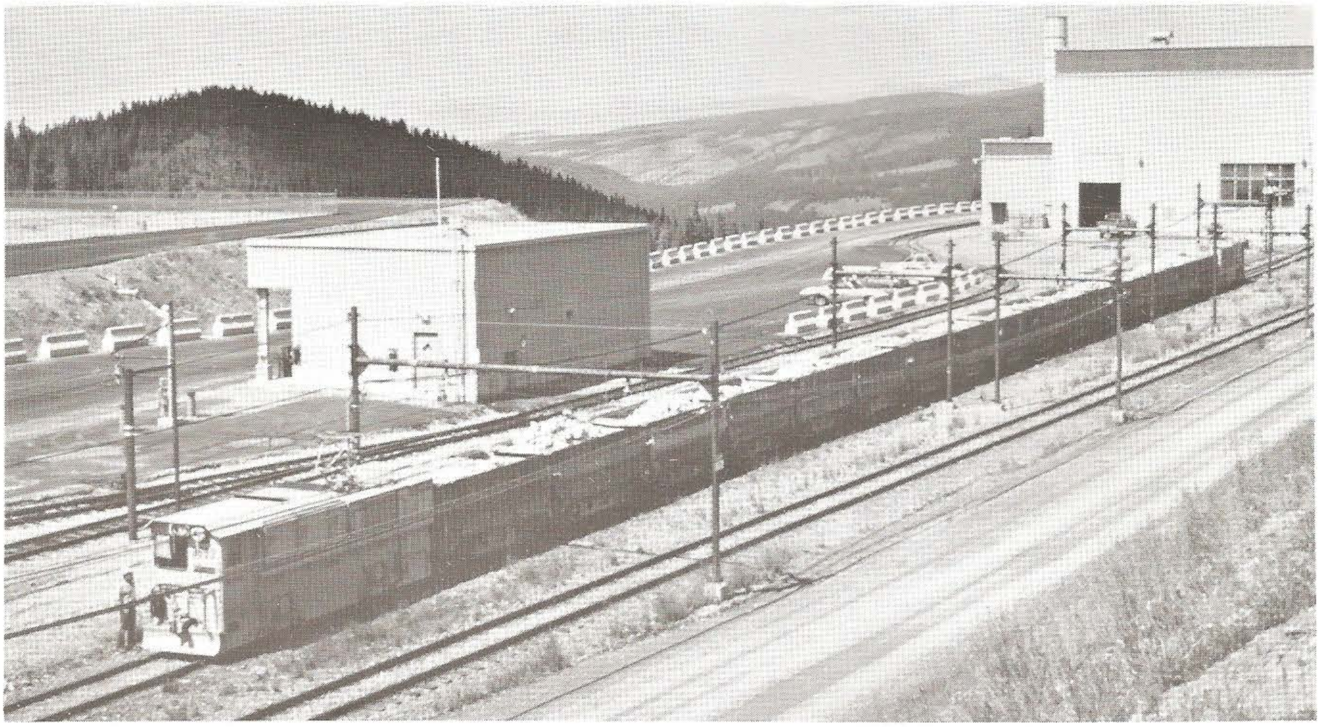
GEC
TRACTION

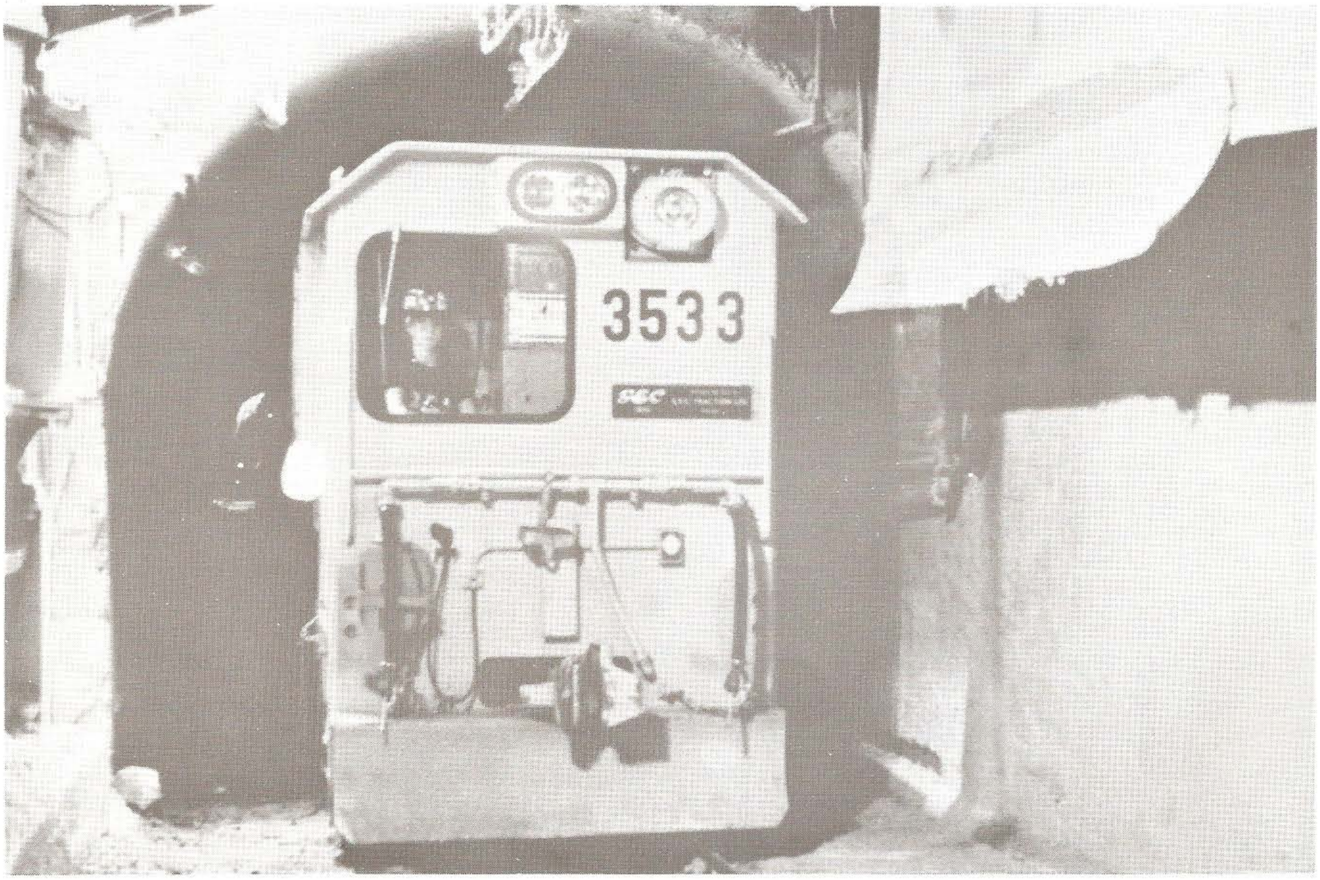
Dual-voltage, chopper-controlled, mining locomotives

LOCOMOTIVE DATA

Type of locomotive	Bo	Weight ready for service	56t (62 short tons)
Track gauge	1067 mm (3 ft 6in)	Length over body	7700 mm
Overhead voltage	1400 V/600 V	Height above rail, pantograph housed	2775 mm
Maximum service speed	40 km/h (25 mph)	Width overall	2010 mm
Overspeed limit	50 km/h (30 mph)	Wheelbase	3500 mm
Speed (continuous rating full field)	32 km/h (20 mph)	Wheel diameter (50% worn)	1190 mm (46.75 ins)
Maximum starting tractive effort	152 kN (34000 lbf)	Electrodynamic brake system	Regenerative and rheostatic
Continuous full field tractive effort	102 kN (23000 lbf)	Brake system (back-up)	Spring applied/air released
Continuous weak field tractive effort	55 kN (12000 lbf)	Traction motors	Two G415BY



Two views of the locos in operation:
(a) in the switching area by the crushing plant and
(b) at the underground loading area.



Dual-voltage, chopper-controlled, mining locomotives

Felix Schmidt, Dipl Ing ETH

INTRODUCTION

A total of four dual-voltage mining locomotives were ordered in 1978 from GEC Traction by the American AMAX Corporation for service in their Henderson molybdenum mine located near Golden in Colorado. The locomotives were delivered in two stages in 1980 and 1981. This is believed to be the first time ever that complete electric locomotives have been imported into the USA from Britain and certainly the first time for many years that a British Company has supplied locomotives of any type to the United States. The working conditions to which the locomotives are subjected and their haulage programme are demanding and required a robust design both mechanically and electrically. A number of novel features and designs were incorporated to meet the customer's requirements.

Fig. 1 The location of the mine to the west of Denver, Colorado.

DESCRIPTION OF THE LINE

The route length is some 24 km overall of which the first 16 km are underground with a grade of 3% against the load. A train can be made up of four locomotives, the two at the head and the two at the rear all controlled by one man, and 32 ore wagons. Mining and haulage operations are carried out around the clock and in this time some eight trips can be made. Regenerative braking is employed with the down (empty) trains, partly to recoup energy, partly to reduce temperatures in the tunnel, but also to prevent excessive wear of the mechanical tread brakes which need to be in excellent condition for emergency use.

Fig 1 shows the railway line and its location in Colorado, USA. The double track route is energised at 1400 V dc throughout except in the loading and unloading areas where the supply voltage is reduced to 600 V dc for safety reasons. The track gauge is 1.067 m (3 ft 6 in).

THE MINING OPERATION

The Henderson Mine was developed to exploit a large deposit of molybdenum bearing ore near Dillon. Henderson in fact is the world's largest single producer of this ore and in 1980 the mine output exceeded 23,000 tonnes (50 million lbs) of molybdenum concentrate. This output required the excavation, hauling and crushing of 4.2 million tonnes of ore.

The mine is located at an altitude of some 2300 m (7,500 ft) above sea level and is 1100 m below the crest of Red Mountain. The mine area actually straddles the Continental Divide with the excavation area on the Atlantic watershed but with the access tunnel portal and other surface facilities on the Pacific watershed. Fig 2 shows a section elevation of the mining operation. The access tunnel is double track and leads to the William Fort Valley, a distance of 16 km. From the tunnel portal to the crusher plant is a further 7.5 km but at a much easier grade (1.3% against the loaded trains) than in the tunnel. The crusher area is situated approximately 2900 m (9500 ft) above sea level.

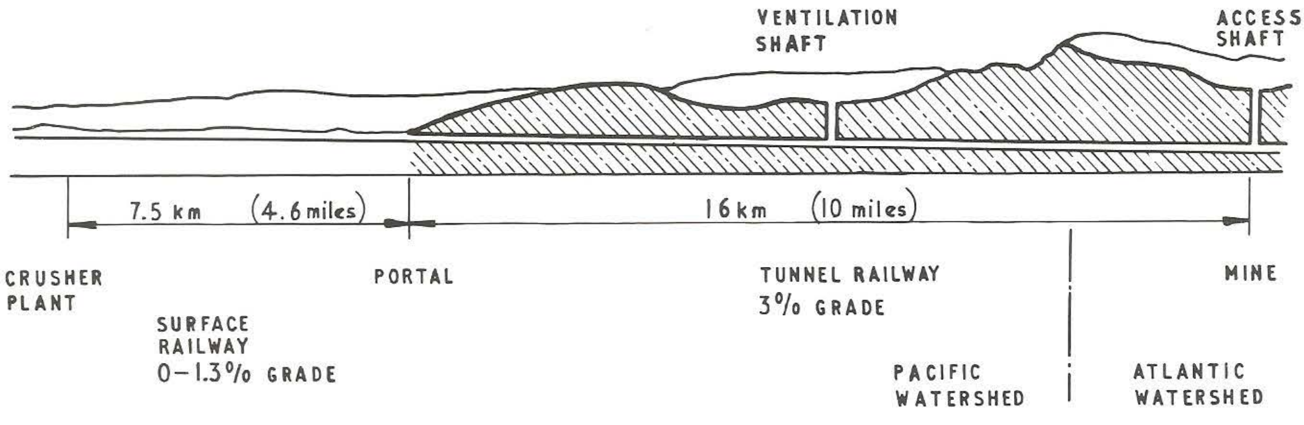


Fig. 2 Sectional elevation of the mine indicating the approximate positions of shafts and plant.

CLIMATIC AMBIENT CONDITIONS

At the bottom of the mine, which is some 1100 m below the mountain crest, the working temperature, even in winter, is typically 40°C, with a relative humidity of 40-50%. About half-way along the access tunnel used air is exhausted through a vertical shaft. At this point, in winter, the temperature is close to 0°C at 100% humidity. Continuing up the tunnel the temperature falls fast until at the portal it can be as low as —30°C. Snowfall in winter can be heavy and is often accompanied by strong winds. By contrast in summer relative humidity outside the tunnel can be as low as 3.4%.

Over a journey time of 30 minutes the temperature changes at an average rate of 2°C per minute with sudden and large variations in humidity.

DESIGN CONSIDERATIONS

The working environment and the special nature of the railway system placed a number of constraints on the design, such as:—

(1) the propulsion equipment must work at supply voltages from 1400 V down to 600 V; the lower value applies for safety reasons in the loading area.

(2) the locomotives must be able to control the train for the entire down-hill run at its service speed of 40 km/h (25 mile/h) using only rheostatic braking although normally regenerative braking is used.

(3) a *prevention of run-back* scheme was introduced on the locomotives. This system must guard against the possibility of a train running back down the grade due to its mechanical brakes having frozen in the "off" state while the control system was shut down.

(4) a single train driver must exercise control over up to four locomotives working in multiple in any position throughout the train.

(5) locomotives operating in pairs need to be laterally coupled to reduce flange wear and improve running performance in curves.

(6) protective equipment in the electrical systems had to be of the *no fuse* type to improve availability of the locomotives.

Fig 3 gives an idea of the restricted loading gauge in the double track tunnel. The overall dimensions of the locomotives had to be kept to the absolute minimum, and this presented major design problems since the accessibility of the equipment was to be maintained.

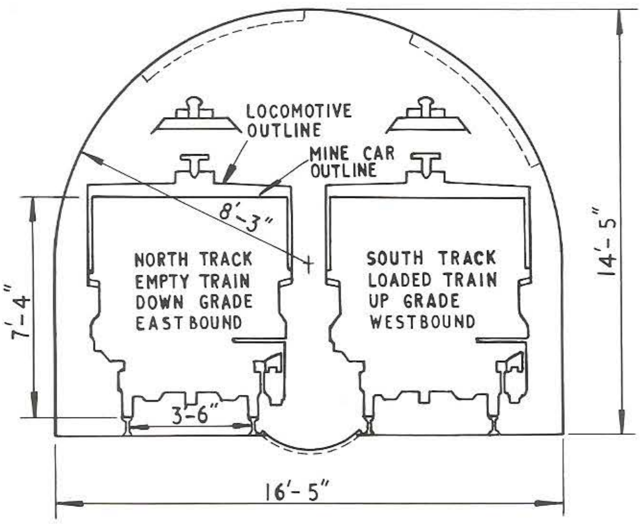


Fig. 3 Cross section through double track tunnel showing profile restrictions on the locomotive design.

MECHANICAL LAYOUT

The outline of the locomotive is shown in Fig 4. It is of two-axle design, both axles being driven by nose-suspended traction motors. The underframe is an all-welded steel structure with side plates and buffer beams of 100 mm material and a top place of 130 mm thickness. This heavy construction was necessary in order to achieve the required adhesion and to conform to the AAR standard buffing loads. Special care was taken in the construction of the cab to protect the driver during the passage under the loading chutes and in the case of a derailment.

The top plate of the underframe is extended on both sides of the locomotive so that its edges can be used as *rails* on which the locomotive glides through the unloading area. The track in this section of the line slopes away from underneath the train so that the ore-car undercarriages swing open to discharge their load. Both locomotives and ore cars travel for some time on stationary pulleys, the locomotives at the front of the train being pushed by those at the back and vice versa.

Besides the standard Willison couplers which are fitted to all the rolling stock the new series of locomotives are equipped with inter-loco spring couplers which give a pair of locomotives the behaviour of a four-axle bogie unit with respect to lateral forces on the rail in curves. This arrangement is illustrated in Fig 5. The two dc traction motors are suspended in the underframe with the motor, reduction gearing and axle forming an easily replaceable unit.

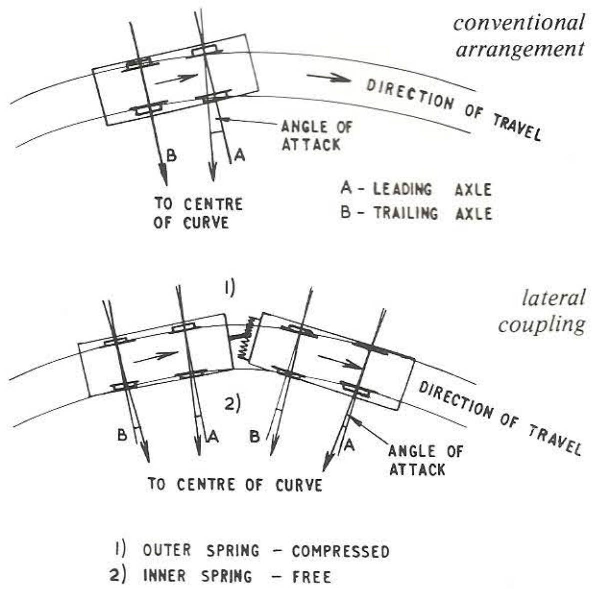
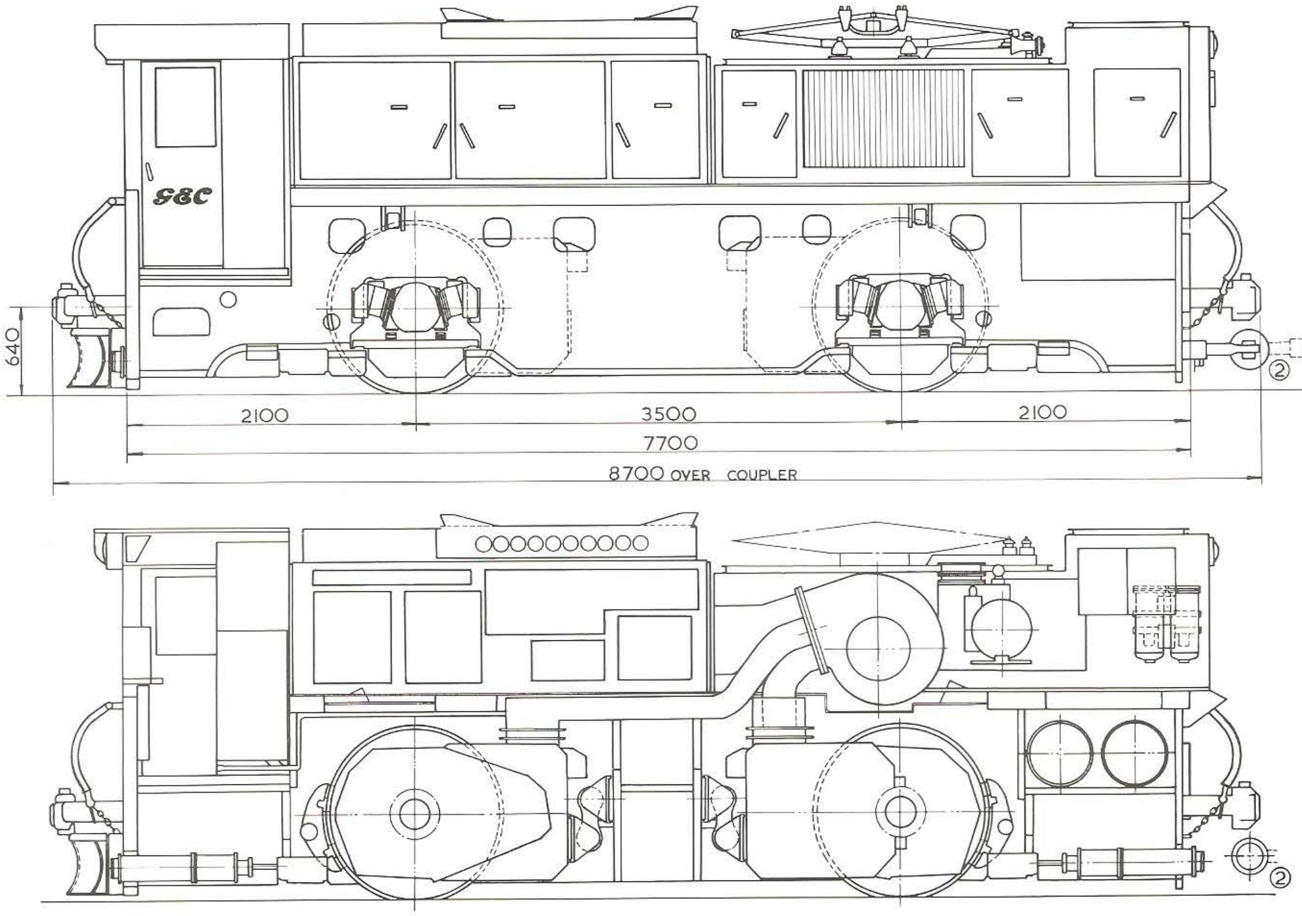


Fig. 5 Diagrammatic representation of twin locomotives showing advantage of inter-locomotive spring coupling which halves the angle of attack between wheels and rails.

The driver's cab at the front of the locomotive accommodates the electronic control systems and the driving and emergency controls. Both the Automatic Train Control (ATC, as yet not in use) and the Intra Train Communication (ITC, a fault reporting system) equipments are located in the cab. Even in the case of a motor failure there is no need for the driver to operate controls outside a cab since he has ready access to the isolating switches. This arrangement was necessary to take account of the restricted space in the tunnel.

Directly behind the cab is the main equipment case, the power module containing the thyristor banks, the filter and commutation networks and the contactor and switching blocks.



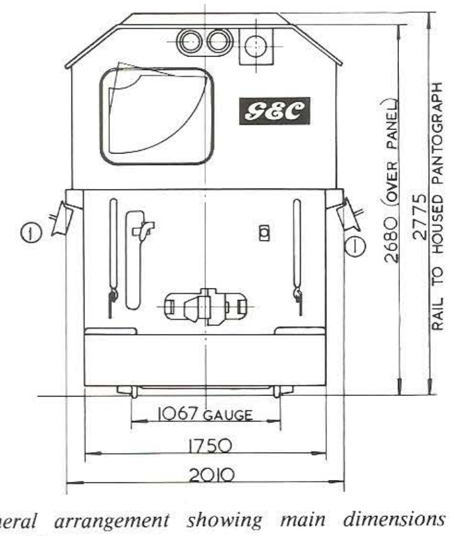


Fig. 4 General arrangement showing main dimensions of the locomotive.
(1) Stationary rollers supporting the locomotives in the unloading area.
(2) Spring for lateral coupling of two locomotives.

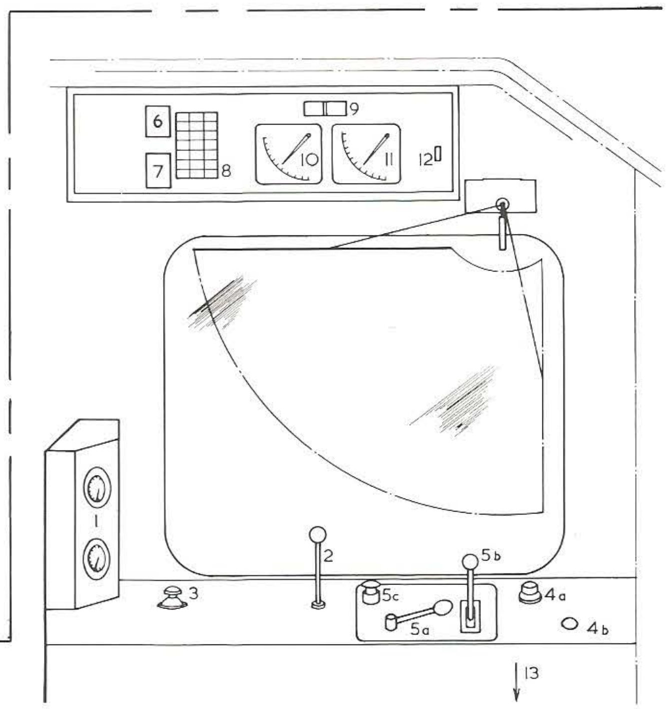


Fig. 6 Arrangement of the driver's controls
(1) Brake pressure gauges
(2) Independent air brake handle
(3) Fire/emergency button
(4a) Windscreen wiper valve
(4b) Horn valve
(5a) Forward reverse handle
(5b) Motor/brake effort handle
(5c) Emergency brake button
(6) Automatic control
(7) Pantograph
(8) Indicator lights
(9) Main indicators (overspeed)
(10) Line current
(11) Speed
(12) Light switch
(13) Deadman foot switch

The superstructure at the rear of the locomotive houses the battery, the low voltage equipment and the auxiliary machines such as the compressor, the air dryer, pneumatic valves, the centrifugal fan for the traction motors and for the air-cooled components in the main equipment case. The cooling air is taken in through an inertial filter system designed for the dusty mining environment. The filters are self-cleaning and the contaminants are extracted with a small fan. The high speed dc circuit breaker is also accommodated in this area, thus the power connection from the pantograph through an insulated roof bushing is the only unprotected length of cable on the locomotive.

Ruggedness and simplicity of design were the main considerations for the mechanical construction of equipment frames and cubicles. Most sub-assemblies are welded constructions made from steel plate and standard sections.

Performance

The locomotives are designed for a nominal maximum service speed of 25 mile/h (40 km/h) because that is the existing speed limit in the mine complex. Because of their single reduction gearing, however, the traction motors can operate safely at more than twice that speed and so there is an ample margin of safety in the event of an accidental overspeed.

Motoring performance is shown in Fig. 7 as are also the calculated likely maximum adhesion and the resistance of a loaded train. Fig. 8 shows the performance in braking whilst Figs. 9 and 10 show system behaviour and servo characteristics in motoring and braking respectively.

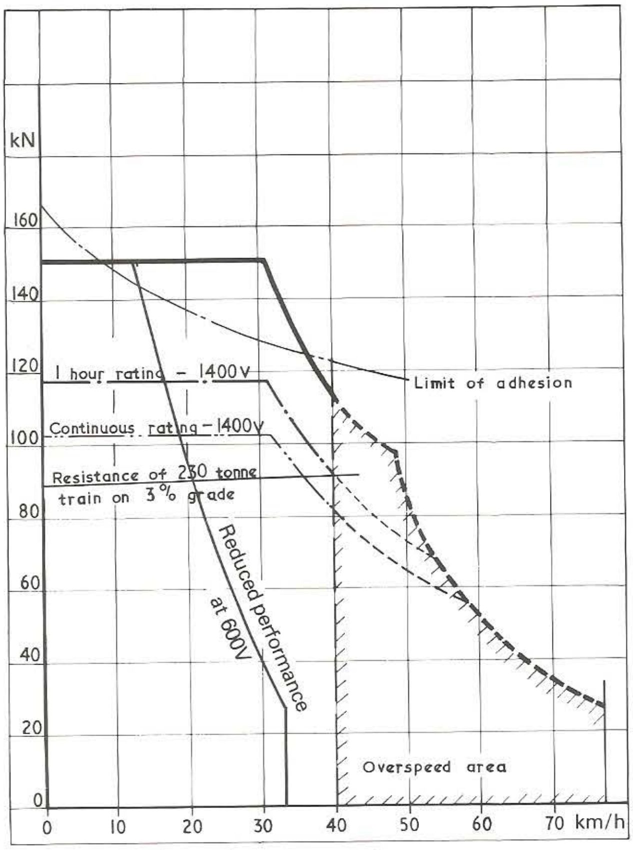


Fig. 7 Locomotive performance motoring

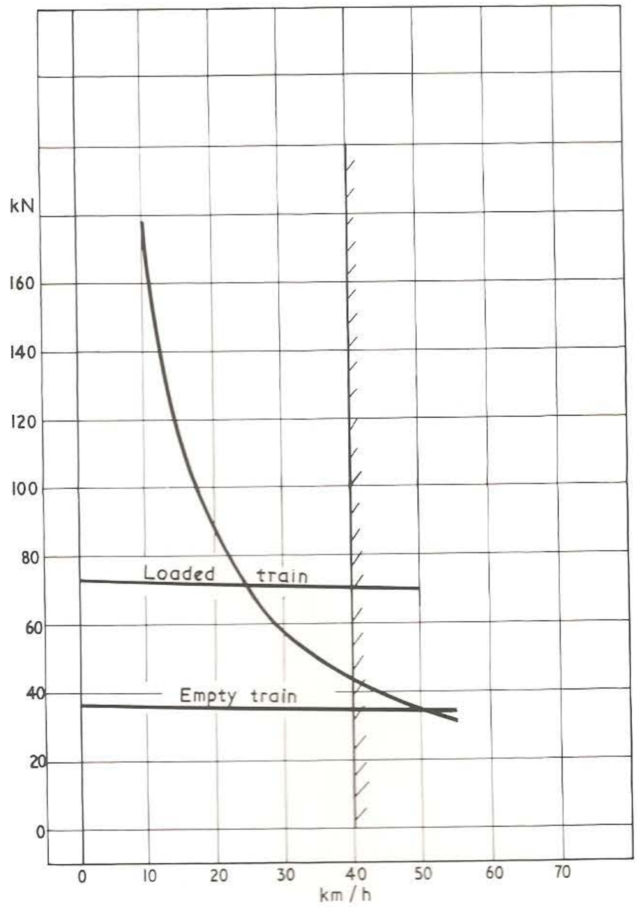


Fig. 8 Performance in braking at 1650V line voltage.

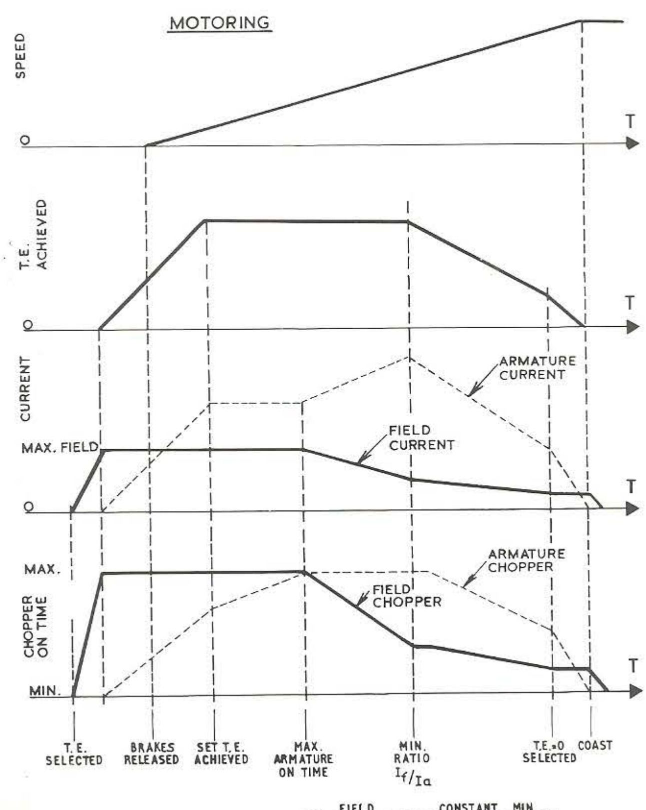


Fig. 9 System behaviour and servo characteristics for motoring

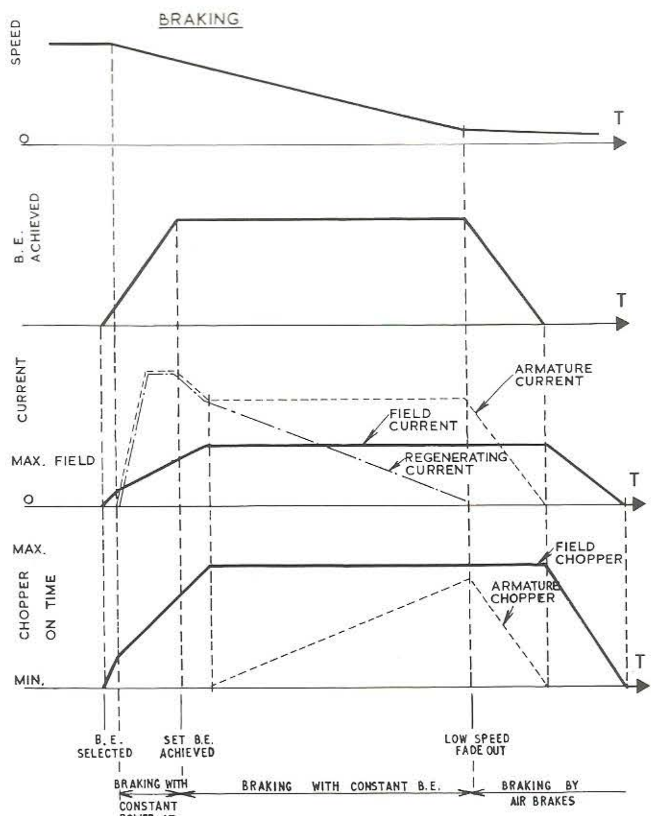


Fig. 10 System behaviour and servo characteristics for braking

TRAIN CONTROL

At an early stage in the development process a decision was taken to keep the control of a whole train as straightforward as possible because many of the men and women recruited to drive the trains are in fact lorry drivers. As a result of this a locomotive driver can now operate one or several locomotives together in the same way as he would handle a lorry. All railway-specific decisions and control functions are exercised by an electronic equipment. The main difference from a lorry lies in the use of hand rather than foot-operated controls.

The electronics follow the driver's instructions up to the maximum permitted speed of 40 km/h where they gradually reduce the tractive effort irrespective of the controller position. At 44 km/h (27.5 mile/h), ie 10% overspeed, the brakes are automatically applied on the ore-cars and the locomotives revert to emergency electric braking. The train will only be returned to driver control when it has reached a complete standstill.

The driver has several options should he himself need to apply full emergency brake for any reason other than overspeed. These range from the release of the deadman apparatus to shutdown of the locomotive in which he travels; this will in turn cause an emergency brake application on the train. The field control loops regulate the field current of each motor to the required level within several restrictions such as maximum current (thermal limit), minimum current (chopping limit) and relation to armature current.

The armature current control servo receives its demand signal from the armature/field changeover module. The armature current is controlled to produce the required motoring or braking effort while the field is kept at its constant (maximum) level. Armature control is the predominant mode since the locos normally operate at speeds below the motor-curve, ie 30 km/h (19 mile/h). The changeover module has no servo functions of its own. It is important in the overall design though since it introduces *dead band* areas and hysteresis. It transforms an *effort* signal into a *current* demand. The effort servos translate an instantaneous change of demand into a slowly varying level which is matched to the motor response. They limit jerking to an acceptable level and prevent wheelslip by their stepless control.

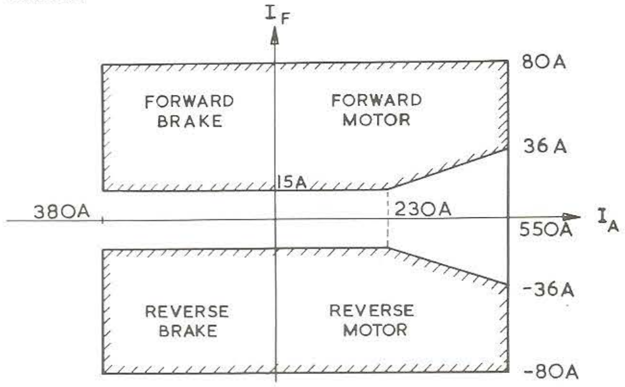


Fig. 11b Limits to current control of armature and field chopper.

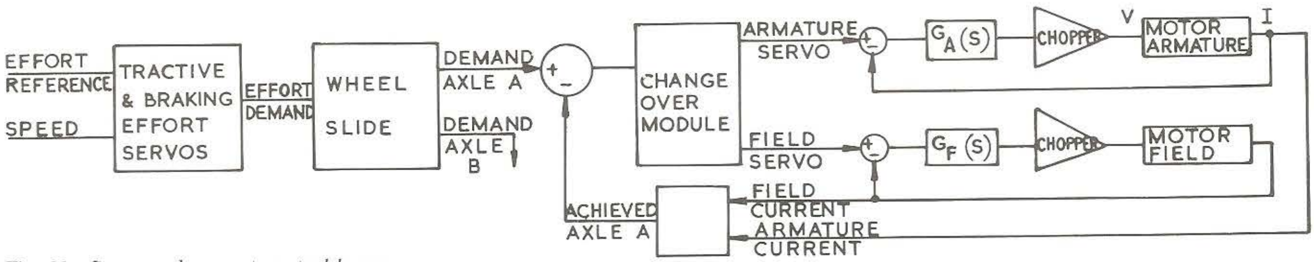


Fig. 11a Servo and current control loops

TRAIN LINE SYSTEMS

Under normal operating conditions there are 32 ore cars in a train hauled by two locomotives at the front and two at the back of the rake. The ore-cars used in the mine are equipped with a six-core cable terminating in jumpers and plugs at each end of the car. Any function of a locomotive in the train must be controlled via these six wires from the driver's locomotive. This is the *master* as opposed to the three *slaves*. The system is different from the conventional multiple unit control in that it does not use a large number of wires energised at control voltage, 110V dc or similar, each of which is dedicated to a specific function such as *forward* or *brake*. Instead it transmits coded information at signalling voltage level, 15-30 V, using the six wires in three pairs allocated to groups of functions:

(a) direction of travel and operating condition,

(b) tractive effort and braking effort to be achieved,

(c) fault information and transmission control.

In order to reach a high standard of safety there are two independent communication systems, one fulfilling tasks (a) and (b), the other dealing with the fault indication (c). A block diagram of these systems is reproduced in Fig 12.

The two equipments are powered by different supplies although they both rely on the main battery as a back-up. A train is operative *only* if both systems are in working order. The fault information system may be cut out if it fails but the affected locomotive must be taken out of service at the end of the shift.

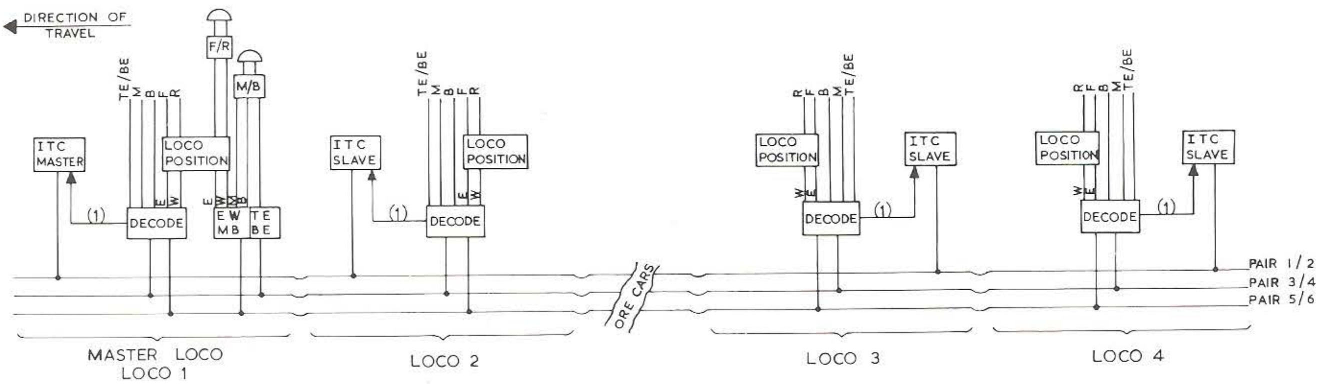


Fig. 12 Schematic diagram of the train line system. Loco 2, a "Slave", is under conventional multiple control whereas 3 and 4 are remote controlled.

TRACTION CONTROL

Train line pair (a) carries the information telling the locomotives whether to go *EAST* or *WEST,* to *MOTOR, COAST* or *BRAKE.* This is encoded in the mark-space ratio and the frequency of the signal. The control logic on the locomotive converts the directional information into *FORWARD* or *REVERSE* depending on its orientation. Train line pair (b) informs the electronics of the tractive or braking effort required which is encoded in the signal's pulse-width. The train cannot be moved unless there are reasonable signals on train-line pairs (a) and (b). This corresponds to the traditional, safe, "two-wire start" feature. Failure of one of the pairs while running at speed immediately causes emergency braking.

COMMUNICATION SYSTEM

The fault annunciator system on train line pair (c) monitors up to 16 fault conditions on each of the locomotives forming a consist. This information is displayed in the *master* locomotive. In the case of a serious fault, for instance if one locomotive reports that it does not receive signals on pair (b), the transmission of information is stopped. All locomotives react to this by applying emergency brakes. In the case of a non-serious fault the driver is warned about the situation. He can then use the system on train-line pair (c) to reset the fault alarm by remote control without stopping the train. The electronic unit of the communication system, shown in Fig 13, displays the following faults:

— overloading of motors and their respective choppers
— overloading of the auxiliary and field choppers
— overtemperatures of thyristors and brake resistors
— tripping of the high speed circuit breaker
— failure of the main blower
— problems with the compressed air system

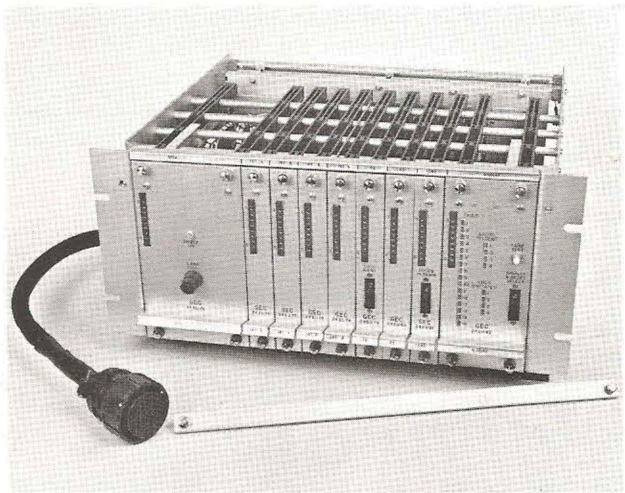


Fig. 13 ITC fault annunciator system, electronic frame

Locomotives suffering a fault of a non-serious nature do not apply emergency brakes, they simply revert to a *coasting* mode of operation. Faults affecting one motor group only may be isolated by the driver at the end of a round trip and the equipment remains operative at half power.

BRAKE SYSTEMS

Under normal service conditions the trains are stopped using only the braking facilities provided on the locomotives. Although the ore cars are fitted with spring-applied/air-released tread brakes these are not used because the locomotive's electric braking saves energy and because the brakes of the ore cars cannot be applied gradually.

A single air pipe running the whole length of the train supplies individual brake reservoirs on the ore cars and the locomotives. As soon as the pressure in the pipe exceeds a value of 7.6 bar (110 lb/in²) the brakes on the cars are released using the air in their auxiliary reservoirs. If the pressure drops below 5.2 bar (75 lb/in²) the brakes on the cars are applied via a pneumatic governor valve on each car, the air being vented to atmosphere. The schematic diagram of a locomotive's air system, similar to the arrangement on an ore car, is shown in Fig 14.

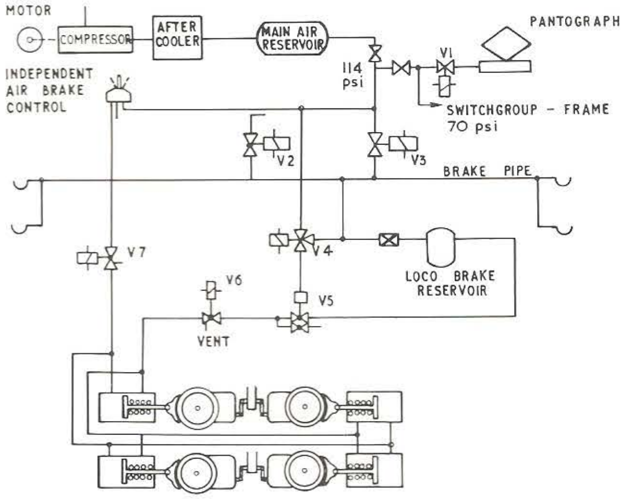


Fig. 14 Simplified air and brake schematic
V1 Electromagnetic pantograph valve
V2 Electropneumatic train brake application valve
V3 Electropneumatic train brake release valve
V4 Electromagnetic locomotive brake isolation valve
V5 Locomotive pneumatic brake valve. V5 applies brakes if brake pipe pressure falls below 5.2 bar and releases brakes with air from the brake reservoir if pressure rises above 7.6 bar. V5 is identical to the brake valves on the ore cars.
V6 Locomotive brake application valve.
V7 Locomotive independent air brake isolation valve.

BRAKE OPERATION

Normal service braking is effected using the locomotives' motors as generators feeding into the overhead line or into roof-mounted resistors. At very low speeds, unsuitable for electric braking, the locomotives' spring brakes are automatically applied to the wheel treads bringing the train to a stop. The running surfaces are cleaned at the same time.

In an emergency situation the spring brakes are applied on the ore cars from the start while the locomotives still use the electric brake at its maximum rate. The brakes on the locomotives and the supply for the main brake pipe are controlled by the propulsion electronics via electro-pneumatic valves. The driver does not have direct control of the air brakes although he can apply the train-brakes with a dump valve as a last resort.

The independent, driver controlled, air brake on a locomotive applies the tread brakes on all four wheels. The brake spring and a controllable amount of air from the main reservoir combine to override the effect of the air from the brake pipe which tries to hold the brakes off. This brake is disabled on all locomotives except for the *master.* In the loading area at the bottom of the mine, for example, the driver selects the minimum tractive effort and then controls the speed with the independent air brake. Speed regulation in the region of 1.5 km/h (1 mile/h) is accurate and much better than anything which could be achieved by alternating between motoring and braking.

RUN-BACK PREVENTION BRAKE SCHEME

The railway system at the mine has been in operation for 10 years. During that time there once was an incident where the brakes on a train froze in the released condition. In order to prevent future accidents of this kind it was decided to fit the locomotives with a run-back brake scheme as shown in Fig 15. Every time the control circuits on a locomotive are switched off and after any prolonged period of *coasting* the circuits revert to an arrangement where current is built up around an armature-field loop relying on remnant flux. The generated power is dissipated in the motor windings. On the 3% grade a fully loaded train will crawl backwards at a speed of less than 3 km(h (2 mile/h) when this feature is operative.

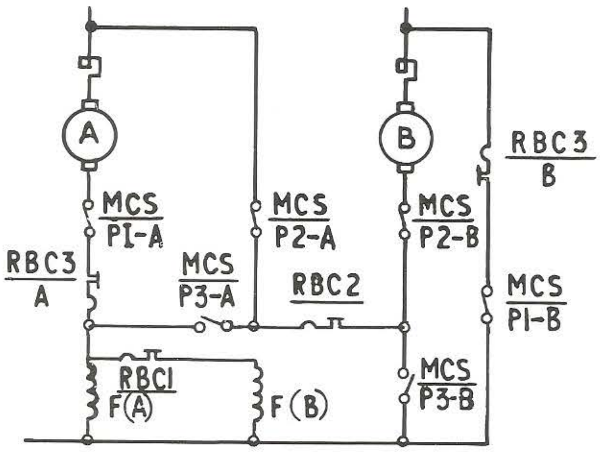


Fig. 15 Runback prevention circuit showing motor cut out switches

DESIGN OF THE ELECTRICAL EQUIPMENT

The locomotive's electrical equipment can be divided into three distinct areas which are mechanically and electrically separated:

- power and high voltage control equipment (600 V-1400 V dc)
- auxiliaries and low voltage equipment (110 V dc)
- electronic control systems (+15 V dc).

Careful segregation of the different control areas was an important design factor aimed at minimising interference and electrical noise transfer between the different circuits. All the equipment belonging to a particular area or function has its connections made in the respective control module. Except for a few high-voltage connections, and an even smaller number of current-carrying control links, the wiring between the different areas is effected using multiway cable harnesses terminating in plug and socket arrangements. The decision to use this connection method, more expensive than conventional point-to-point wiring, was taken in order to achieve modularity and reduce test times. Most building blocks could, for example, be used, with minor modifications, to assemble a four-axle locomotive of double the rating.

Fig. 16

HIGH VOLTAGE CONTROL EQUIPMENT (Main Case)

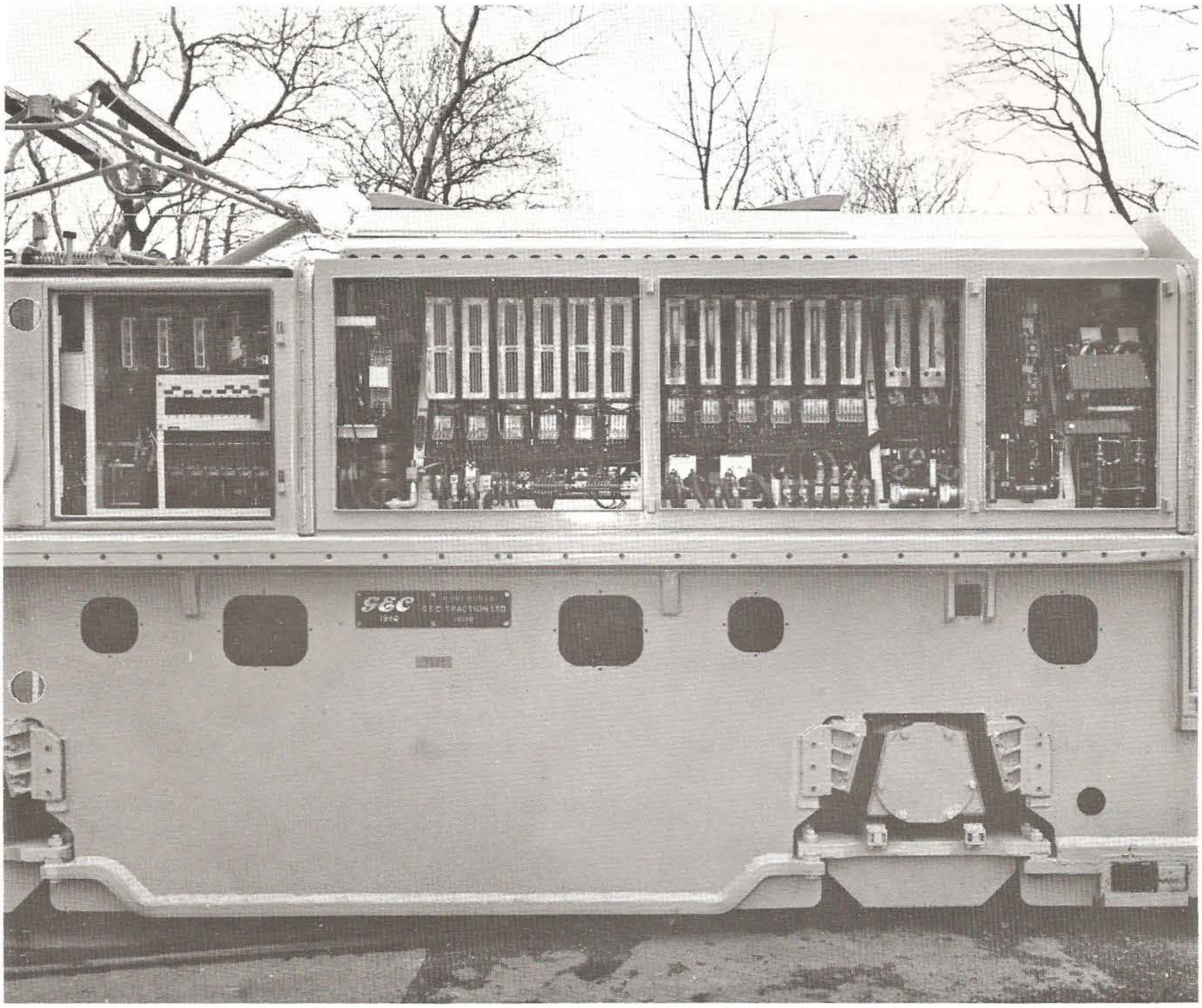


Fig. 17 View of the switchgroup frame mounted in the locomotive's power equipment case

A single, modular case (volume 6.3 m^3) accommodates the high voltage switchgear, except for the high speed dc circuit breaker, and the power conditioning equipment together with the brake resistors. The case is mounted in the centre of the locomotive above the traction motors thus minimising the length of power cabling. Due to the high power density required it was necessary to pack the equipment tightly. A ratio of 250 kW/m^3 was achieved for the control gear; nevertheless it was possible to physically segregate the electro-mechanical equipment, the active and passive components and the brake resistors.

The switchgroup frame on the right-hand side of the case (see Fig 17) mounts the air-operated power contactors and linear switches (motor/brake, forward/reverse), control relays, the current and voltage measuring devices and the overload protection equipment.

The inductors and capacitors for the smoothing and commutation circuits are arranged in a central *tank,* force ventilated by the main fan with cooling air leaving the tank at the cab end. A second stream of air flows past the heat sinks of the converter devices in a narrow duct which also terminates at the cab end. The air-flows in the tank are shown diagrammatically in Fig 18. From the outlets the air returns to the superstructure at the rear (the machines compartment) where it serves to pressurize the locomotive body thus preventing the ingress of snow and powdered molybdenum ore which is highly conductive.

The power devices are clamped to aluminium heatsinks in two different ways according to their duty. Sharing, snubber and firing circuits are either mounted directly above the respective power component or, for ease of access, on a cubicle door.

The converter area is split into four functional groups of devices, one for each motor armature, one for the two fields and one for the auxiliary chopper. The wiring pertaining to a function is arranged so as to minimize interference with other functions, for example all the cables of the armature chopper of group "A" pass in one bundle to the switchgroup frame on the far side of the central *tank*.

The space immediately beneath the roof is divided into two areas. Power and electronic circuits for the field control are located to the front while the main part of the roof space is taken up by the brake resistors. These latter are arranged in two banks and are naturally cooled with the help of air-scoops on the roof. Each bank is rated at 450 kW (300 A at 1500 V) continuously. This corresponds to the power generated by an empty train travelling down the steepest grade (3%) at 40 km/h (25 mile/h). The speed must be reduced, however, if a full train is to be braked under these circumstances for more than 10 minutes. The resistor framework is equipped with temperature-sensing devices which prevent the use of the rheostatic braking function when the resistors overheat — except for emergency brake application where this signal is overriden.

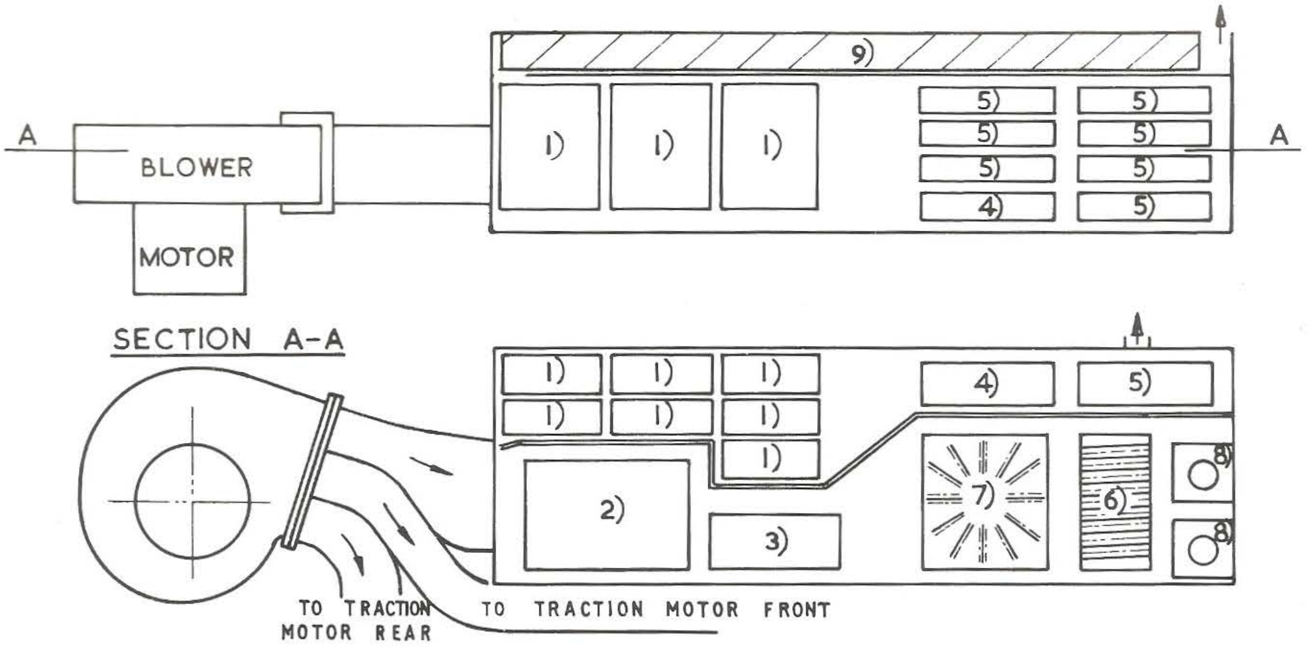


Fig. 18 Air flow diagram
(1) Line filter capacitors
(2) Line filter indicator
(3) Auxiliary smoothing inductor
(4) Auxiliary smoothing capacitor
(5) Commutation capacitors
(6) Field and auxiliary commutation inductors (solenoids)
(7) Armature commutation inductors (toroids)
(8) Soft communtation inductors
(9) Heatsinks with thyristor and diodes

AUXILIARIES AND LOW VOLTAGE EQUIPMENT

The 110 V dc control equipment is contained in the control cupboard in the cab and the LV cubicle situated in the machines compartment. The cupboard houses the relays, delay relays, push buttons and circuit breakers associated with the driver's controls. It serves as a terminal point for the equipment in the cab and as an intérface between the conventional and electronic control systems. The fault annunciator equipment is built into this cupboard.

The apparatus in the low-voltage cubicle controls the auxiliary machines, the high-speed circuit breaker and the battery charger. It includes the LV circuit breakers which need not be accessible during normal operation — due to the restricted loading gauge it is impossible for the drivers to operate any controls outside the cab while the train is in the tunnel. Operation of the auxiliary machines is automatic and failures are indicated to the driver in the *master* locomotive who can intervene at the end of the round trip since the equipment always reverts to a safe condition.

ELECTRONIC CONTROL SYSTEM

The electronic control equipment is physically split up into four areas:

- the encoder in the driver's desk,
- the main electronic control in its cubicle in the cab,
- the fault indication module in the LV cupboard,
- the interfacing equipment in the main power case.

Structurally the electronic control system is built up from five blocks:

- analogue and logic inputs.
- combinatory logic processing unit,
- analogue servo systems,
- pulse control outputs to thyristors,
- logic and analogue outputs.

Most of the electronic modules needed to fulfill the functions of these blocks are standard units which can easily be adapted to any application. They are of the plug-in type to facilitate testing and maintenance. The main control electronics, depicted in Fig 19, may be removed as a whole and tested independently from the locomotive. It is mounted in a sealed, heavy duty steel case. The connections are via multi-way plugs, test boxes allow rapid in situ testing of the main functions.

Wherever possible electrical shielding is provided for groups of electronic modules. Full insulation has been incorporated between equipment which is directly connected to high voltage and the control systems. Current and voltage monitoring equipment has its inputs and outputs isolated via transformers and in the case of firing pulses the protection extends over two levels of isolation. Firing transformers separate the thyristor leads from the firing amplifiers which are supplied direct from the locomotive battery and are themselves opto-isolated from the pulse generation modules in the cab.

The electronic systems are capable of reliable operation over the entire environmental working range of the locomotive, ie at ambient temperatures between —40°C and +40°C and relative humidities from 5% to 100%.

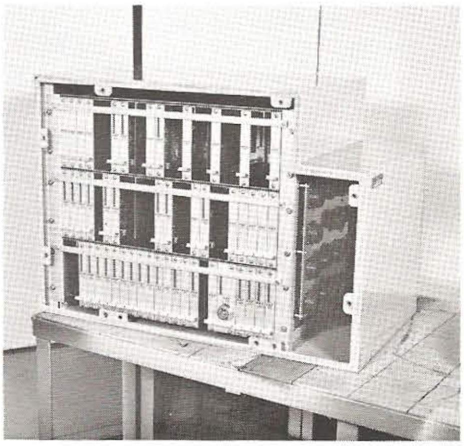


Fig. 19 Main electronics frame, note the multiway connectors on the righthand side.

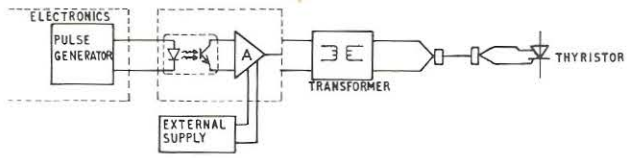


Fig. 20 Thyristor firing arrangement showning the two isolation stages.

DESCRIPTION OF THE POWER CIRCUITS

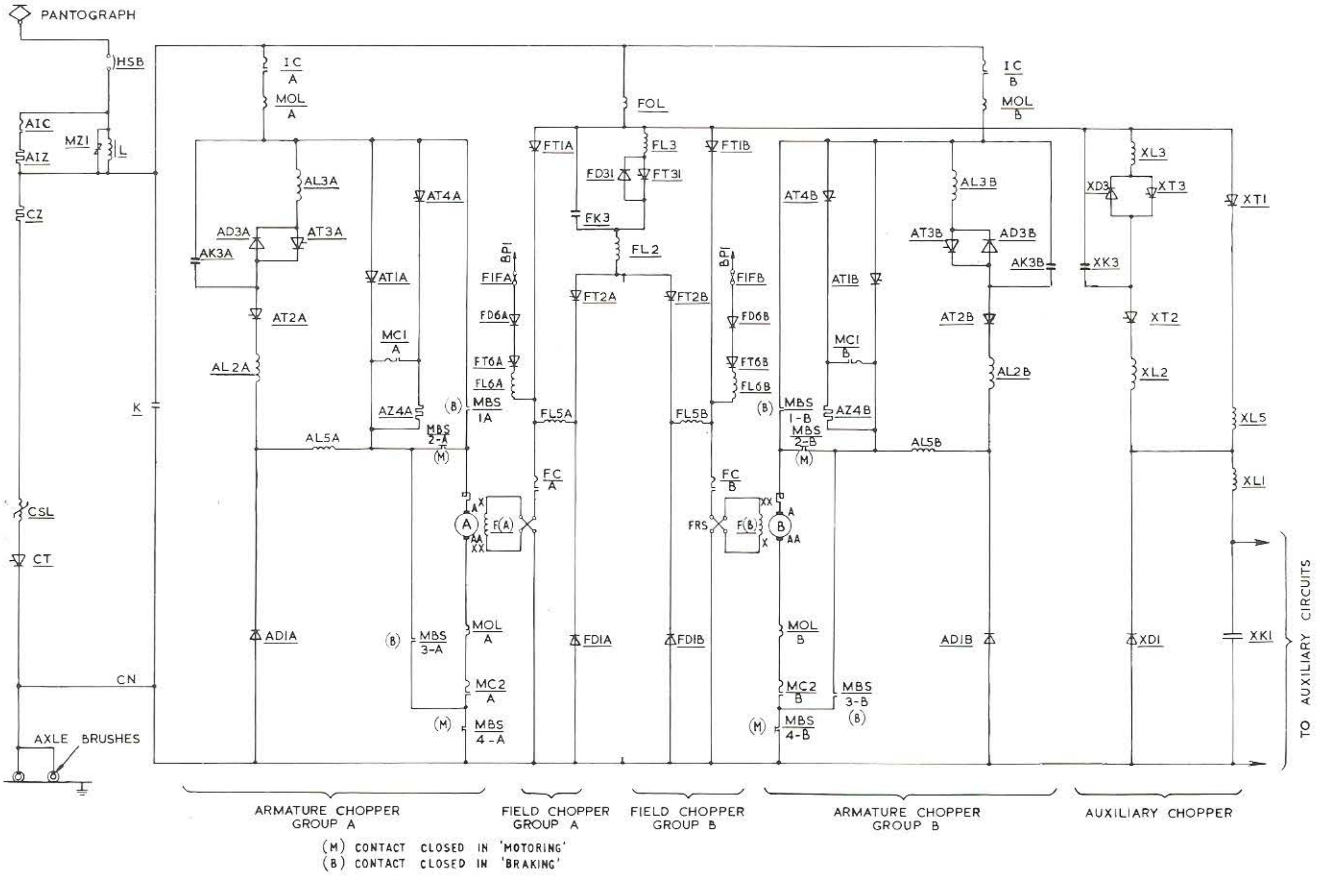


Fig. 22 Schematic diagram of power circuits

HSB	*High speed DC circuit breaker*
AIC	*Inrush contactor*
AIZ	*Inrush resistor*
IC (A/B)	*Isolating contactor*
MOL(A/B)	*Overload relay*
MC1(A/B)	*Motoring contactor*
MC2(A/B)	*Loop contactor*
A(A/B)	*Armature of motor*
F(A/B)	*Field of motor*
FRS	*Forward/reverse switch*
MBS	*Motor/brake switch*

Device notation (example)
AD1A
└ Equipment group: A (motor A), B (motor B)
└ Location/function number (optional)
└ {L (inductor), K (capacitor), T (thyristor), D (diode) / FI (injection fuse), Z (resistor)
└ A (armature), C (HT protection), F (field), X (auxiliary)

DESCRIPTION OF THE POWER CIRCUITS—*Continued*

Fig 22 shows a schematic diagram of the power and traction circuits. The input and protection circuits comprise the high-speed dc circuit breaker, line filter inductor and capacitor, damping circuits and the high voltage protection device. The main circuits are arranged in five converter blocks, each *chopper* controlling the supply to one of the armatures, the motor-fields or the auxiliaries. The two armature blocks are linked to the positive supply line through isolating contactors and overload relays. Since the combined load of the auxiliary and field blocks is much smaller than that of the armature, overload protection acting on the high-speed breaker is sufficient for the duty.

Although this is not shown on the simplified power circuit diagram the devices are provided with sharing and stored charge protection circuits. Computer simulations were employed to determine optimum values of the components, their predictions being confirmed by the results of the commissioning trials.

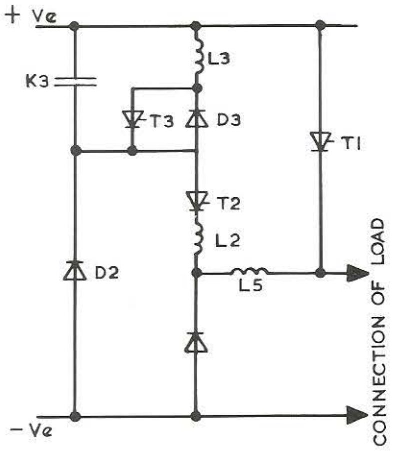


Fig. 23 GEC standard chopper circuit.

Fig 23 is a schematic diagram of the GEC standard chopper used on the AMAX locomotives to regulate the supply for the traction motors, fan motors and other loads. The design of this chopper has evolved over a period of 20 years and can now be used for almost any conceivable dc traction application, and is suitable for supply voltages from 600 V to 3000 V dc with devices arranged in series or parallel combinations according to the duty.

The operation of the chopper is perhaps best understood by reference to the electrical processes which occur during a complete cycle. The description which follows, in fact, is of the auxiliary chopper because of its relative simplicity but the same principles apply to the power choppers.

AUXILIARY CHOPPER

Operating at a constant frequency of 300 Hz the converter produces an output voltage across XK1 with a minimum ripple of 3-5 V_{pp} at the nominal 110 V dc. The nominal current range is 150 A to 300 A but transient currents reach 400 A.

For the discussion of the chopper's behaviour it is assumed that, initially, the supply breaker is still open. The electronic system produces T2 gate pulses even though the locomotive's line filter capacitor K is discharged. Once the pantograph is raised the high-speed circuit breaker closes and the filter capacitor charges up to the level of the supply voltage. At the same time the commutation capacitor K3 of the auxiliary chopper is charged through the conducting T2 and the load. As soon as the voltage of the main filter capacitor comes within the operating range the T3 gate pulses are released, at first as close to the following T2 as possible. Fig 24 captures the first five converter cycles from the moment when the chopper is released.

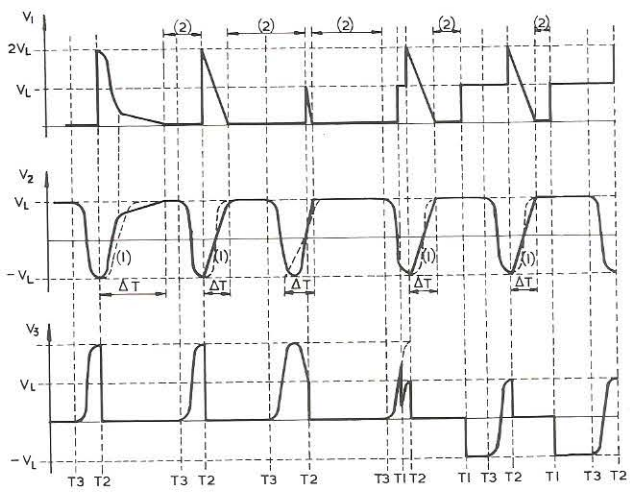
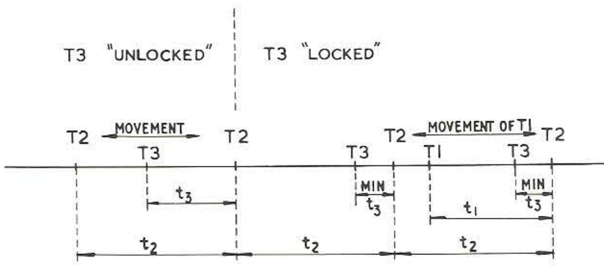


Fig. 24 Waveforms of the standard chopper.

V_L	*Supply voltage*
V_1	*Voltage across traction motor armature (and D1)*
V_2	*Voltage across communtation capacitor*
V_3	*Voltage across T2*
T	*Triangle time (depends on supply voltage and load current*
(1)	*D3 current (ringing) content, dashed line*
(2)	*D1 conducts*

Since the voltage of the commutation capacitor K3 is equal to supply volts at the time when T3 is *fired* (made conducting) the discharge current through the ring-round inductor L3 will, by reversing the charge on the capacitor, force the voltage of the load end of K3 to twice line volts. Firing of T2 at this point quickly establishes a load current and brings the auxiliary volts within the specified range. The firing point of T3 can now be phased back, away from T2. The load end of K3 will correspondingly reach twice line volts well before T2 firing. A ring-round current will reverse through the diodes D3 attempting to bring the volts on K3 to the condition prior to firing of T3. The firing of T2 at this time produces a much smaller current through the load. When the line volts are high or if the auxiliary load is small the control method of moving T3 with respect to T2 will suffice to regulate the output current. When the load requirements cannot be met by moving T3 closer to T2 then T3 is *locked* in its *maximum* position and T1 gate pulses are released as necessary.



$t_2(t) = \frac{1}{f_c}$ = CONST. $\quad t_{cc}$ = CYCLE TIME OF $K_3\ L_3$

$t_3(t) < t_{cc}$ AND $t_3(t) > \frac{1}{2} t_{cc}$ (T3 "UNLOCKED")

$t_3(t) = \frac{1}{2} t_{cc} + \Delta t$ = CONST. (T3 "LOCKED")

$t_1(t) < (t_{cc} - \Delta t)$ AND $t_1(t) > \Delta t$ = SAFETY INTERVAL

Fig. 25 Relationship between T2 and T3 pulses

The load current is now supplied by the T1 string and line volts are applied to the load as long as T1 conducts. Firing of T2 will raise the voltage transiently to a level of almost twice line volts. T1 therefore becomes reverse-biased and turns off. K3 is recharged through the load via T2. Once K3 is fully charged the current through T2 stops and since the load current cannot change fast it is forced into a freewheel path using the diode D1. T3 being fired rings the voltage on K3 around and the circuit is ready for the next cycle which starts with the firing of T1.

The load types encountered in dc traction applications are usually highly inductive. The load current will therefore be reasonably constant and will not change, regardless of whether it is carried through T1, T2 or the freewheel diode D1. The changeover from one conduction path to the next in sequence, ie commutation, is very rapid. The transfer from D1 to T2 for example entails, when T1 is not fired, a step corresponding to twice line volts in the connection point. The inductors L2 and L5 have been introduced in the circuit to limit the rates of rise and fall of the device (diode and thyristor) currents during commutation. This *soft commutation* method allows the use of *slower* devices with reduced switching losses.

FIELD CHOPPERS

The field chopper blocks are derived from the standard design which is modified insofar as the two groups share a common ring-round circuit. Since the power requirement of the motor fields is small (each a maximum 80 A at 100 V) the chopper *on* time is short even at low line voltage. The high inductance of the separately excited motor fields equalises the current by extending the FD1 conduction time. A chopping frequency of 150 Hz is therefore sufficient and the commutation energy stored in FK3 can alternately be assigned to one or the other of the field choppers. The ring-round circuit, managed by FT3, FT2A and FT2B, runs at 300 Hz, in antiphase to the auxiliary chopper. Field and auxiliary chopper together present the supply with a combined load oscillating at 600 Hz.

The field chopper circuits are augmented by the field injection paths which are only used in the rheostatic braking mode. When FT6 (A or B) is *fired* a current flows from the battery into the field thereby exciting the machine to generate an armature voltage. The field contactor allows rapid interruption of the field current to limit the rise of the armature voltage in emergencies. Reversal of the field current changes the direction of travel.

ARMATURE CHOPPERS

The armature choppers are versions of the GEC standard chopper extended for both motoring and electric braking. The two groups are *interlaced* electronically in the same way as the field circuits although they do not share components. Each chopper works at 300 Hz and their combined frequency is 600 Hz irrespective of the operating mode. The commutation and the ring-round circuits perform the same functions as in the auxiliary and field choppers. The functions of the other components vary according to the mode for which the driver has asked, ie, motor or brake.

MOTORING CONDITION

The chopper is arranged to feed the motor armature from the supply line as shown in Fig 26. The diode AD1 assumes its normal freewheel function carrying the armature current when T2 has stopped its conduction period after having commutated the feed through the main path. Thyristors AT1 and AT4 perform the function of main thyristors together. They are turned on in alternate cycles of the chopper and the thermal duty of each string of devices is halved because they conduct for less than 50% of the time.

The tractive effort developed by the motors is controlled by varying the armature current up to the moment when the motor reaches its base speed. The maximum armature current is then held constant while the supply to the field is weakened.

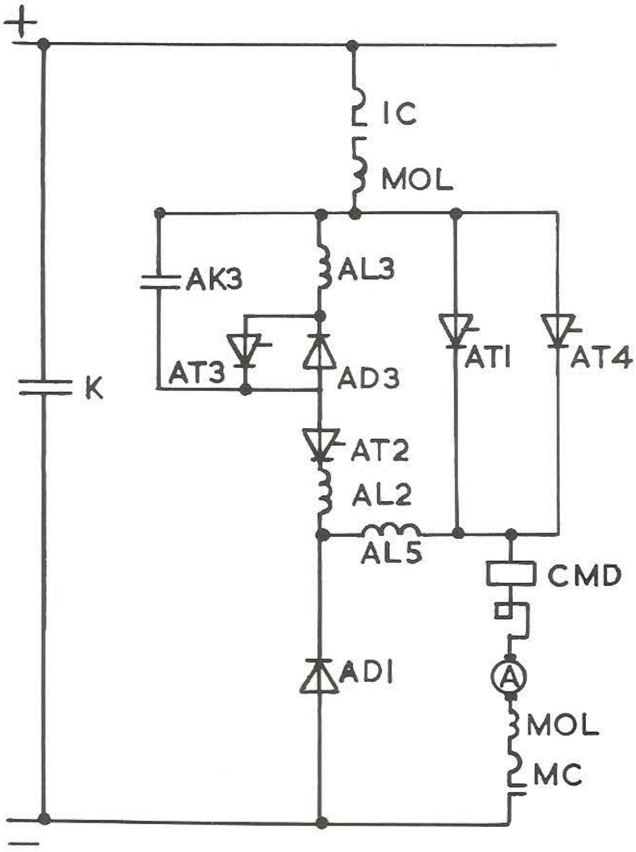


Fig. 26 Armature chopper in motoring mode

BRAKING CONDITION

The armature chopper as set out in Fig 27 is re-arranged for the braking duty. The diode AD1 prevents a feed from the supply to the chopper circuit and motor.

Once the control system has verified that the power circuits have changed to the braking condition it releases the field chopper at a level, up to 80A, which is linked to the locomotive's speed. The motor acts as a generator and a positive voltage appears across its armature terminals. AT2 is turned on and charges AK3 to the motor voltage.

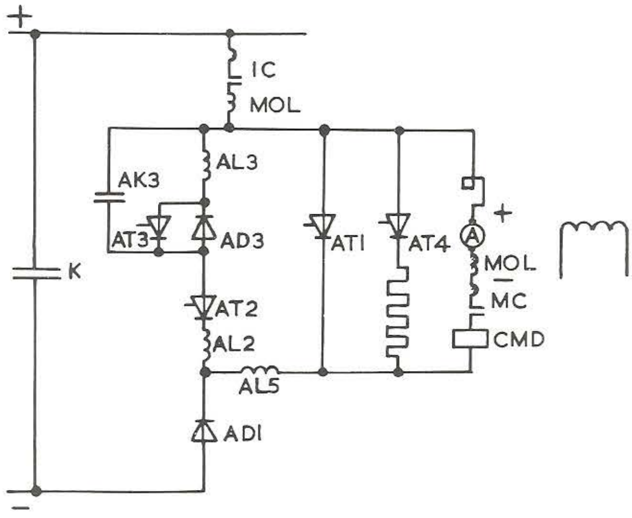


Fig. 27 Armature chopper in braking mode

At high speeds the generated voltage is higher than the supply voltage and current is fed back at a rate determined by the supply resistance. If the braking power is insufficient at this rate it is boosted by the *store and let fly* method described below.

AT3 is fired at a suitable time before AT2 and reverses the charge on AK3 (refer back to Fig 24 for details). When AT2 is turned on a current flows which is limited only by the armature and loop resistances. As soon as the voltage on AK3 is again equal to the motor output the current through AT2 stops. Since the armature current cannot change rapidly it is forced to freewheel into the filter capacitor K which is discharged by the auxiliary and field choppers and, if available, the overhead supply line.

At low speeds, once AT3 cannot be advanced any more (refer back to Fig 25), AT1 is turned on for increasingly larger proportions of the cycle so that eventually only a short current *burst* is fed back into the supply.

The control electronics constantly monitor both the voltage of the overhead system and of K. If the voltage on K exceeds 1650 V the system calls for a blending of rheostatic and regenerative braking. If the voltage of the overhead supply rises above 1800 V or falls below 1200 V the high-speed circuit breaker opens and rheostatic braking is enforced.

In rheostatic braking as much of the current as possible is still allowed to freewheel into K for supply to the auxiliary and field choppers. To keep the filter voltage below 1650 V though, the brake thyristor AT4 is also fired. This limits the armature voltage to a level determined by the field current, armature current, the combined resistance value of armature and rheostat and the AT4 *on* time. AT4 is commutated in the same way as AT1 by the turning on of AT2. If an AT1 pulse is initiated during the cycle to boost the armature current then AT4 is turned off through lack of current.

OUTPUT REGULATION OF THE STANDARD CHOPPER

The main advantage of the GEC standard chopper design is to be found in its wide regulated output range, achieved without recourse to variable frequency operation. For this reason the design is specially suited for applications where, for signalling or other factors, no harmonic content may be allowed to appear in some areas of the frequency power spectrum.

Chopper *on* time is defined as the time during which line volts are applied to the load. The standard GEC design allows regulation over a range stretching from less than 5% *on* time (where T1 is not used and T3 is at maximum distance from T2) to more than 95% *on* time (where D1 is allowed to conduct for but a few microseconds to ensure that T2 has turned off). The two extremes are compared diagrammatically in Fig 28.

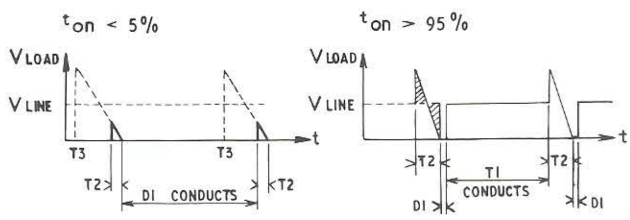


Fig. 28 Minimum and maximum chopper "on" time

Almost full line voltage (RMS) across the load is in fact possible while the main thyristor is still turned off after every cycle. This guarantees that commutation is always possible and substantially increases the speed with which the chopper can be phased back to prevent overloading of the power supply. The regulation can be maintained over the full range of the supply voltage, ie from 450 V to 1750 V in this application.

Fig 29 shows voltages and currents during a typical converter cycle lasting about three milliseconds.

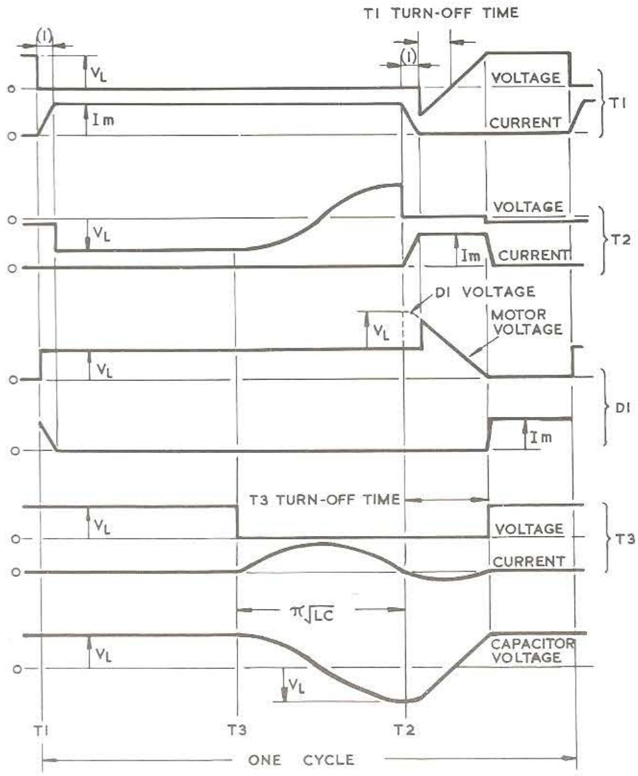
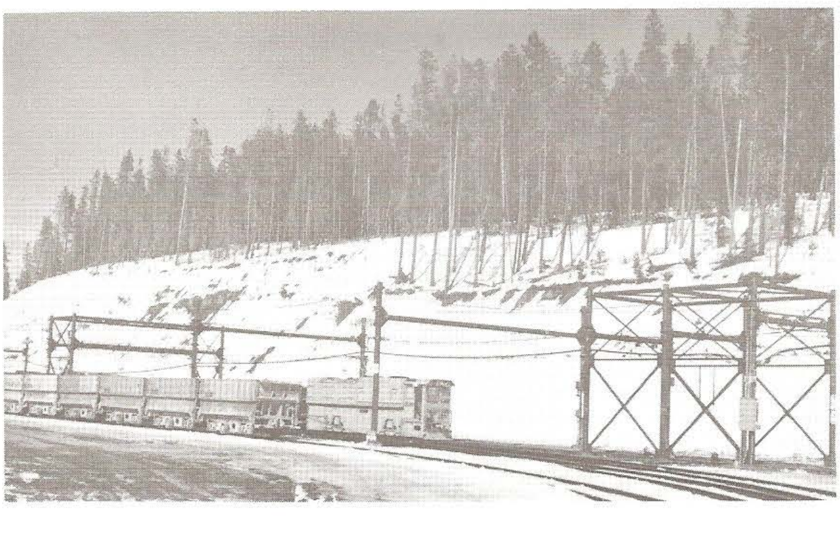
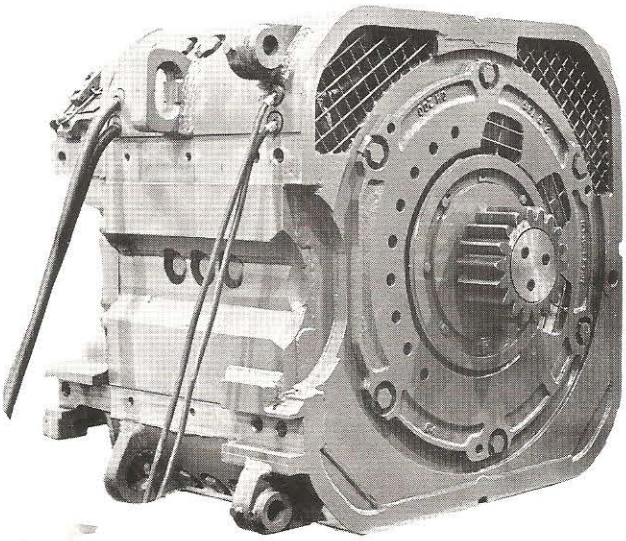


Fig. 29 Currents and voltages during a typical converter cycle lasting approximately 3 milliseconds.
(1) "Soft" commutation zones



TRACTION MOTOR

The G415 BY traction motors are force-ventilated, pulsating-current, separately-excited, four pole machines, axle hung on roller bearing U-tube suspension units and driving through a single reduction spur gear. They are very similar to the type G415AY machines used on the 50kV Sishen-Saldanha heavy freight locomotives. Both designs are modified and uprated versions of the G283AY motors for which current orders exceed 4000 for the South African Railways Class 6E1 3kV locomotives.



Traction motor G415BY

Motor type	Axle hung, nose suspended
Design track	1067 mm
Weight including gearcase	4450 kg
Clearance between rail and gearcase (used tyres)	70 mm
Gear ratio (for low speed operation)	83/18
Excitation	Separate field winding
Armature voltage (nominal)	1400V/600V
Field voltage (nominal)	110V
Insulation: Armature	H
Field	F
Maximum rating (starting)	625kW (1400V/485 Amps)
One Hour rating	526kW (1400V/400 Amps)
Continuous rating	460kW (1400V5350 Amps)

Ratings at appx. 620 rpm (32 km/h) with maximum excitation and through gears.

CONCLUSION

Although many important features of the AMAX locomotives were first developed for use on other projects their successful combination represents a step forward in the evolution of high powered general purpose industrial vehicles.

The major *true* innovations are the replacement of the motor/alternator set by the auxiliary chopper for the provision of the control voltage at 110 V dc and the application of the electro-dynamic (regenerative/rheostatic) brake in emergency conditions. This brake is available even under a short-circuited overhead through the recourse to a field injection system fed from the locomotive battery. Advances on earlier designs are the time-sharing between strings of devices and chopper, and more importantly the *soft commutation* converter design which allows the use of cheaper semiconductor devices and reduces the noise emission of the equipment.

Added advantages of the design related to the nature of the static power conditioning equipment, are the wear-free operation of the electromechanical components and the wide range of input voltages.

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