

# **THREE PHASE DRIVE FOR NO. 1 PROTOTYPE TRAIN**

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## **INTRODUCTION**

The attractive nature of cage induction motors for traction applications has never been in doubt, but until recently practical implementation has been unattractive. Both the availability of a suitable fast power switch (GTO's), and real time computing capability in the form of the microprocessor has changed this situation, to a point where the a.c. drive is considered viable and economic. In these circumstances BRUSH built the a.c. drive propulsion equipment for a Class 457, the no. 1 prototype train.

## **CLASS 457 INVERTERS**

The two inverters were fitted at opposite ends of the propulsion case with a short term rated braking chopper in the middle. Each inverter powers two 165kW traction induction motors, and each equipment powers a two car EMU (one motored plus one trailer car) similar to the Class 455, but with an acceleration rate 25% greater than the normal Class 455 performance. Two identical propulsion cases were provided to drive a 4 car unit.

Six gate turn off thyristors (GTO) with anti-parallel diodes are employed in each compact, lightweight, inverter, in a regenerative bridge arrangement. The power circuit is kept simple with normal snubbing circuits on each GTO (fig. 1), designed to minimise the voltage overshoot when the device is switched off. In this way 2.5kV devices can be reliably operated from d.c. supplies that do not exceed 900V. The cooling of the inverter is achieved by a novel phase change cooler, with a boiler placed between devices in both the GTO and diode stacks respectively. In this design the corresponding boilers in each stack feed a common insulated radiator where the coolant condenses back to its liquid phase, before returning via gravity feed to replenish the boiler (fig. 2). Just sufficient coolant is used to ensure that under maximum acceleration the level in the boiler is not depleted.

By controlling each inverter individually, wheel diameter variations only effect motors on a common bogie. This helps to minimise one of the few disadvantages of this type of drive. The inverters are operated in a voltage sourced, variable frequency mode. The voltage sourced inverter is simpler than a current sourced inverter in terms of power circuit design, and offers lower motor current harmonic content. Each GTO is operated by a gate drive circuit local to the inverter. The input to the gate drive is via a fibre optic link from the main electronics rack, providing interference free transmission.

## **PWM AND SIGNALLING COMPATIBILITY**

Voltage control of the inverters is achieved from a Motorola 68000 processor dedicated to the real time generation of PWM, where low order harmonics are eliminated. This form of harmonic elimination is best for minimisation of motor losses because the resulting higher harmonic currents are more effectively attenuated by the filtering of motor inductance, although winding capacitance may diminish this benefit. By constraining the motor voltage when operating with harmonics at critical signalling frequencies, the same PWM strategy is ideal for minimising supply side harmonics. In practise the lineside components are not eliminated, but are reduced to very low levels. This is because of the small (<25us) but essential dead time between the switching of devices in the same arm of the inverter. A greater problem is the generation of unwanted components due to 3 phase unbalance, caused by impedance and timing mismatch. Because the system is 3 phase, any asymmetry always causes a third harmonic motor current to not perfectly cancel. Furthermore, because of the low resistance offered by the motors to d.c. any systematic voltage mismatch (such as different volt drops across devices) can cause a significant d.c. current to flow in the motor. The presence of d.c. and third harmonic, as well as the desired large level of fundamental in the motor current, then appears demodulated on the supply side as fundamental and second harmonic. These undesirable effects make the requirement that they are kept to a minimum a prime concern.

As a consequence of stringent conducted signalling interference requirements and the need to maintain or replace hardware, the attention for signalling protection turned from software to hardware. Thus the possibility of a bad device spread, a high impedance connection, a wrong value snubber component fitted, a failed snubber diode, or incorrectly routed motor cables could lead to substantial increases in supply current at signalling frequencies. It is part of the manufacturers task to ensure that all reasonable steps are taken to minimise these potential problems at design stage. It is the task of a monitoring unit, also evaluated on the prototype trains, to ensure any subsequent faults to the propulsion equipment does not cause the maximum permitted signalling interference level to be exceeded.

### **T.E. CONTROL SYSTEM**

The rest of the microprocessor system (fig. 3) on no. 1 prototype train was responsible for the supervisory and torque control functions governing the operation of the inverters. The torque controller, like the PWM, has to update rapidly, and also requires a M68000 processor dedicated to the task. Together the torque controller plus PWM constitute a single board with 'dual' microprocessor communication via dual port RAM. One 'dual board' is required for each inverter. A common supervisor processor directs demands to and reports from both 'dual boards' in the electronics rack.

The torque controller is a scalar control specifically designed for traction applications. It makes use of the assumption that for any tractive effort the ideal flux level is approximately constant. The instantaneous inverter input power is measured using two transducers. Dividing by scaled inverter frequency instead of speed an allowance is automatically included for rotor losses. From a knowledge of the demand the stator losses (copper and iron) can be estimated and allowed for. The resulting measure is the T.E. achieved from the motor.

Having computed the T.E. achieved it is compared to the demand to generate an error signal. A non-linear compensator then acts on the error to generate the frequency demand, which is updated to the PWM upon interrupt from the PWM.

The great virtue of this control scheme is that no flux measurements are necessary, and that only low precision speed measurement is required for resynchronising the inverters when taking power. It was demonstrated on the Class 457 that the system would operate satisfactorily without a speed probe signal (albeit with an increased delay time to take power). By only peripheral measurement of instantaneous d.c. link power, dynamic performance similar to that of more complex field oriented (vector) systems is achieved. During the course of mileage accumulation on the prototype train the design was improved to achieve a 10Hz control bandwidth, adequate for all normal traction operating conditions, with an acceleration lag of only 2%. The most probable source of error in the calculated T.E. achieved at the wheel is the estimation of transmission loss in the drive.

### **ENHANCED ADHESION CONTROL**

The adhesion system is integrated into the torque control software to maximise both the sensitivity and speed of response to changes in track conditions. The system uses the knowledge of the tare weight of all cars that comprise a unit in order to establish a reference frequency slew rate. This reference is then compensated by the load weight signals and the driver demand, if constant T.E. is required. If constant acceleration rate is required the slew rate reference is compensated by driver demand, and the driver demand has to be compensated by the load weight. Both variations were successfully tested on Class 457, requiring only minor software changes to the supervisor to enable this. The setting of the reference level is important for extremely good adhesion control and should be set to a calculated value based on tare weights. Should a load weight signal fail, the software detects this condition and makes its calculations on the other load weight signal only. In the unlikely event of both load weight transducers failing tare weight operation is assumed, resulting in degraded adhesion control when heavy laden.

During adhesion tests it was observed that the two motors on one bogie did behave as one motor and that as one axle slipped the second immediately followed. This phenomenon had been predicted because of the steep natural characteristic of the induction motor. When both motor begin to slip or slide the control system starts to advance the frequency to compensate. At this point the controller recognises that the slew rate exceeds what should be expected, and backs off the torque level pro-rata. In this way a limited form of creep adjustment is achieved. If and when the excess slew rate is greater than 20% of the compensated reference level for 0.25s, a large step reduction in T.E. is made. Re-adhesion is tested for by analysing both slew rate and T.E. error. If re-adhesion occurs a jerk rate limited recovery commences back to 90% of the driver demand, otherwise a further reduction in demand is made. If there is no re-adhesion within 2 seconds then the inverter is resynchronised to make another attempt. While recovery is being made the creep regime may be entered (fig. 4), prior to the full demand being achieved or the whole process repeating.

## **EXTENDED REGENERATIVE BRAKING**

The Class 457 achieved high levels of regenerative brake, experiencing good levels of receptivity at most times of the day. Electric braking was fully blended with air brakes via back-off valves in two different configurations:-

- (i) By cross blending to maximise the use of available electric brake, whilst equalising brake wear on all cars.
- (ii) By own weight braking to directly substitute electric brake for air brake on the motored cars only.

The cross blend scheme was particularly successful in regularly achieving regeneration down to standstill, without adverse effects due to different overall brake efforts from motor and trailer cars. On occasions when the line was unreceptive the chopper operated producing a controlled fade-off of electric brake whilst the air brakes built up to their normal level.

## **CONCLUSIONS**

The Class 457 has demonstrated that three phase drives are both practical and beneficial for modern EMU operation. It was successfully tried in passenger service on 9<sup>th</sup> September 1988, within three months off the start of commissioning. Subsequent extensive mileage accumulation was performed over a six month period, resulting in 10,000 miles operation. Although initially, a number of failures did occur, the Class 457 always returned safely under its own power. Just prior to being taken out of operation to be modified for 25kV a.c. electrified supply in May 1989, the Class 457 had performed faultlessly for several months, and since the conversion the four inverters have continued to perform quite satisfactorily with 100% availability.

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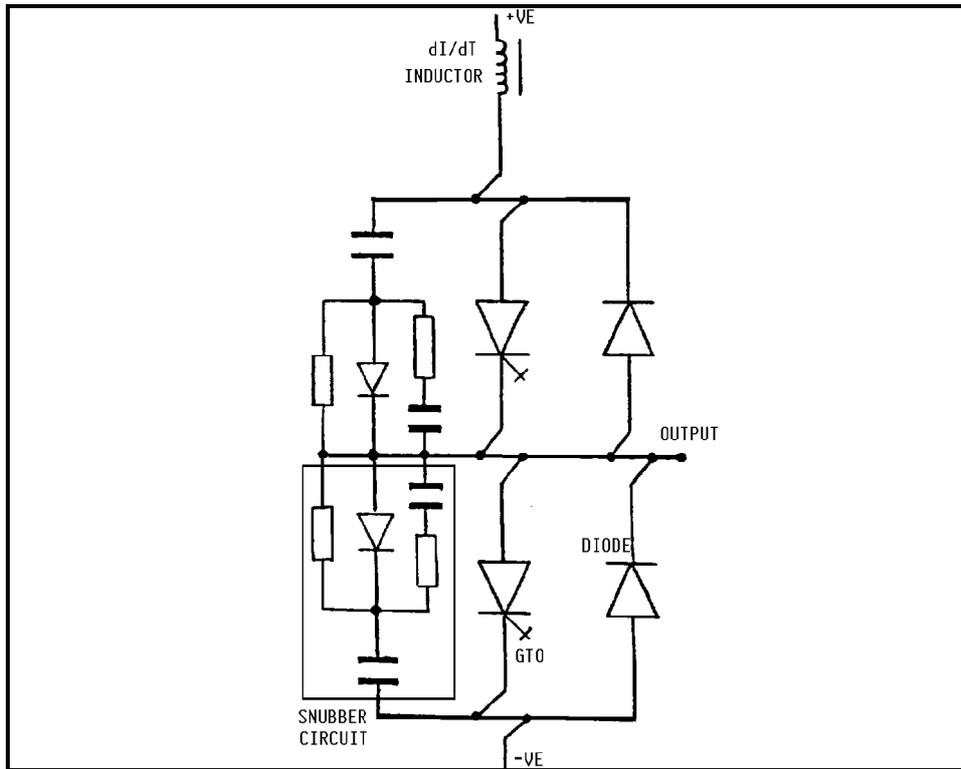


FIG 1 POWER CIRCUIT OF AN INVERTER ARM

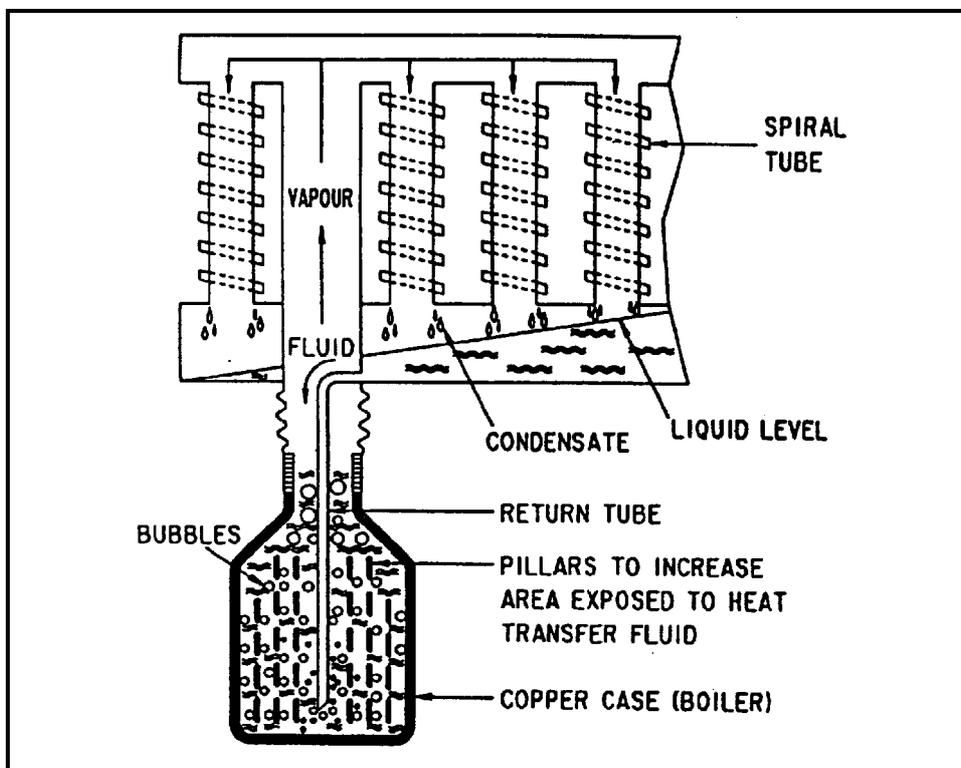


FIG 2 ONE HALF OF PHASE CHANGE COOLER

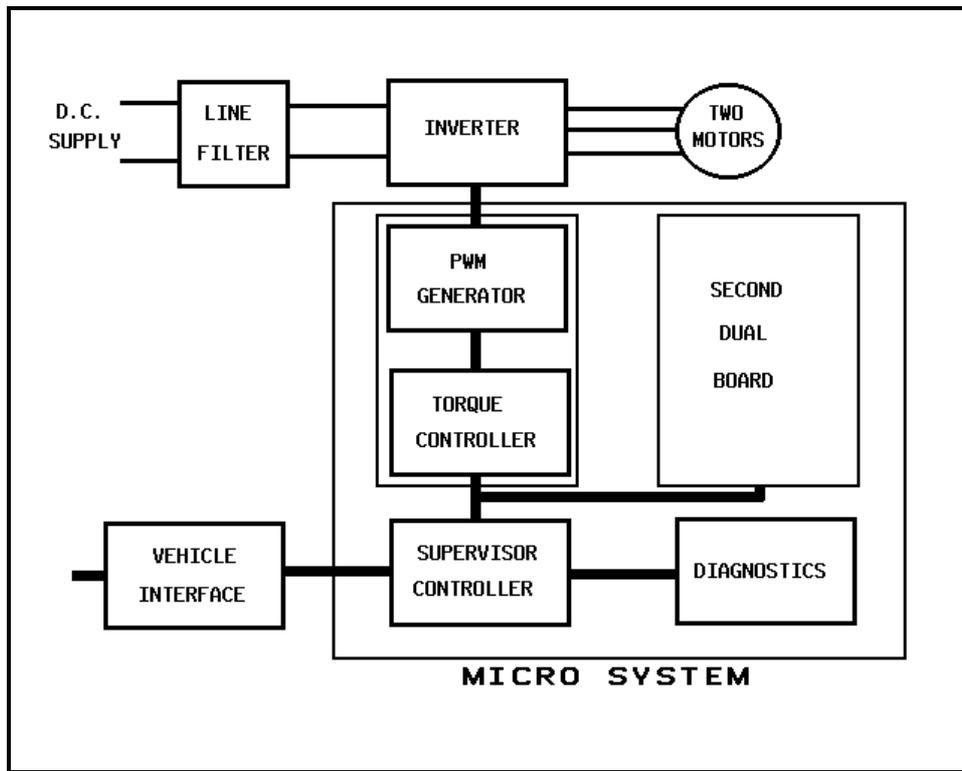


FIG 3 SYSTEM BLOCK DIAGRAM

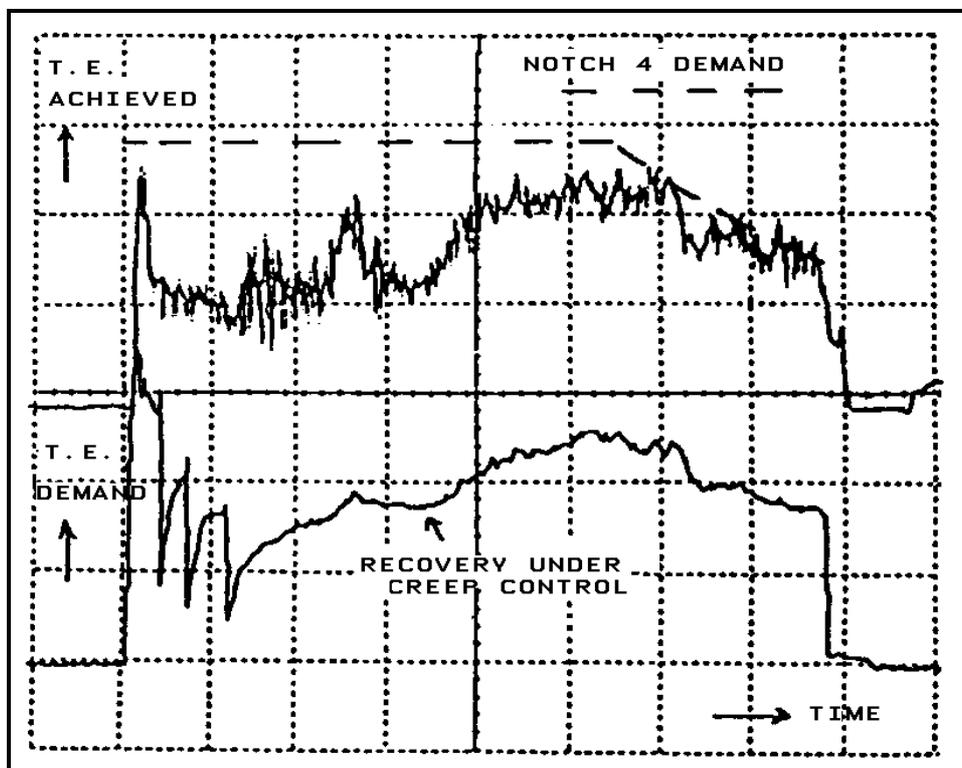


FIG 4 CL 457 MEASURED ADHESION CONTROL