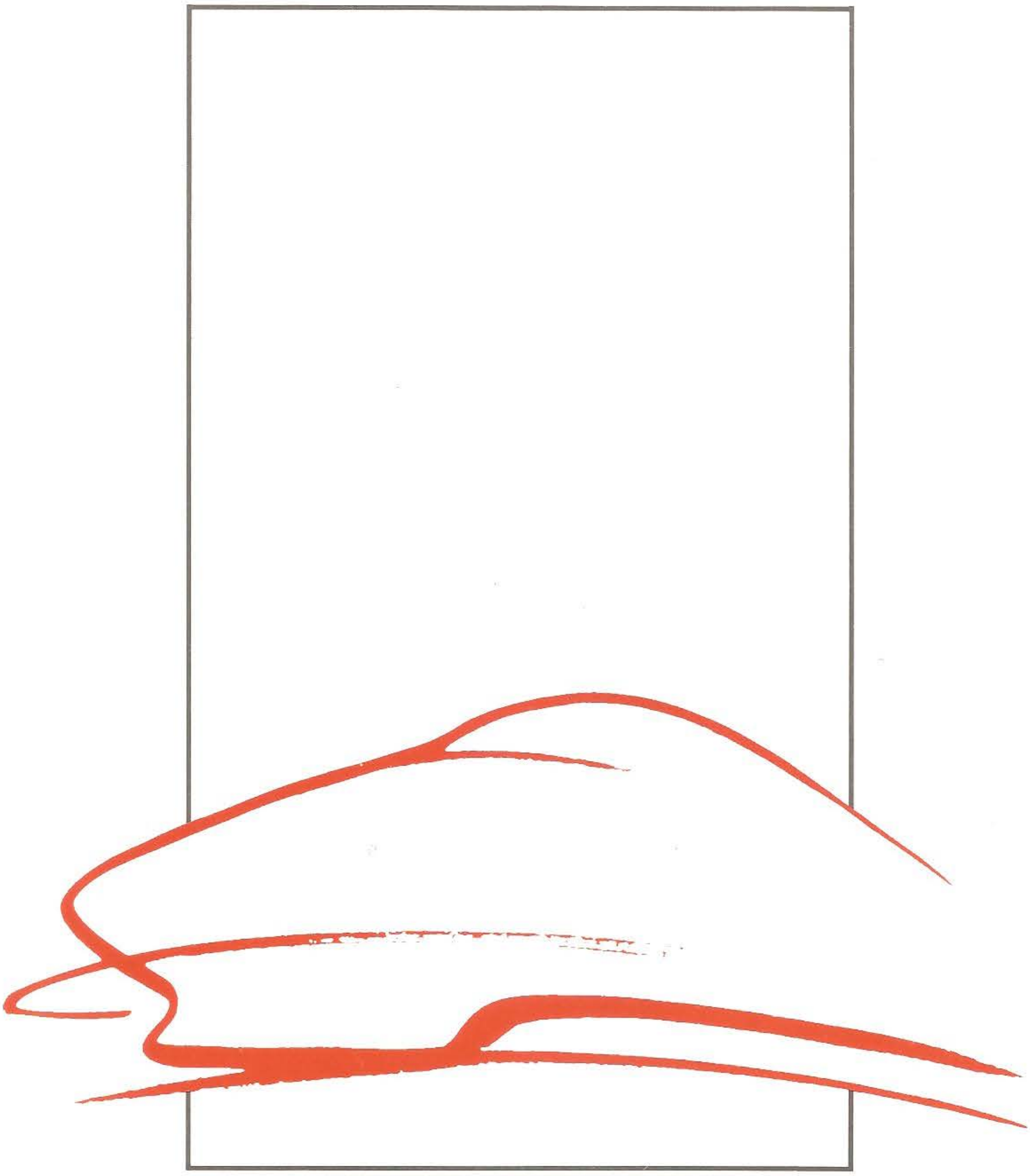
THE EFFICIENT DRIVE
FLEET CONVERSION TO CHOPPER CONTROL

by

M. Borup and S. Simpson
GEC ALSTHOM Traction UK

GEC ALSTHOM – TRANSPORT DIVISION



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HONG KONG MTRC – THE EFFICIENT DRIVE

M. Borup and S. Simpson of GECA Traction

GEC ALSTHOM Traction Ltd., UK.

Introduction

Rapid advances in power electronics over the last ten years have brought with them major improvements in rolling stock propulsion equipment performance particularly in relation to efficiency in motoring and to regenerative brake capability. The savings and benefits available are such that replacement of older systems based on resistance control with solid state control systems can sometimes be justified especially where a substantial part of the rolling stock life remains. This paper describes the equipment used on one such replacment programme which is currently taking place on the camshaft controlled stock of Hong Kong MTRC.

Project requirements

Each railway system operates under different conditions and constraints. For example, energy costs, labour costs, operating patterns, configuration of the power supply system and proportion of track in tunnel can all vary widely between railway systems. The savings and benefits to be gained by equipment upgrading must therefore rely heavily on information supplied by the railway operator.

In the case of Hong Kong MTR it was MTRC themselves who conducted the entire cost/benefit analysis and specified their technical and programme requirements to potential suppliers.[1]

Before identifying the project requirements as perceived by the equipment suppliers it is useful to review briefly some key features of the Hong Kong MTR system and MTRC's perception of the likely benefits to be gained from equipment upgrading.

The Hong Kong Mass Transit Railway Corporation operates one of the most intense metro services in the world, carrying over 2 million passengers daily on a system with only 43.2 route kilometres and 38 stations. There is 1 minute 45 seconds headway between 8 car trains during the rush hours and even that will be reduced further when the MTR's signalling is updated in the near future. Hence it is essential that all traction equipment supplied has high reliability and availability.

MTRC's rolling stock fleet included 224 two car units using camshaft controllers for resistance control in motoring and rheostatic dynamic brake.

The introduction of small numbers of units using chopper control high-lighted the relative disadvantages of camshaft control in mass transit type operations compared with modern solid state power control techniques.

In essence the disadvantages of camshaft control equipment are

— significant energy losses in motoring due to the resistance control scheme.

— no regenerative brake capability leading to loss of all potential energy during braking

— high maintenance costs are incurred due to the large numbers of moving parts in the equipment.

As the half life stage of the camshaft equipment approached, MTRC undertook a comprehensive study of the costs involved in converting all 224 camshaft controllers to chopper control.

The expected benefits from this were

— low energy losses in motoring, by elimination of the starting resistors.

— regenerative brake capability, enabling a large proportion of the braking energy to regenerate into the overhead line for use by other vehicles.

— low maintenance requirements, due to low numbers of mechanical parts.

— Operational enhancements resulting from the use of modern microprocessor based control e.g. the chopper equipment can smoothly blend the acceleration and braking of the train and this results in a smoother ride.

Other expected benefits specifically directed to passenger comfort were

— reduced wheel flats, hence reduced noise and damage to the rail and track which is a direct result of the improved wheelslip control.

— less waste heat released by trains into tunnels, resulting in improved station environment.

MTRC concluded from their analysis that the greatest benefit by far of equipment upgrading would be reduced energy costs and that these would result in a substantial net saving over the remaining vehicle life provided estimated conversion costs could be achieved in practice. Energy efficiency therefore became a prime technical requirement.

Hong Kong MTR operates on very high levels of availability and reliability. This places severe constraints on the number of units that can be held out of service for the purposes of a conversion programme. MTRC therefore specified that a maximum of four units could be withdrawn for this purpose at any one time. In addition, stringent reliability and availability requirements were laid down to ensure that the impact on the railway was limited to the withdrawal of the conversion units only and that re-entry into service after conversion did not produce even temporarily a deterioration in fleet reliability.

We can now examine the project requirements as perceived by the equipment supplier.

(a) Maximum equipment reuse. This contributes directly to lower conversion costs.

(b) Maximum energy efficiency. Any verifiable claim of reduced energy consumption was to be taken into account by MTRC in tender assessment.

(c) Maximum reliability. Failure to meet availability and reliability requirements carried potentially heavy penalties.

(d) Minimum conversion time leading to an increased conversion rate.

(e) Minimum development time. Use of proven equipment could allow the programme to be brought forward.

(f) Naturally cooled power electronics. MTRC had expressed a strong preference for such a design.

It should be noted that whilst all of the above points affected the technical design they also, with the exception of (c) and (f), provided an opportunity to create a real competitive advantage since additional savings resulting from improvements in these areas were readily calculable by MTRC.

Design Philosophy

The means by which the project requirements outlined above are fulfilled by the design adopted is described below

(a) **Maximum equipment reuse.**
It is readily apparent that a major advantage is to be gained by retention of the existing traction motor. Conversion to AC induction motor drives or even to sep-ex DC machines which can be achieved by a simple rewind, carries substantial cost penalties both in terms of new equipment cost and conversion time and cost. MTRC themselves had identified these as options which were extremely unlikely to be worth pursuing. It can be seen from Figure 1 that the existing motors were indeed retained and this will be shown to have a major impact on the circuit design. It can also be seen that major items of other equipment have also been reused.

(b) **Maximum Energy Efficiency**
The effect of the change from resistance to chopper control on motoring energy consumption needs little explanation here. Two refinements should be noted however. The use of GTO thyristors as the switching element in the circuit enables the chopper to reach full conduction thereby minimising losses. Losses in the line filter inductor have also been minimised by adopting a low resistance iron cored design. These

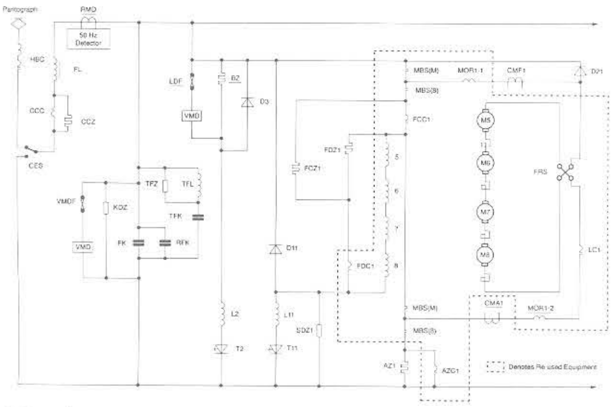


Fig. 1

two factors enable the chopper circuit to achieve the same overall motoring performance as the camshaft equipment with a reduction in weakfield ratio of only 3% (from 60% to 57%).

The principal energy saving arises from the introduction of regenerative brake. The use of a relatively low characteristic motor on the camshaft controlled stock required particular attention to be paid to the regenerative braking scheme if maximum efficiency is to be obtained. The salient points can be understood by reference to Figure 2.

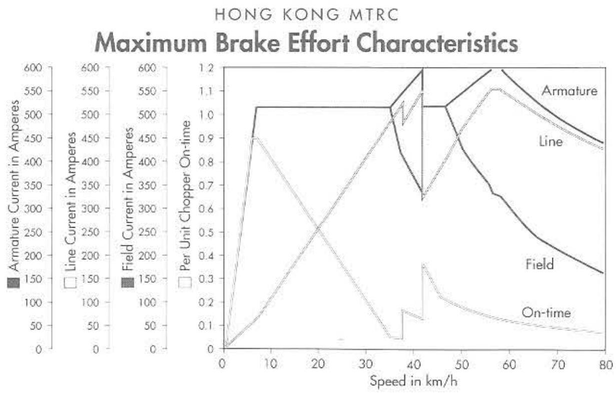


Fig. 2

Low speed braking is achieved using a self excited series brake circuit operating in a 'store and let fly' mode. At higher speeds the braking Diode becomes forward biased and this allows a separately excited mode of braking to be employed. However, to enable a constant braking effort to be produced the armature current has to be higher than the full field motor current. Limits on this area of operation are therefore determined by the armature current limit which for this particular motor is set at 600A. At still higher speeds, armature resistance is required to allow increased armature voltage to be developed. Once again a limit is imposed by the armature current limit. In addition, the motor commutation limit defines the highest speed at which full braking effort can be achieved.

The method of control of the chopper in brake is illustrated by Figure 3. It can be seen that there are

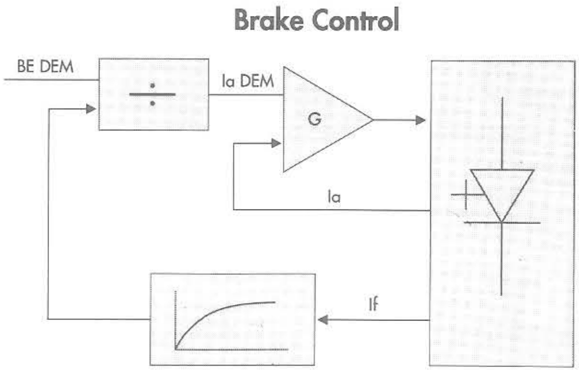


Fig. 3

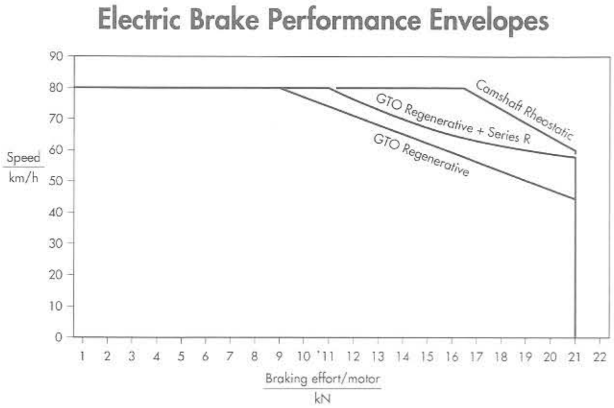


Fig. 4

effectively two control loops: an inner loop controlling armature current and an outer brake effort control loop. The maximum Braking envelope achieved is shown in Figure 4.

(c) **Reliability**

The method specified by MTRC for assessment of reliability and availability was based on measurements on either a small group of units or a larger group of units over a short period. In outline the two conditions to be met were that the reliability on a group of eight units should exceed 150,000 km MDBF over the second six months in service and that the number of faults on a group of 104 units should not exceed 4 in any four week period. Whilst these conditions appear relatively easy to meet, the effect of random distribution of faults over time and over the fleet has a dramatic effect on the reliability required if a reasonable probability of avoiding penalties is to be achieved. Calculations showed that equipment reliability was required to exceed 1,000,000 km MBDF to achieve a 95% probability of avoiding penalties over the whole of the conversion programme.

To meet these requirements several items of electronic equipment were redesigned to reduce component counts and provide further component derating. In addition the level of routine testing was increased for some components, at least initially.

(d) **Natural cooling**

The two elements in the chopper circuit which principally determine the cooling requirements are the GTO devices themselves and their associated snubber networks. Equipment supplied previously to MTRC by GEC Alsthom had employed forced cooling for both the GTO's and their snubbers but the need for forced cooling was largely governed by the use of a standard GTO snubber network. In 1500v systems the losses in the snubber capacitor discharge resistor are high reaching 2.7 kW per GTO in the MTRC application. The need for forced cooling of the GTO's themselves was far smaller given that a double sided live heatsink design had been adopted. However the change to a single sided earthed heatsink design for the convesion progamme did require considerable development of the GTO device cooling arrangement.

The outcome of this development is detailed in 'Equipment Description' below. High dissipation in the snubber resistors made a compact naturally cooled design difficult to achieve and a snubber energy recovery network was therefore adopted. The basic snubber circuit is shown in Figure 5 and it can be seen that the additional components are limited to two diodes. Dr and Di and the capacitor Ci. In practice, stray circuit inductances cause undesirable oscillations and these have to be controlled by the insertion of a small resistance in series with diode Dr. Nevertheless the reduction in overall dissipation is significant with mean snubber losses at 65W per GTO.

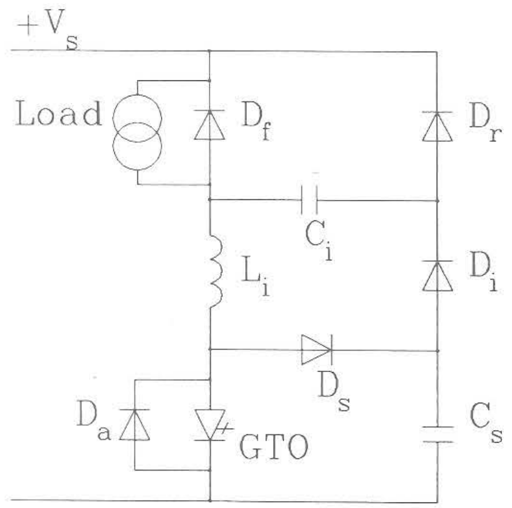
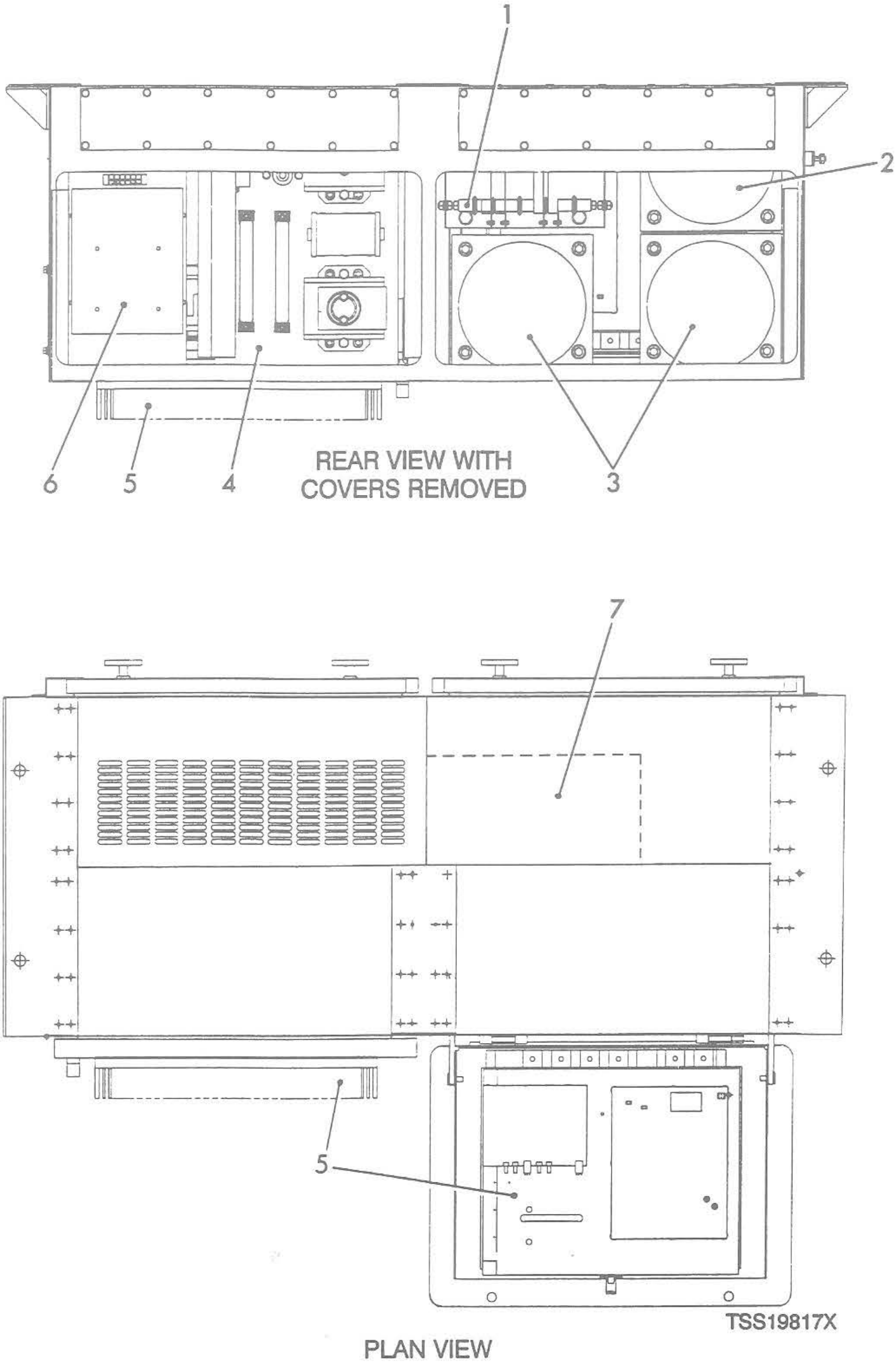


Fig. 5 Simplified schematic diagram of chopper

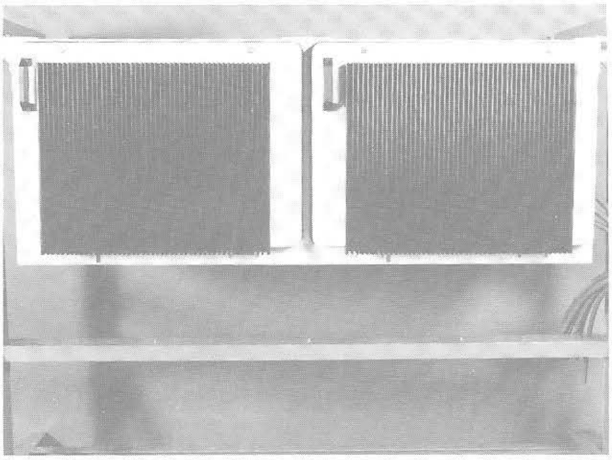
Equipment Description

The chopper equipment supplied was mounted in a number of small equipment cases, with the chopper power electronics equipment mounted in the chopper equipment case shown in Figure 6. The fins of the two heatsinks protrude from the case and these can be hinged down from the case for easy access to the equipment mounted on them. They can also be easily removed for maintenance/repair off the vehicle.

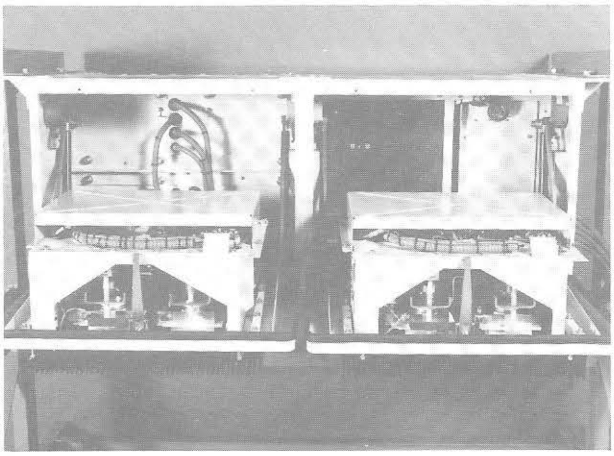


1. Recovery resistor
2. di/dt inductor G97LM
3. di/dt inductor G97KN
4. Rheo chopper assembly 23RA015B2
5. Heatsink assembly 23RA014B2
6. Supply inverter 30EU013B1
7. Rheo gate drive panel assembly containing:
   PCU panel 05EP063B1
   GDP panel 05EP059B1

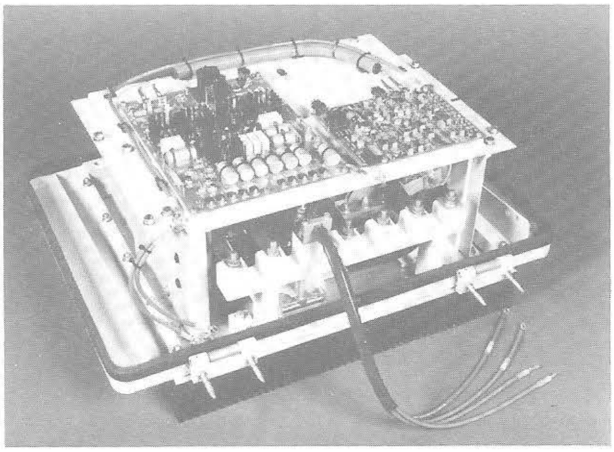
Fig. 6



Chopper equipment case



Chopper case with fins down showing the heatsinks



Heatsink with top cover removed

Each heatsink assembly, illustrated in Figure 7 has the GTO firing circuitry mounted on a removable top panel and beneath this, mounted on the heatsink itself, are three main assemblies, the main GTO thyristor, the freewheel diode and the braking diode assembly. In addition there are various other snubber components which make up the complete snubber network with the exception of the di/dt limiting inductor and a resistor which is used to damp any ringing in the circuit which are mounted elsewhere in the case. The devices are mounted on copper blocks which are electrically insulated from the earthed heatsink using a piece of ceramic which has a high thermal conductivity. The thermal drop across the ceramic in this application is 3 C/kW. In the rear of the case there is the short time rated rheostatic brake chopper assembly which is fired in the event of the filter capacitor volts rising above 1800V or in the event of trying to regenerate energy into a non receptive line.

Both the main chopper assemblies and the rheostatic chopper assembly are controlled by a microprocessor based system. This equipment is also mounted on the underframe of the vehicle in the electronic case shown in Figure 8.

Microprocessor control has been used to optimise the regenerative brake characteristic, to smoothly blend acceleration and braking of the train, to control the vehicle in the event of wheel slip or wheel slide and also to diagnose faults and log this information to enable rapid identification of faults by the maintenance staff.

Underframe Layout

It was necessary to mount the equipment in the area vacated by the redundant camshaft equipment.

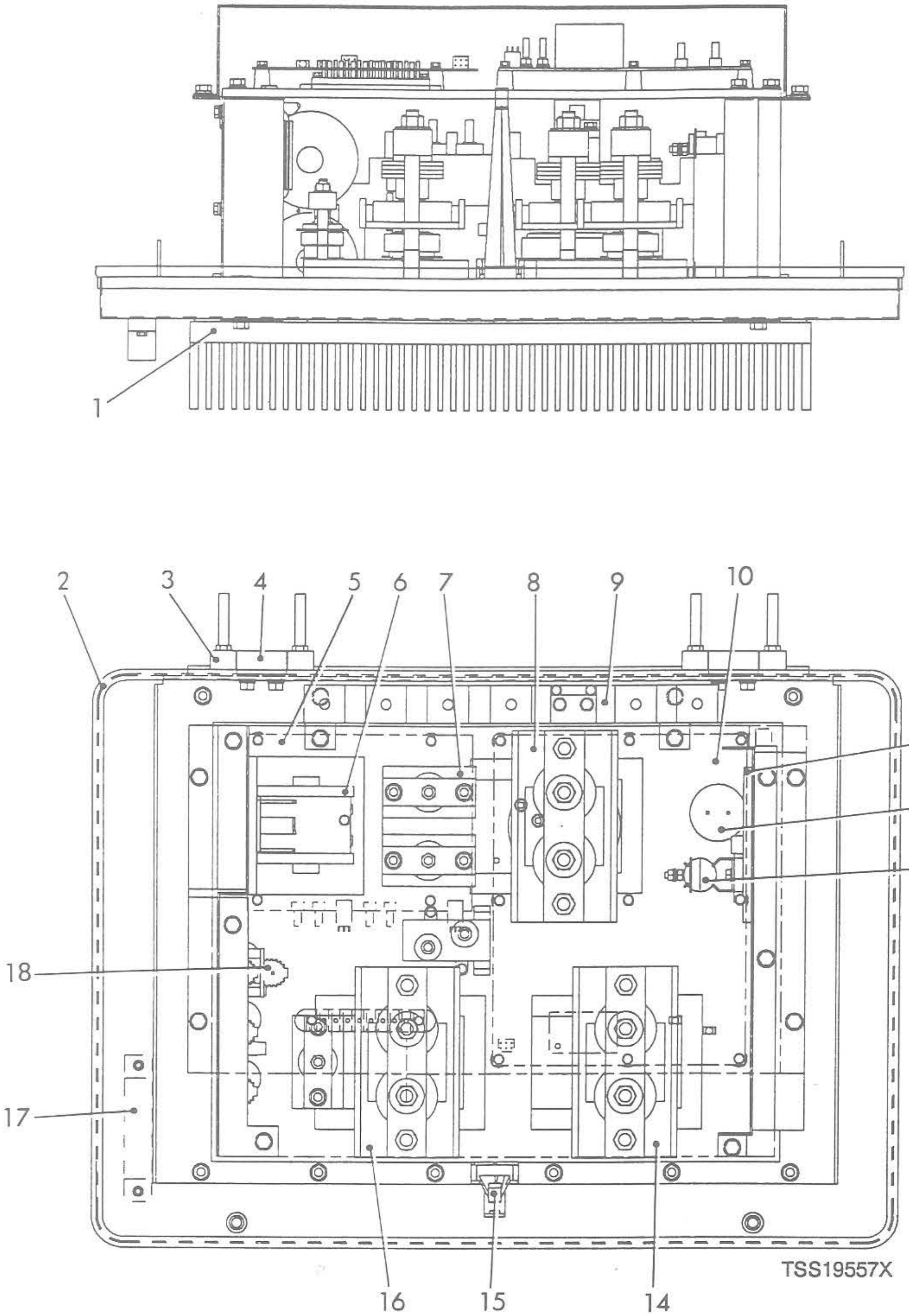
MTRC's camshaft fleet consists of two different camshaft arrangements. The earlier fleet known as M stock consisted of two small camshaft equipments mounted one on each of the two cars in the two car unit. The later fleet, known as T stock consisted of one large camshaft equipment mounted on one car of a two car unit. Therefore for M stock cars it would be necessary to substantially modify both cars of a two car unit whereas essentially only one car of a T stock 2 car unit need be modified. Figure 9 shows the layout of that car before and after its conversion. This highlights the equipment which was to be removed and that which replaced it. It was necessary to design equipment which could be mounted directly in the vacated area. The prototype GTO chopper delivered by GECA in 1988 was in fact fitted to a camshaft vehicle and therefore the equipment to be supplied could be based on that design.

It was estimated that the conversion of the earlier stock (M stock) would take longer than conversion of T stock and therefore applying the principal of converting the fleet in the shortest time to take advantage of the accumulative energy savings the decision was taken to convert the T stock vehicles first.

The final result was an underframe layout which was very similar to that of T stock and is as shown on Figures 10 & 11.

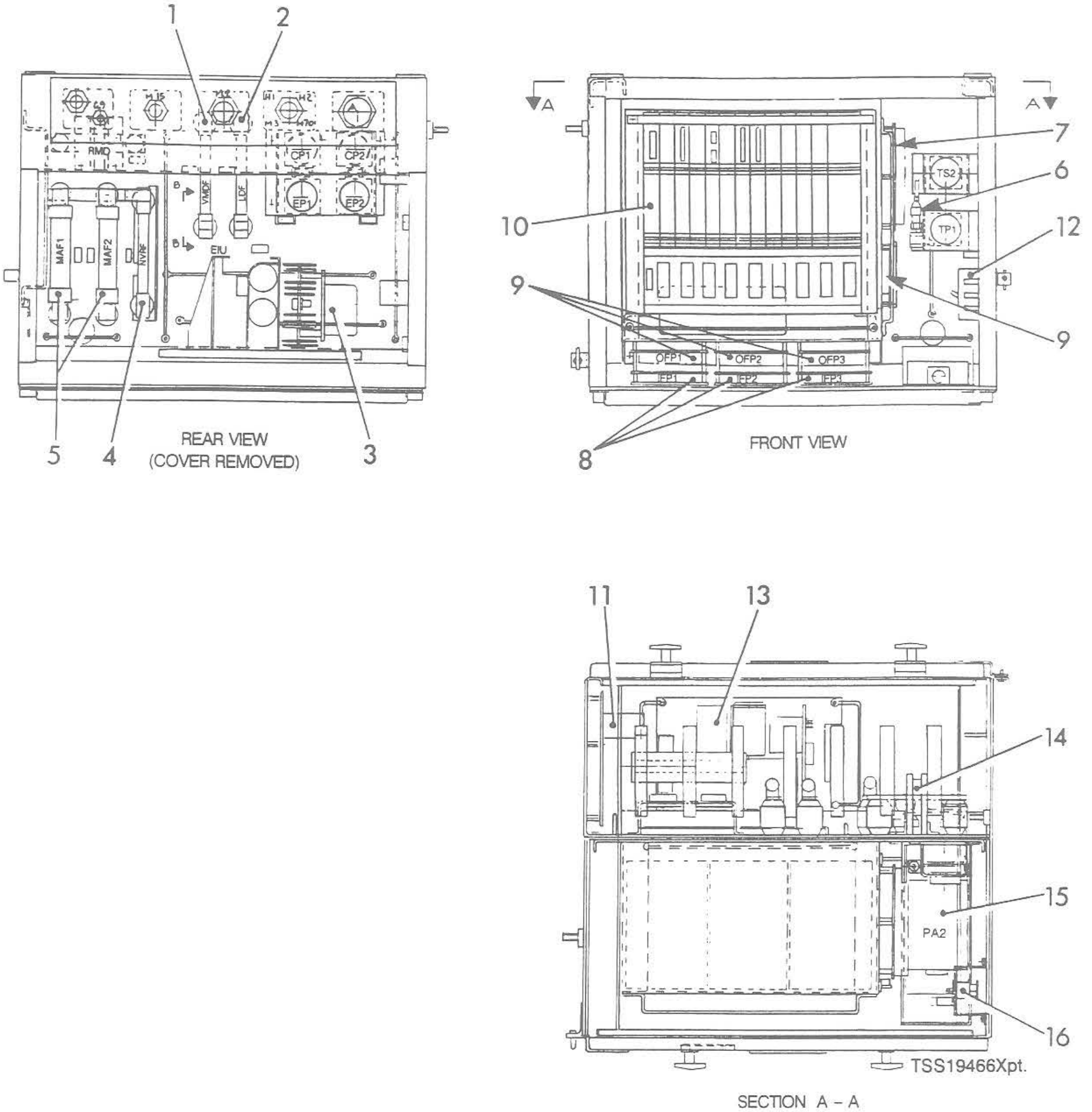
Installation

The conversion was performed using the latest techniques, with tables similar to that shown, it was possible to manoeuvre the cases into the exact horizontal and vertical positions in a relatively short period of time. As speed is an important consideration in the



1. Heatsink
2. Door assembly
3. Hinge (Female)
4. Hinge (Male)
5. Capacitor panel
6. GTO snubber capacitor
7. Energy transfer capacitor
8. GTO assembly
9. Terminal bar
10. Top panel terminal block
    PCU panel type 05EP063B1
    GDP panel type 05EP059B1
11. Brake snubber panel
12. Brake snubber capacitor
13. Brake snubber resistor
14. BD assembly
15. Door catch
16. FD assembly
17. Door handle
18. R-C snubber panel

Fig. 7



1. VMD fuse
2. LD fuse
3. Inverter unit
4. NVR fuse
5. MAF fuses
6. Transducer
7. Brake interface
8. Input filter panel
9. Output filter panel
10. Electronic frame
11. VMD panel
12. 50 Hz oscillator panel
13. Inverter unit
14. 50 Hz Detector coil
15. 50 Hz detector panel
16. Cut-out switch

Fig. 8

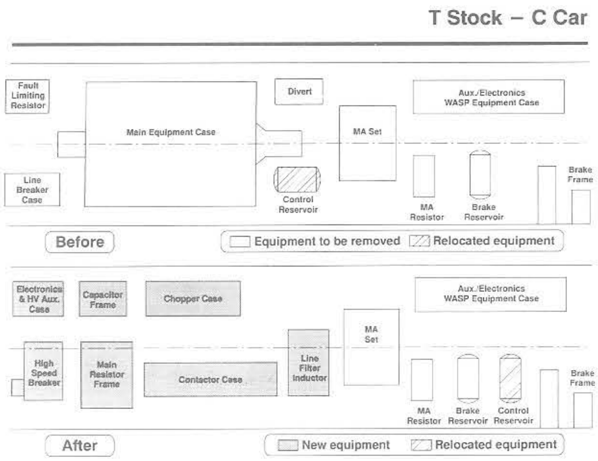


Fig. 9

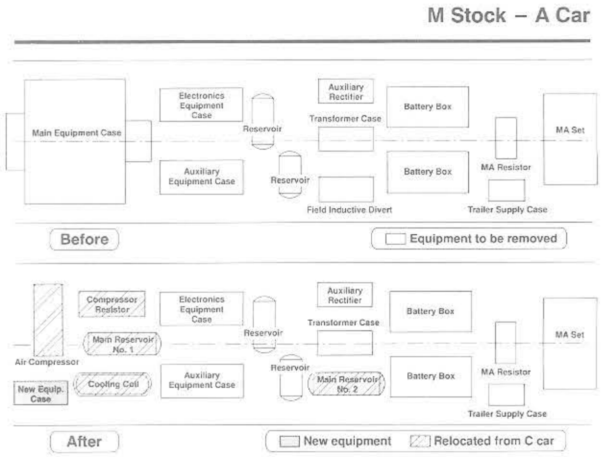


Fig. 10

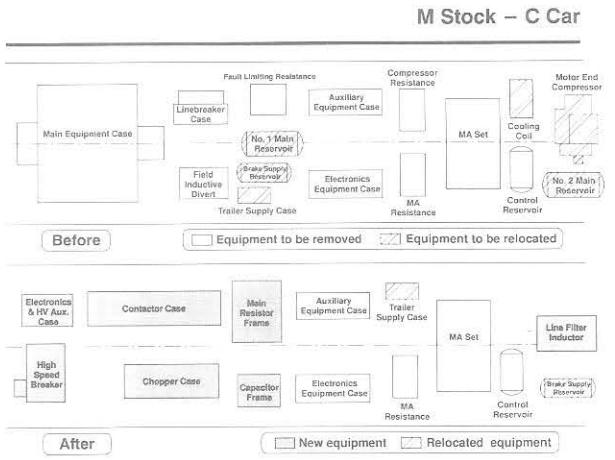
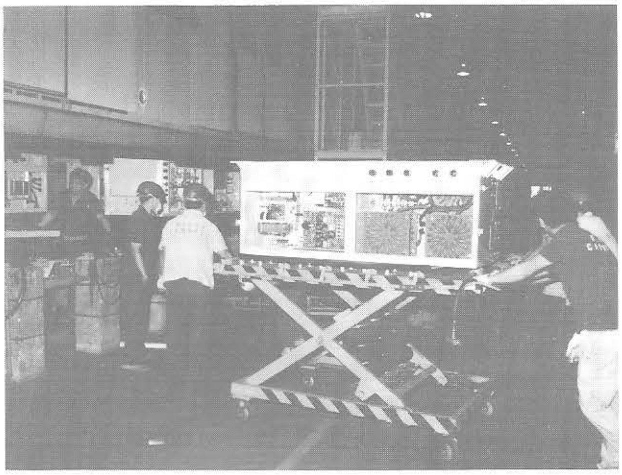
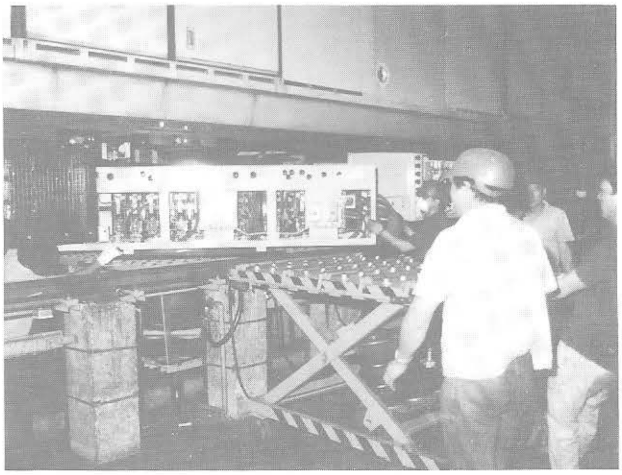
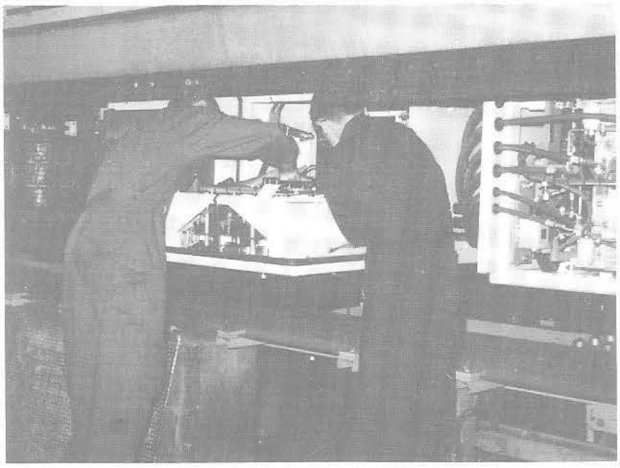


Fig. 11

conversion, any time saving device was utilised. Wherever possible existing cross beams were used to mount the new equipment, using adapter frames to minimise conversion time where possible. However it was necessary in some instances to put in new cross beams.







Refitting the new chopper equipment

Results

Programme	Start	Finish
Specified	30.11.92	7.8.95
Achieved	7.9.92	31.3.95

No. of units now in service 125
Conversion Time 7 days (T Stock)
Units withdrawn at any one time 3
Conversion Rate 11 per month

Energy Consumption

At the mid point of the programme the average energy consumption has been reduced from 3.5 kWh per car km to approximately 3 kWh per car km.

In November 1993 is was announced by MTRC that the measured savings were 19 thousand MW hrs, which was equivalent to HK$9.7 million.

Reliability and Availability

For the month fo January 1994 the number of car km per casualty was announced by MTRC as being approximately 1.25 million.

Conclusions

Our experience on this programme and the results obtained have shown that a conversion of resistance control to chopper control is not only feasible but can also be finally and operationally beneficial.

It has been shown that such a programme can be implemented, even on intensively used systems, without any disruption to existing service.

Acknowledgements

The authors would wish to thank Mr. O.J. Fried of Hong Kong MTRC for permission to use the reliability and energy consumption figures contained in this paper.

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GEC ALSTHOM

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GEC ALSTHOM Traction Ltd PO Box 134 Manchester M60 1AH United Kingdom
Tel: 061-872 2431 Fax: 061-875 2288

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