GEC

THYRISTOR CONTROLLED ELECTRIC LOCOMOTIVES FOR 25kV

GEC Traction Limited

ENGLISH ELECTRIC | AEI

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PAKISTAN WESTERN RAILWAY ELECTRIFICATION

Thyristor-controlled locomotives

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Members of the British Consortium for the Electrification of Pakistan Railways

WHEN THE DECISION to electrify the Khanewal–Lahore line was taken in 1966, it was as a result of a UKRAS report submitted to the Pakistan Western Railway in 1965. It was considered that 29 locomotives would be required to handle the traffic on this line. The first of these locomotives has now reached Pakistan, and delivery will be complete by next spring in time for inauguration of the electrification next summer.

The 29 locomotives are being built by the British Rail Traction Group as a member of the Consortium. BRTG consists of the Traction Divison of the English Electric Co. Ltd. and AEI Traction Limited. Subcontractor for the mechanical parts superstructure is Metropolitan-Cammell Limited, the bogies being supplied by English Electric to the Washwood Heath Works of Metropolitan-Cammell where erection takes place. Electrical equipment is supplied jointly by AEI and English Electric (Fig. 1).

The 178 route-miles between Khanewal and Lahore are relatively flat with a ruling gradient of 0·2 per cent, but electrification may be extended from Lahore to Rawalpindi, a further 179 route-miles, containing sections of 1 per cent gradient. For this reason, the locomotives are capable of hauling the required loads over both sections of line and can:—

1. start a trailing load of 2,250 tons on a 0·2 per cent gradient;
2. start a trailing load of 1,125 tons on a 1 per cent gradient;
3. haul a 650-ton passenger train at 75 mile/h balancing speed;
4. haul a 1,125-ton goods train at up to 40 mile/h on the Lahore–Rawalpindi section.

For this second stage of electrification rheostatic braking will be required on the locomotives, and therefore provision for its accommodation has been made, although the actual equipment has not been fitted.

The climate conditions prevailing in West Pakistan include ambient temperatures up to 48 degC with relative humidities of 100 per cent, and at certain seasons considerable quantities of wind blown sand also present a problem. The locomotive has been designed to operate under these extreme conditions.

The equipment is capable of working satisfactorily over the voltage range 16·5 to 27·5 kV. The performance characteristic of the locomotive is given in Fig. 2.

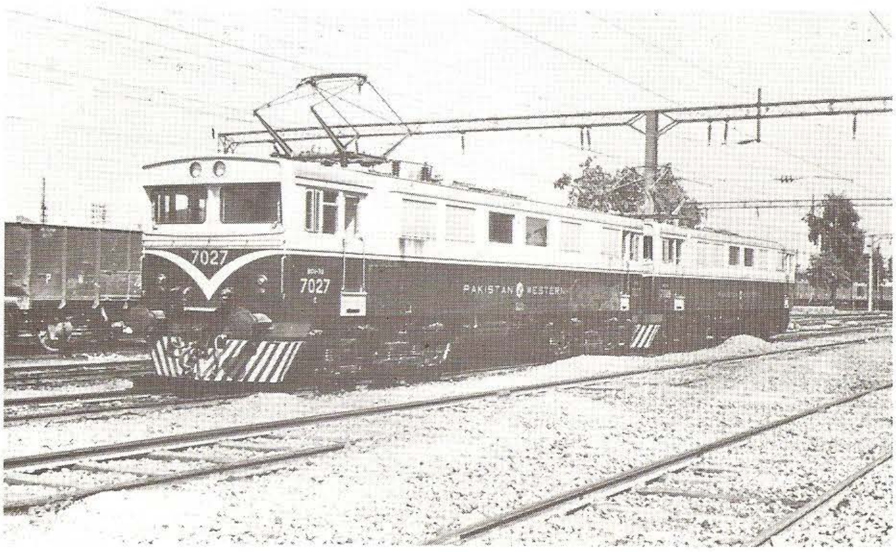
Thyristor control

So far as the main power equipment is concerned, the principal feature of interest is the thyristor controlled variation of rectifier voltage to the traction motors. This is the first application of the principle to a British built locomotive, although the principle has been applied and thoroughly tested on equipments of lower power by the thyristor control conversions of BR Eastern and Scottish region electric suburban trains; a full description of these two equipments appeared in THE RAILWAY GAZETTE on October 21, 1966. Fig. 3 is a schematic diagram of the traction power and auxiliary circuits.

Power at 25 kV is fed from the overhead line to the primary of the main traction transformer through the single lightweight pantograph and air blast circuit breaker. The transformer design was based on the AL6 locomotives of British Railways, and is of semi-core construction with disc type coils mounted in sandwich formation on the centre limb of the core.

The primary rating is 3,310 kVA at 22·5 kV with forced oil circulation and air blast cooling. The secondary winding is in four equal sections, the ends of which are brought out through bushings in the tank.

Mounted directly on the secondary terminals are the seven electro-pneumatic tapping contactors which operate under the control of static logic circuitry. Under normal operating conditions these break negligible current, but they are fitted with arc chutes and are capable of breaking full accelerating current under fault conditions.



Two of the 29 thyristor controlled 25kV locomotives in Lahore Yard, Pakistan.

The oil conservator, oil pump, radiators and fans are all mounted directly on the transformer tank, and the whole assembly can readily be withdrawn from the locomotive after the removal of the centre roof section. Cooling air is drawn in at floor level from the rectifier cubicles at each side of the transformer and flows up through the two oil coolers and fans and out through two louvred roof outlets.

When the fans are not in operation the louvres are automatically closed to prevent the locomotive being flooded if it is left standing in the open during the monsoon.

Rectifiers

The output from the secondary winding of the transformer is fed via the tapping contactors to the main rectifier equipment, which comprises 96 silicon diodes and 32 thyristors connected together in bridge formation as in Fig. 3. The diodes have a nominal rating of 372 A, 1,300 V peak transient voltage and the thyristors a rating of 170 A, 1,300 V peak transient volts.

There are eight parallel paths in the rectifier diode bridge, but in the event of failure of one rectifier string, the remaining seven paths can carry the accelerating current of 4,600 A for 5 min without damage.

The rectifier embodies the first application to a locomotive rectifier of beryllium oxide as an insulator and heat conductor, although the material was used on the naturally-cooled rectifiers on many BR multiple-unit trains. The use of this material as an insulator between each individual rectifying device and its heat sink enables all devices to be mounted on a common earthed heat sink, and there is consequently no possibility of flashing over between cooling fins at different potentials due to the build up of dirt.

The rectifier consists basically of an aluminium heat sink of open-ended box construction, the cooling fins projecting into the box and the rectifying devices being bolted on to machined pads on two outside faces of the box. The heat sink is fabricated from standard aluminium extrusions. Each of the thyristor and rectifier cells is permanently bonded to a beryllia (beryllium oxide) cup, which is in turn bonded to a gold-plated copper block incorporating the four holes through which the device is bolted to the heat sink.

The whole is mounted in the cubicle so that cooling air passes down through the centre of the heat sink box while the rectifying devices and fuses and the firing circuits associated with the thyristors are housed in a completely air tight and dust proof enclosure. The two cubicles per locomotive each house 48 diodes and 16 thyristors.

Cooling air is drawn in through louvred inlets high on the locomotive side, ducted to the top of the rectifier cubicle, and after passing over the fins is ducted at locomotive floor level to the transformer oil coolers. This latter duct incorporates a sand trap which can be emptied periodically by removing a cover below the locomotive floor.

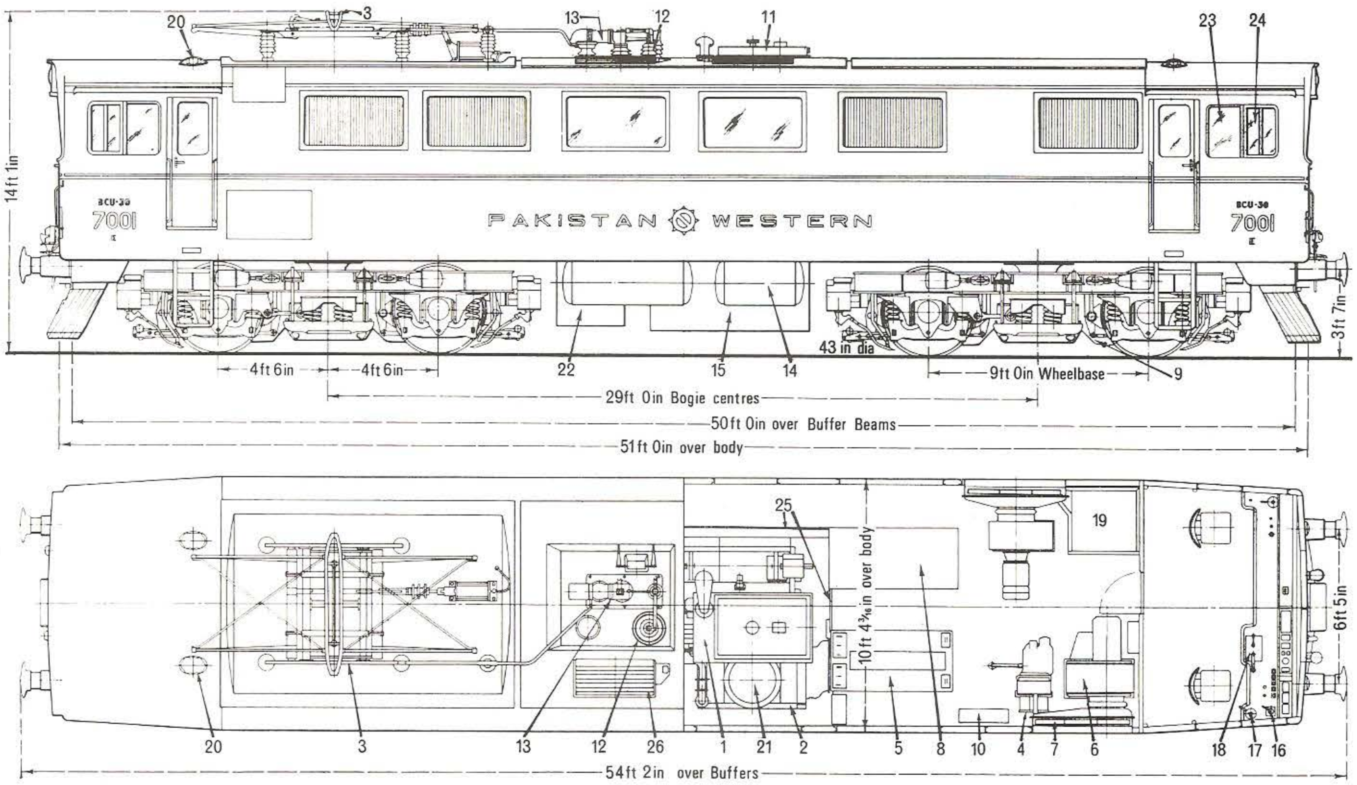
Each rectifier cubicle has a total cooling air flow of 6,000 ft^3/min. The thyristors enable the output voltage of the rectifier to be varied smoothly from zero to full voltage (1,150 V at 22·5 kV line volts) according to the tractive effort requirement.

The output voltage waveforms for various tap positions and stages of thyristor firing are shown in Fig. 4.

A single iron-cored reactor is provided to limit ripple on the rectified current to an acceptable level. This is mounted on the tank with the transformer and shares the same cooling circuit. The traction power is fed via this reactor to the four traction motors, which are connected in parallel.

Traction motors

The traction motors are four-pole series-wound force-ventilated machines, continuously rated at 790 hp. They are axle-mounted in the conventional manner with roller axle suspension bearings, and are insulated to Class H standards with slot wedges and glass banding on the end windings of the



1. Transformer
2. Radiator
3. Pantograph
4. Compressor
5. Rectifier
6. Traction motor blower
7. Air filters
8. Control cubicle
9. Traction motor
10. Brake equipment stand
11. Oil conservator
12. H.T. bush
13. Circuit breaker
14. Air reservoir
15. Batteries
16. Air brake valve
17. Vacuum brake valve
18. Master controller
19. Dynamic brake (when fitted)
20. Ventilator
21. Radiator fan
22. Battery charger
23. Drop window
24. Swivel window
25. Screens
26. Air shutters

Fig. 1. General arrangement of 3,650 hp electric locomotives for the Khanewal–Lahore line

armature. The drive to the wheels is by spur gearing with resilient gears on the axles.

The traction motor fields have a tapping to improve the locomotive performance at the high speed end. A permanent divert resistor is connected across each motor field circuit to improve commutation conditions with 100 c/s ripple.

Protection

The power circuits are protected by an overload relay in each motor circuit which trips the air blast circuit breaker in the primary circuit, while fuses are provided for protection of the main rectifier equipment.

The rectifier transformer is protected by a primary overload relay and a Buchholz device. Earth faults are detected by an earth fault relay, in all cases tripping the air blast circuit breaker.

Power for the auxiliary circuits is provided by a centre-tapped tertiary winding on the main transformer supplying the a.c. auxiliary machines, the electronically-controlled battery charger, a bi-phase auxiliary rectifier for the compressor, and exhauster. This rectifier is mounted on top of one of the main rectifier cubicles.

The a.c. auxiliaries comprise two radiator fan motors rated at 8 hp 131 V a.c., and four traction motor blower motors of similar rating. The frame size of these machines has been chosen to suit the wide variations in tertiary voltage associated with a.c. electrification. They are all capacitor start and run, squirrel cage induction machines with cast aluminium rotors and sealed maintenance free bearings. The transformer oil pump is driven by a completely immersed oil cooled motor of 4·3 hp rating at 1,420 rev/min.

The battery fitted to the locomotive is the normal nickel-cadmium alkaline type of 40 Ah capacity with 72 cells, and supplies locomotive lighting and control circuits.

The battery charger is of the static type, underframe mounted and designed specifically for traction use. The unit is divided into two compartments by a partition; one half, which is ventilated, containing the supply transformer, output choke and current limit resistor, while all other components including a printed circuit control panel are resiliently mounted in the second compartment which is totally enclosed. This panel can be withdrawn on slides for ease of maintenance.

The battery charger circuit is of the half thyristor bridge type. Output voltage is 110 V and is controlled to ± 3 per cent of nominal up to 25 A. At higher currents a current limit circuit comes into operation, the limit being set at 35 A which is the continuous rating of the charger.

Should the battery become disconnected from the charger, a circuit in the latter prevents the r.m.s. output voltage from exceeding 115 V. The charger is designed to maintain its characteristic over the full range of input voltage variation (190 to 320 V).

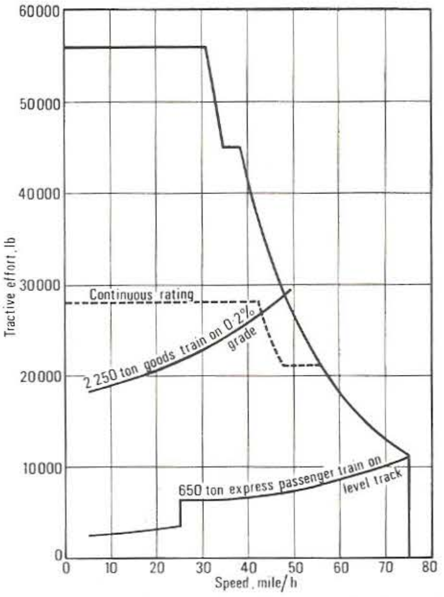
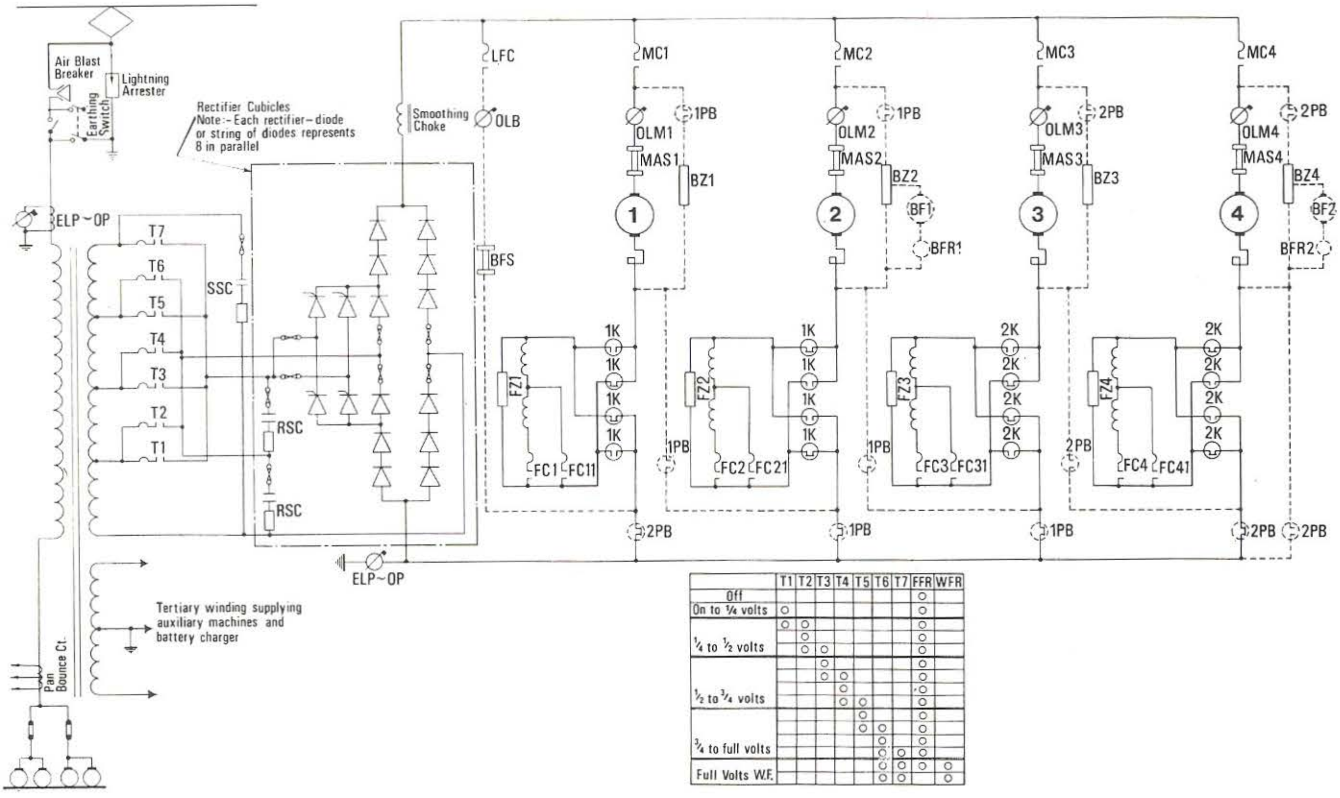


Fig. 2. Performance characteristics of the PWR electric locomotives



	T1	T2	T3	T4	T5	T6	T7	FFR	WFR
Off								o	
On to ¼ volts	o							o	
¼ to ½ volts	o	o						o	
		o						o	
		o	o					o	
½ to ¾ volts			o					o	
			o	o				o	
				o				o	
				o	o			o	
¾ to full volts					o			o	
					o	o		o	
						o		o	
						o	o	o	
Full Volts W.F.						o	o	o	o
						o	o		o

BF1-2	Braking blower motor
BFR1-2	Braking blower relay
BFS	Braking field shunt
BZ1-4	Braking resistors
ELP-OP	Earth leakage and primary overload relays
FC1-4	Main field contactors
FC11-41	Weak field contactors
FZ1-4	Permanent field diverts
1-2K	Reversers
LFC	Braking field contactor
MAS1-4	Motor armature shunts
MC1-4	Motor contactors
OLB	Braking field overload
OLM1-4	Motor armature overloads
1-2PB	Braking set-up switches
RSC	Rectifier suppression
SSC	Secondary suppression
T1-7	Transformer contactors

Fig. 3. Schematic diagram of the traction power and auxiliary circuits

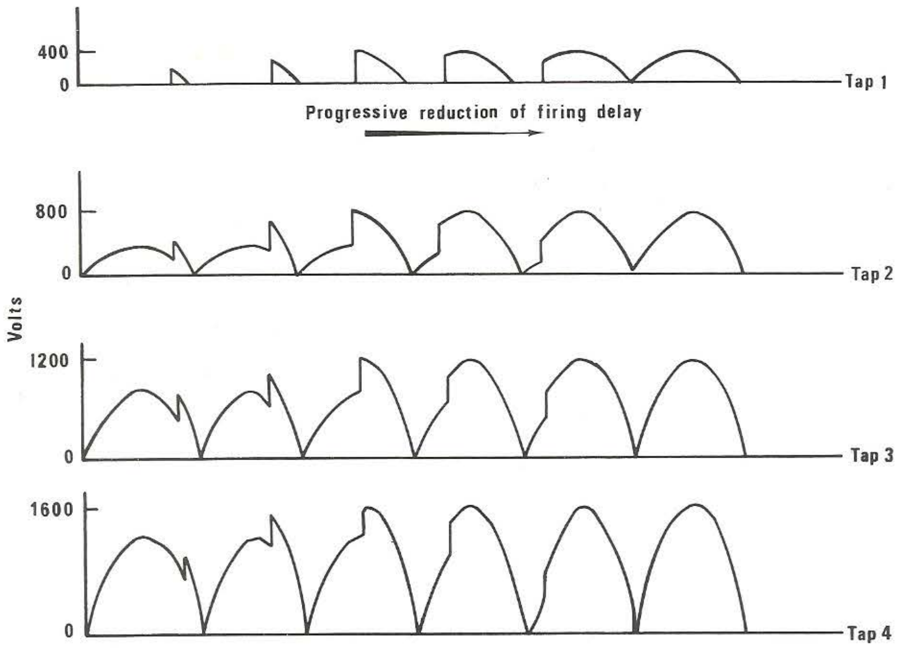


Fig. 4. Output voltage waveforms for various transformer tap positions and stages of thyristor firing

The locomotive is fitted with one compressor of 40 ft^3/min displacement, giving a free air delivery of 28 ft^3/min and driven by a d.c. motor rated at 6·7 hp. Two exhausters of the rotary oil free type are provided; these are each rated at 5 hp. Two speeds are provided for " normal " and " release " operation, and one of the exhausters is so connected that it can be operated from the battery during a temporary interruption of the overhead line supply.

A small compressor, fed from the battery, is provided for initial operation of the pantograph and air blast circuit breaker.

Initial control functions

Increase or decrease of power in the traction motors is initiated by moving the main control handle of the master controller. A potentiometer in the master controller provides a reference signal representing the required armature current, proportional to the angular movement of the control handle from the " off " position.

This voltage-variable signal is passed into an encoder which converts it into a constant-voltage, variable mark/space ratio signal. This signal is fed to the train lines, by which it reaches a decoder on each locomotive. The decoder reconverts the mark/space signal into a variable-voltage signal suitable for control of the servo. The use of a mark/space ratio eliminates any differences between locomotives connected in multiple due to volt drop in the train lines.

The input demand signal to the servo is compared with a feedback signal which represents the highest of the four traction motor armature currents, as measured by static current monitoring devices. The difference or error between demand and feedback signals is amplified and used to adjust the firing angle of the thyristors to change the motor current and bring the error to zero.

This correction of error is a continuous process and so the current will always remain at the value demanded, even though the locomotive is accelerating or decelerating.

The output of the servo feeds into the gate circuits which control the firing angle of the thyristors. A pulse generator gives a series of pulses during each positive half cycle, each pulse being capable of firing the thyristors. The gate circuits override this pulse chain by preventing it from reaching the thyristors when the gates are not required to be fired.

Control of motor current by the variation of thyristor firing angle can only take place over one quarter of transformer secondary voltage. To change from one voltage range to another requires a tap change, this being controlled entirely by a static logic unit, using NOR logic elements in its design.

When the servo reaches the limit of its control, the firing angle will be $\alpha = 0°$ (thyristors firing continuously) when the locomotive is accelerating, or $\alpha = 180°$ (thyristor switched off) when it is decelerating. In either case the servo will lose control of the motor current and the error between the current reference and the current feedback signal starts to grow. When this error reaches 1·5 per cent the servo system instructs the tap changing logic to initiate upwards or downwards transition as required.

In the case of an upward transition, say from tap 2 to tap 3, the firing angle is clamped to $\alpha = 0°$ while the diode contactor T2 is opened and the next higher diode contactor T4 is closed. (When in the bottom range of voltage there is no lower diode contactor to be opened). The thyristor firing angle is then clamped to $\alpha = 180°$ while the thyristor contactor T3 is opened and the next higher thyristor contactor T5 closed. This completes the transition, the clamp is released, and the servo once again takes control of the firing angle and thus the motor current.

In the case of a downward transition the thyristor firing angle is clamped at $\alpha = 180°$ while the thyristor contactor is opened and the next lower thyristor contactor closed. The clamp is changed to $\alpha = 0°$ while the diode contactor is opened and the next lower diode contactor closed. The clamp is then released to allow the servo to regain control of the firing angle.

An advantage of this tapping contactor sequence is that none of the contactors breaks current and thus electrical wear is avoided.

When operating in the top voltage range (T_6 and T_7 closed) the presence of an $\alpha = 0°$ signal initiates weak field, provided that the traction motor armature current is less than 1,000 A. Weak field is selected by closing the weak field contactors and opening the main field contactors.

To maintain constant tractive effort the taking of weak field increases the output of the decoder by 17 per cent, so that the current in weak field is 17 per cent higher than in full field for any given power handle setting, and the tractive effort is constant.

At 1,000 A handle setting in full field the current increases to 1,170 A in weak field, the maximum armature rating. If the control handle is set higher than this then the logic allows the current to decay along the full field characteristic until it reaches 1,000 A, at which point the weak field is taken.

Rheostatic braking

If dynamic braking is fitted after electrification to Rawalpindi, movement of the main control handle in the direction opposite to that for motoring will operate a power-brake changeover switch, connecting the motor fields in series across the main rectifier, with a fixed braking resistor across each motor armature.

The thyristors will be controlled to maintain constant traction motor field current corresponding to the control handle position selected.

Incorporated in the main static control circuits are several safety and auxiliary circuits.

A maximum speed control is included such that at above 70 mile/h the output of the locomotive is curtailed in such a way that by 75 mile/h the traction output has reduced steadily to zero.

In the event of pantograph bounce

there is a dual protection: if the bounce is less than 200 ms the power is cut back, and if greater, then power is shut off to prevent surging on re-application of the primary volts.

Wheelslip correction for the locomotive is provided and is based on the comparison of motor armature currents. If there is a difference between the highest and lowest currents in each of the four motors (after due allowance is made for normal machine tolerances) there is an immediate reduction of a portion of the current reference signal, this causing the traction voltage to phase back.

Further reduction of motor current is achieved by a " ramp " reduction of reference current within 2½ sec, or until wheelslip is arrested. On cessation of wheelslip the current is restored to its original level in a similar manner.

Weight transfer

Mechanical weight transfer compensation is provided to limit wheelslip when starting heavy trains under adverse conditions. It is selected by a desk switch which causes air to be admitted to one of a pair of air cylinders mounted on the inner headstocks of each bogie. This device is under the control of the electronic servo, and gives a fixed amount of weight transfer compensation during periods when the tractive effort exceeds 10,000 lb per motor.

For speed controlled functions an axle-mounted induction generator gives an a.c. output, the frequency of which varies with locomotive speed.

This frequency is used to control, by means of electronic circuits, the speed indication and mileage counting instruments. These circuits also control the vigilance apparatus of the locomotive which must be reset by the driver by operation (releasing and depressing) of the driver's safety device pedal or hand push switch on the other side of the cab. This must be done every 2 min or every mile of travel, whichever is the sooner.

If the reset is not made, a warning buzzer sounds for 6 sec followed by a brake application. Once the brakes have been applied, the driver can only release them by operating the driver's safety pedal twice. The equipment also prevents the driver from coasting with the reverser handle in the off position by initiating a brake application if the reverser handle is so moved.

The main electronic equipment is mounted on racks within a removable box in No. 2 control equipment frame. Each rack is hinged for easy access to its connections and can be quickly replaced if necessary by a spare unit. Full equipment for testing the electronic equipment, when removed from the locomotive, is to be installed in the locomotive workshops.

Pilot lights are provided giving indication of line voltage, wheelslip, weight transfer operation, and general faults. Detail fault lights on the fault indication panel in one of the control equipment cubicles give warning of motor overload operation, hot transformer oil, Buchholz operation, battery charger failure, rectifier use failure, oil pump or cooling fan failure, and weight transfer fault. In addition a pilot light is fitted to facilitate off-load testing of correct sequence operation of the tapping contactors.

Body structure

The superstructure comprising the underframe, side frames, and bulkheads is designed as a unit stress-bearing structure. The main longitudinal members are inter-connected with cross stretchers at the pivots, equipment mountings and drag boxes, and the whole top surface is covered with steel plate welded to the members. The body side panels are of steel, arc welded to the framing, with all joints butt welded and ground flush.

Aluminium alloy floor plates in the equipment compartment are readily removable for access to cables and piping, and the roof sections are removable to facilitate installation and removal of large items of equipment. Bulkheads between the equipment compartment and cabs are lined with sound insulating material, and provision is made for lifting and jacking the superstructure.

The central drawhook, screw coupler and side buffers are of standard PWR type, and cowcatchers fabricated from steel sections and plate are mounted at each end of the locomotive.

Four sand boxes for each direction of travel are mounted on the bogies. This sanding gear is pneumatically operated.

Bogies

The bogie frame is of fully-welded box frame construction in which the side frames are fabricated from two rolled steel section members welded together. The transoms and headstocks are also made from rolled steel sections, and the side frames, transoms and headstocks are joined by gusset plates to form a complete bogie frame. The completed frame is stress-relieved before machining where necessary.

Axlebox guides are attached as separate castings by fitted bolts to machined pads on the bogie frame. They are provided with renewable manganese steel liners on the driving and side thrust cheeks, the liners being checked in position and secured by set bolts according to standard BR practice.

The superstructure load is carried on a flat centre pivot fitted with the renewable liner on the bearing face and manganese steel liners on the thrust face. The top half of the pivot is a steel casting spigotted and bolted to the underframe, while the bottom half is integral with the cast steel swing bolster. Two side steady bearers are mounted on the swing bolster adjacent to the pivot which is supported from the bogie frame by inclined swing links. Secondary coil springs are interposed between the spring seats and the bolster.

The swing links and the secondary coil springs are external to the bogie frame, and to eliminate lateral loading on the secondary coil springs the spring seats are anchored to the swing bolster by long arms with pin joints. Friction dampers are provided on the primary and hydraulic dampers on the secondary suspension systems, and lateral hydraulic dampers are also provided between the bogie frame and the swing bolster.

The traction and braking forces are transmitted through the vertical faces of the pivot, and from the bogie frame to the swing bolster by two traction links. The traction link pin is jointed to the bogie frame and the swing bolster through spherical rubber bushes in each end of each traction link. The centre pivot thrust face and the traction links are positioned below axle level.

The bogie frame is supported at each axlebox on a short forged steel spring beam and two helical coil springs. The spring beam is pin jointed to two lugs integral with the underside of the axlebox housing.

The wheels are of the rolled steel disc type fitted with tyres. Axleboxes are one-piece steel castings fitted with SKF roller bearings.

Vacuum-controlled air brakes are provided on all wheels, and an independent brake cylinder operates the brakes on each wheel with clasp rigging. The brake force is approximately 80 per cent of the adhesive weight and brake adjustment is by air-operated slack adjusters.

Driver's cabs

Apart from the master controller and brake valves, traction motor ammeters, speedometer, air and vacuum brake gauges and various pushbuttons and switches complete with engraved labels are also installed on the driver's desk; the electronically operated drivers vigilance equipment is fitted in No. 2 end cab desk.

Leading particulars of PWR electric locomotives

Track gauge	5 ft 6 in
Service weight	80 tons
Maximum axleload	20 tons
Length over headstocks	51 ft 0 in
Width over body sides	10 ft 6 in
Height, rail to roof	12 ft 0 in
Height, rail to pantograph (down)	14 ft 1 in
Bogie centres	29 ft 0 in
Bogie wheelbase	9 ft 0 in
Wheel diameter (new)	43 in
Clearance to rail with worn tyres	4 in
Minimum curve radius	560 ft
Continuous rating	3,160 hp at 22·5 kV
UIC rating	3,650 hp at 25 kV nominal
Maximum starting tractive effort	56,000 lb
Continuously-rated tractive effort, full field	28,200 lb
Continuously-rated speed, full field	42 mile/h
Continuously-rated T.E. weak field	21,000 lb
Continuously-rated speed weak field	55·9 mile/h
Maximum speed	75 mile/h

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