Power converters for feeding asynchronous traction motors

B. West, BSc, *Principal Engineer, Systems Engineering*

1. INTRODUCTION

At present the vast majority of traction vehicles throughout the world utilise the dc motor as a traction drive. The dc motor has proved to be equally suited to both dc traction and as a rectifier fed motor to ac traction. The only alternative to the dc motor until recently has been the single-phase series wound motor used by some European countries on ac systems. Both these types of motor have mechanical commutators which impose several restrictions for both design and operation.

Traction designers have long desired to make use of the three-phase induction motor in order to eliminate the commutator and brushgear. Numerous attempts have been made over the years to utilise the cage motor as a traction drive but few have had much success because inverter technology was not sufficiently advanced.

Recent years have seen significant improvements in both power semiconductor technology and control electronics. developments are now reaching a stage where the power conditioning equipment needed with induction motors can be economically realised and ac drives could soon be offering significant cost advantages over their dc counterparts.

This paper investigates two possible inverter configurations for controlling induction motors. The requirements of the complete drive system are also examined with particular emphasis on the power supply interface. A converter, for use on an ac fed system, is described which virtually eliminates the generation of reactive and harmonic power normally associated with static converters.

2. THREE-PHASE INDUCTION MOTOR

The three-phase squirrel-cage induction motor is probably the cheapest, most rugged and most reliable of electrical machines. A comparison of the induction motor against both a dc motor and a single-phase motor at a common continuous rating of 820kW, Table 1, clearly shows its size and weight advantages. In addition, the absence of the mechanical commutator improves reliability and significantly reduces maintenance costs.

Frequency	**16⅔Hz**	**50Hz**	**Variable Hz**
Type	ac commutator	dc commutator	squirrel cage
Overall height	115cm	85cm	70cm
Weight bare motor	3500kg	3000kg	1630kg
Weight per kW output	4.2kg/kW	3.6kg/kW	2.0kg/kW

TABLE 1

The motor parameter of main interest for traction is the torque generated by the machine. A typical torque speed curve for an induction motor operated at constant frequency is shown in Fig. 1. It shows that a positive slip frequency produces a positive torque (motoring), a negative slip frequency produces a neative torque (regenerative braking) and zero slip frequency produces zero torque (coasting). A typical value of slip frequency would be 1-2 herz. The torque can be controlled by controlling the volts per herz and the slip frequency. Fig. 2 shows how an induction motor can be controlled to produce a tractive effort speed profile the same as that used for a dc motor.

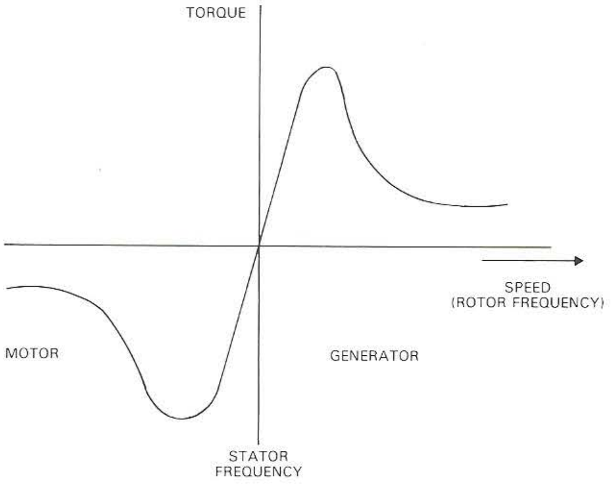


Fig. 1 Induction motor typical torque speed curve.

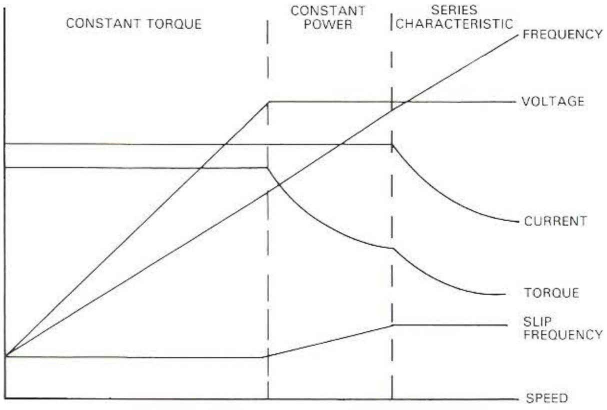


Fig. 2 Control strategy for induction motor.

It is clear that to utilise an induction motor requires a three-phase supply of variable voltage and frequency. The rapid change in torque for small changes in slip frequency suggests the use of one inverter per motor to overcome potential load share problems. In addition, the necessary fine control of slip frequency together with problems of rotor resistance variation with temperature, indicates a very precise control system is needed.

3. INVERTERS

In contrast to the stated advantages of the induction motor over the dc motor, its associated power conditioning equipment is more complex both in design and control. An inverter is used to generate the required three-phase supply from a dc input. The inverter must provide a variable frequency output having a range exceeding 100:1 and must be self-commutating. In addition, the dc input must be regulated (either constant current or constant voltage) which assumes the use of energy storage elements.

The basic control parameter in traction power equipments is the torque produced by the machine. The torque of an induction motor is produced by air gap flux and rotor current, and it is the control of these parameters (either directly or indirectly) which has to be achieved. Unlike the dc machine, where the field and armature currents are readily available, an induction motor does not lend itself to direct measurement of the rotor currents. All torque determination has to be done either by search coils embedded in the machine or from the measured terminal parameters.

It is the latter of these options which is favoured by GEC Traction and we are presently engaged, both by ourselves and in collaboration with universities, in developing methods of determining machine torque from machine terminal measurements.

There are two basic forms of inverter circuit available for feeding induction motors: current fed inverters and voltage fed inverters. GEC Traction is examining both configurations as a comparative study. Details of each type are outlined below.

3.1 Current fed inverters (CFI)

A current fed inverter is one which connects a direct current source to an ac load and generates rectangular ac-side current. The simplest form of such an inverter is one using phase-sequence commutation, that is each phase commutates off the previous phase. A typical scheme for such an inverter is shown in Fig. 3. This scheme makes use of slow turn-off thyristors but requires a large dc link inductor and large commutation capacitors. Commutation times are primarily influenced by the motor leakage reactance and a low value is desirable for satisfactory inverter operation, particularly at the higher frequencies. Typical inverter waveforms are shown in Fig. 4. The classical six step approximation to a sine wave is clear.

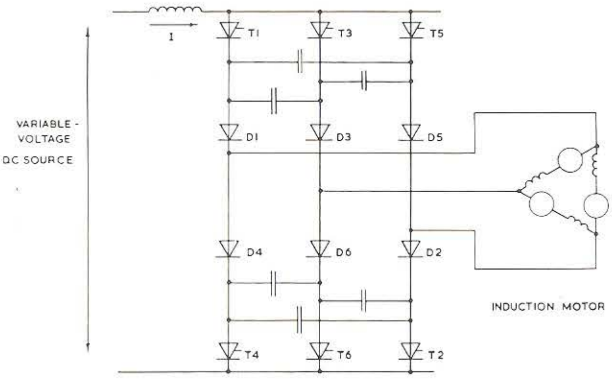


Fig. 3 Current fed inverter.

Figure 4 also shows the expected motor torque and associated torque oscillations. The dominant torque harmonic is at six times the fundamental frequency and of significant amplitude. These torque oscillations are potentially hazardous to the vehicle drive system.

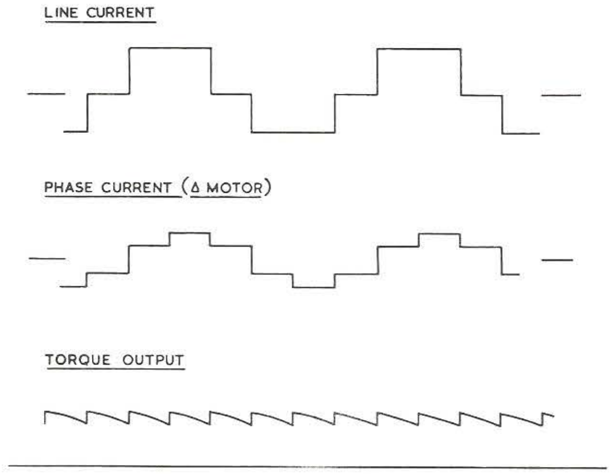


Fig. 4 Current fed inverter waveforms.

As the fundamental frequency of the motor currents is varied the frequency of the torque oscillations is also varied. This has it most serious consequence at low speeds when resonances may occur between the torque harmonics and the mechanical transmission system.

This problem can be overcome by pulse modulation of the motor currents to remove the lower order harmonics and thereby, avoid the embarrassing torque oscillations. Such a scheme forms part of our present development programme. Alternatively, a mechanically resilient drive system can be used to absorb the torque oscillations.

The current fed inverter has no facility for changing the average value of the impressed current and has to be preceded by a controlled current source. For dc systems, this control would be a chopper circuit, whereas on ac systems a phase-angle controlled bridge would be used.

3.2 Voltage fed inverters (VFI)

A voltage fed inverter is one which connects a direct voltage source to an ac load and generates rectangular ac-side voltage. Pulse width modulation techniques (PWM) are normally employed, both to vary the mean voltage and also to reduce lower order voltage harmonics. Forced commutation is essential to achieve the pulse width modulation and consequently inverter grade devices must be used.

A typical power schematic for a voltage fed inverter is shown in Fig. 5. The commutation circuit shown, repeated for each inverter leg, is one of a number available. The merits of each circuit lie in the relative ratings of the commutation components and the choice of which circuit to use depends upon the

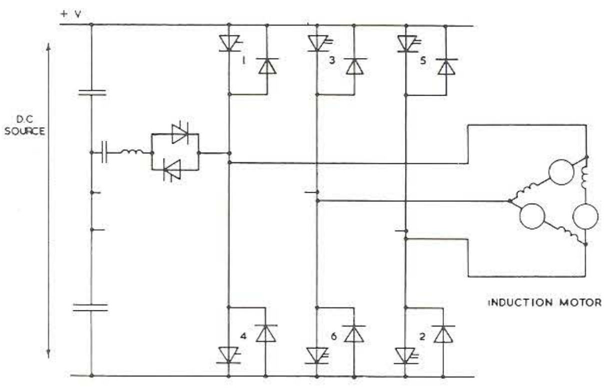
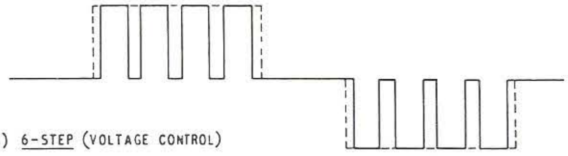


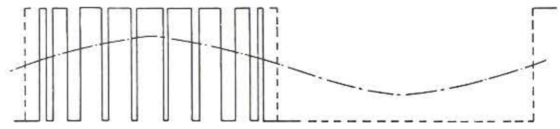
Fig. 5 Voltage fed inverter.

particular application being considered. Commutation times depend upon the maximum current to be commutated and the energy available in the commutation capacitors. The latter can be well defined providing the input voltage can be assumed constant.

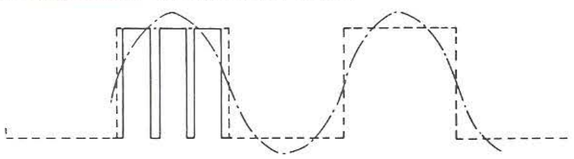
In contrast to the current fed inverter configuration some reactance on the ac side (ie traction motor leakage reactance) is desirable as this is beneficial in smoothing the voltage ripple. Some typical voltage fed inverter waveforms are shown in Fig. 6.



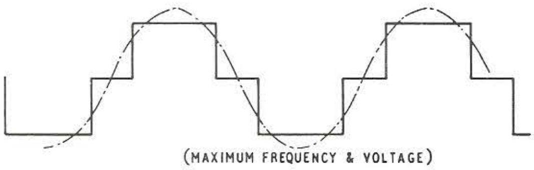
(a) 6-STEP (VOLTAGE CONTROL)



(b) SINE MODULATION (LOW FREQUENCY & VOLTAGE)



(MEDIUM FREQUENCY & MAX. VOLTAGE)



(MAXIMUM FREQUENCY & VOLTAGE)

Fig. 6 PWM Inverter output voltages.

The advantage of using pulse width modulation techniques is that the voltage impressed upon the motor can be controlled so that phase currents approximating to sine waves are achieved. This results in a much smoother torque and less harmonics in the motor. Torque ripple is now at twice the inverter chopping frequency which is high enough to be readily absorbed by normal mechanical time constants.

The classical method of pulse width modulation generation is to compare a sine wave (modulating signal) with a triangular wave (carrier signal) as shown in Fig. 7. The resultant waveform defines the thyristor switching instants. The modulating signal corresponds in both amplitude and frequency to the fundamental component of the inverter output. The carrier signal, which defines the chopping frequency of the inverter, must be an integer multiple of the modulating signal in order to avoid problems with sub-harmonic resonance and signalling interference. This type of sampling is known as natural sampled pwm and was common on early pulse width modulated systems, using analogue circuit implementation.

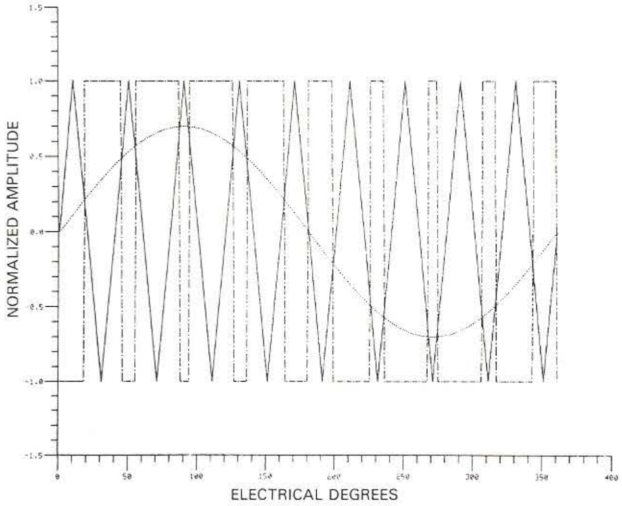
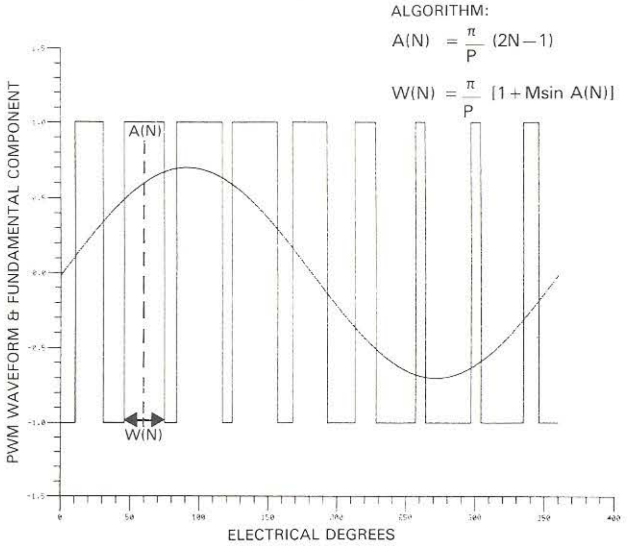


Fig. 7 Natural sampled pwm.

The recent addition of the microprocessor to the designer's toolbox has produced a number of techniques for digital waveform generation. Digital techniques are inherently more accurate and reliable than their analogue counterparts and are obviously an attractive proposition for such a complex task. Natural sampled pwm is not suitable for digital implementation because it is impossible to devise an algorithm to define the thyristor switching instants. However, a number of other sampling systems have evolved such as the regular symmetric sample pwm shown in Fig. 8.



ALGORITHM:

$$A(N) = \frac{\pi}{P}(2N-1)$$

$$W(N) = \frac{\pi}{P}[1 + M\sin A(N)]$$

Fig. 8 Regular symmetric pwm.

For a locomotive application an inverter might have to work over a frequency range of typically 0.1 hertz to 200 hertz. In order to achieve a reasonable compromise between harmonic currents, torque ripple and inverter switching losses, the carrier frequency is constrained to be within an upper and a lower level. To achieve this as the motor increases speed requires the ratio of carrier frequency to modulating frequency to be decreased as the inverter output frequency increases in a manner similar to that shown in Fig. 9. At very low speeds asynchronous operation of the inverter can be used, to reduce the number of frequency ratio changes. At maximum inverter output voltage, pwm operation ceases and the inverter is operated as a normal six-step inverter.

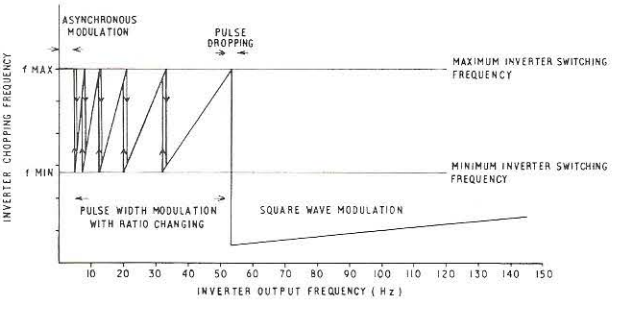
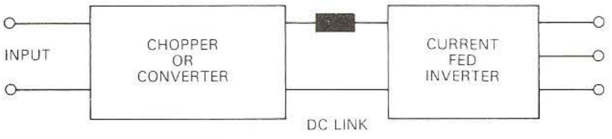


Fig. 9 Ratio changing.

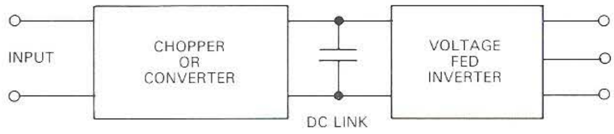
The voltage fed inverter is capable of operation over a range of input voltages. However, in traction applications where the starting tractive effort must be maintained even at reduced supply voltages the voltage fed inverter is best utilised if the dc input voltage can be maintained constant. This enables device ratings and commutation circuits to be optimised and minimises both cost and size of the equipment. Again, the input control would nominally be a chopper for dc systems or a phase angle controlled rectifier for ac systems.

4. LINE-SIDE CONVERTERS

The need to precede both types of inverter circuit by some form of input control results in a vehicle equipment having two stages of power conditioning is shown schematically in Fig. 10.



(a) CURRENT FED INVERTER



(b) VOLTAGE FED INVERTER

Fig. 10 Two-stage power conditioning equipment.

On dc systems the input control must be capable of correct operation over a line voltage variation of perhaps +20% to —30% of nominal voltage. In addition, to avoid possible signalling interference supply harmonics must be minimised. These criteria can be met using presently available chopper equipments.

On ac systems similar criteria also apply. These can be met using phase-angle controlled rectifiers. However, a problem peculiar to ac systems is the reactive and harmonic power generated by such static converters. Reactive power and harmonic power contribute to both additional losses and supply voltage distortion. Ideally, to avoid such problems the supply-side power factor should be unity. GEC Traction is presently developing a pulse converter circuit which utilises inverter technology to achieve unity power factor operation. A description of this pulse converter is described in Section 4.1.

4.1 Pulse converter

The pulse converter power circuit is shown in Fig. 11. The circuit consists of a diode bridge in which each diode arm has an anti-parallel force commutated thyristor. The converter input must be a high reactance supply, normally an inductor connected in series with the supply transformer, and its output is connected to a dc link which comprises a smoothing capacitor and a second harmonic filter.

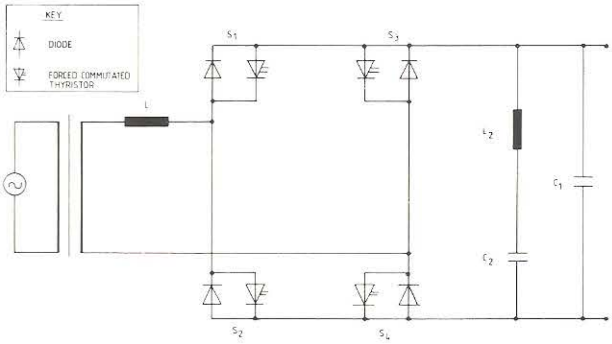


Fig. 11 Fixed voltage dc link converter power circuit.

The converter, capable of multiple commutations per half-cycle of supply, is controlled to maintain the dc link voltage constant independent of supply voltage variations and load variations. Its switching sequence is controlled in such a way that the current drawn from the supply approximates to a sine wave and has a fundamental component in phase with the supply voltage.

The converter operates in a manner very similar to the pwm mode of operation of the voltage fed inverter discussed earlier. The measured dc link voltage is compared with the demanded value and the error signal is combined with a supply voltage reference in such a way as to produce a modulating signal representing, in phase and magnitude, the fundamental component of voltage required at the converter input. The modulating signal is then compared with a triangular carrier wave, Fig. 12, to obtain a signal which will pulse-width-modulate the converter. The circuit works equally well for either polarity of dc link voltage error and hence regeneration at unity power

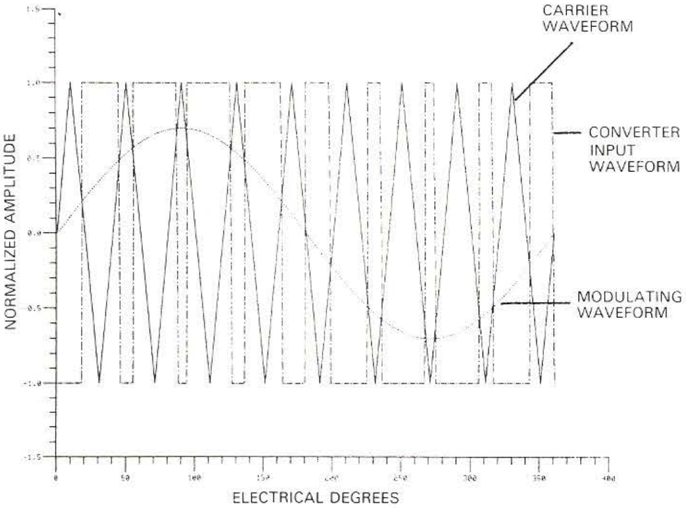


Fig. 12 Comparator waveforms

factor is possible. Representative waveforms for the converter working in motoring and regeneration are shown in Figs. 13 and 14 respectively.

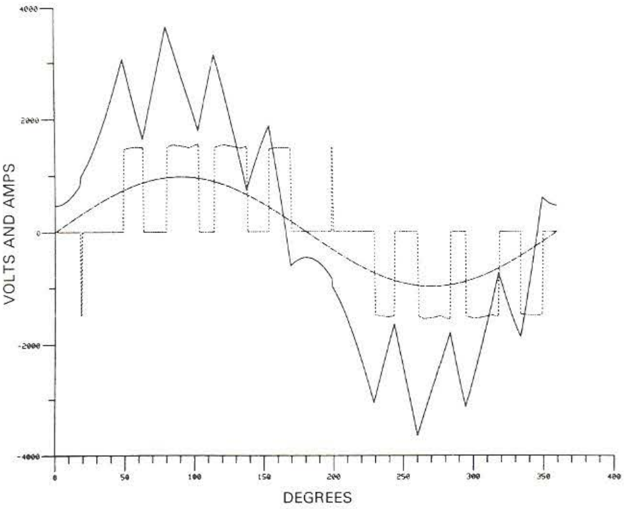


Fig. 13 Power circuit waveforms: motoring.

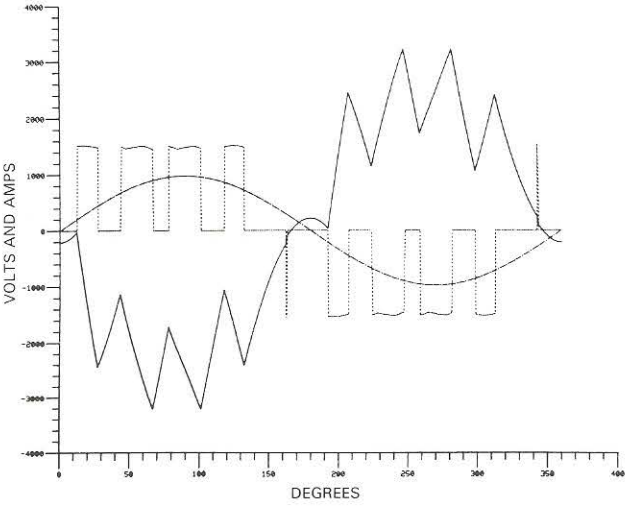


Fig. 14 Power circuit waveforms: Regenerative braking.

In order to reduce the harmonic content still further, without increasing the switching frequency, two or more converters can be operated interlaced. Fig. 15 shows a power schematic with four converters arranged in two groups of two in parallel. The secondary currents for each converter of this arrangement together with the composite primary current are shown in Fig. 16. A power factor of $\lambda = 0.98$ is possible using such an arrangement.

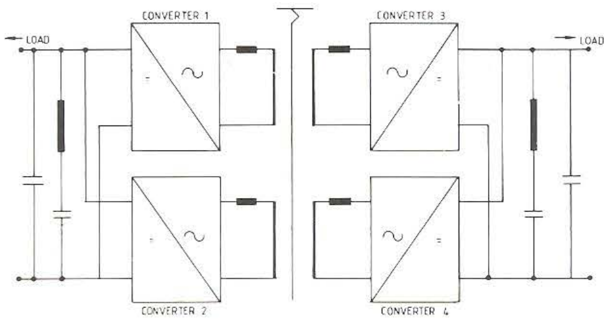


Fig. 15 Power circuit to achieve interlacing.

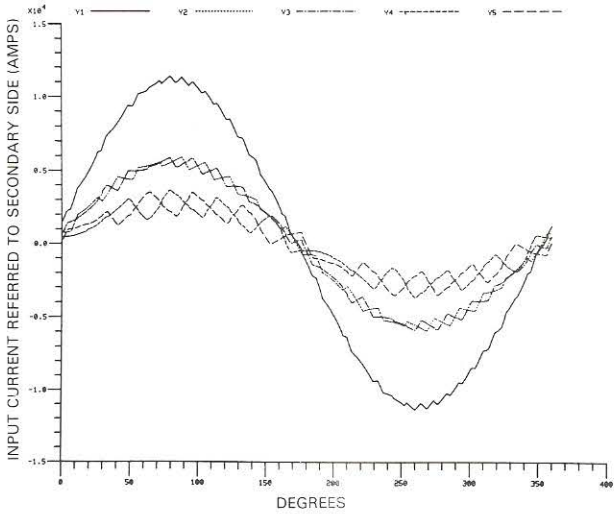


Fig. 16 Interlacing of secondary currents.

The performance available from this type of equipment is demonstrated by Fig. 17 which shows variation in power factor against load for both motoring and regenerative braking assuming a 5MW rated equipment.

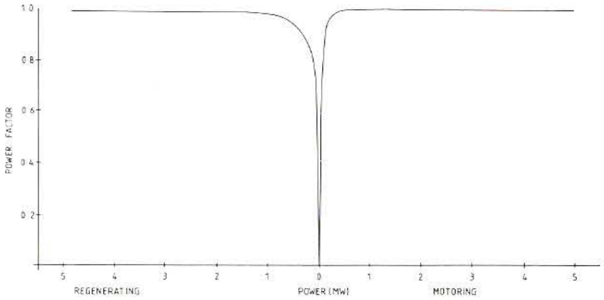


Fig. 17 Variation of power factor with power.

CONCLUSIONS

The squirrel cage induction motor has been reviewed. It is clear that such motors offer railway operators advantages of reduced maintenance and improved reliability. Two types of inverter for controlling induction motors have been described. The current fed inverter is of simple and robust design but has a torque ripple problem at low speed. The voltage fed inverter has an excellent performance characteristic but is much more complex in design.

The inverter circuits need to be preceded by a line-side converter either for input control purposes or for optimal inverter design. Conventionally, this input control would be a chopper on dc systems or a phase-angle controlled rectifier on ac systems. A converter for use with voltage fed inverters on ac systems has been described that will operate at unity power factor, thereby optimising energy usage and power demand.

At present, inverter drives are larger, heavier and more expensive than their dc equivalents. However, developments in power electronics are steadily eroding these disadvantages and in many cases the high initial equipment cost can be justified by the reduction in running costs. A number of inverter drive systems are now in operation on railway systems throughout the world. It is expected that systems such as these described, in 10-15 years time, will prevail over their presently accepted alternative.

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GEC Traction Limited
Holding Company — The General Electric Company, p.l.c., of England
PO Box 134, Manchester M60 1AH
Telephone: 061-872 2431 Telex: 667152 Telegrams: Assocelect Manchester

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