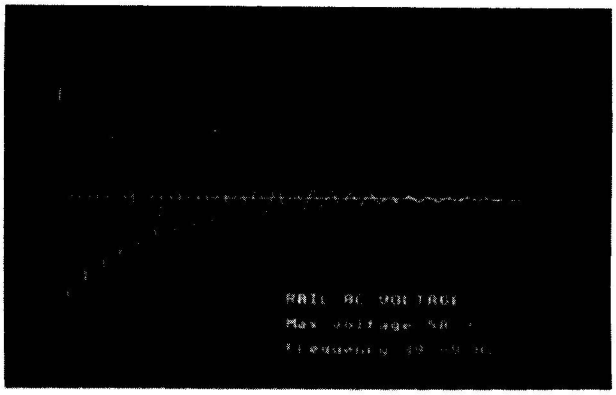

Fig 16 Longitudinal rail voltage

rents at the resonant frequency are seen in the system. However, if a conventional train switches off power by opening contactors there will be a voltage step on the line that will cause the line and filter to ring. A more extreme supply disturbance occurs if there is a fault on the overhead line. This will depress the substation voltage which will quickly recover to the normal value when the track breaker trips. This surge will be impressed on all other circuits fed from the substation. As a design case a step of 30 percent of the supply voltage is usually taken as an extreme worst case.

Analytical studies have shown that the amplitude of the longitudinal track voltage increases as the length of the track circuit increases and the decay time reduces as the distance from the substation increases. The worst case is thus on the longest track circuit adjacent to a substation. Fig 16 shows the calculated longitudinal voltage for a 260 m track circuit when the input filter has the values 3,45 mH and 4,2 mF.

6. Conclusions

The prospective rate of build and/or renovation of urban railway systems is now at a very high level. This paper has tried to show some of the aspects of railway engineering applicable to these systems and how the various engineering disciplines are combined to provide a working railway.