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Recent advances in the application of GTO thyristors in rapid transit vehicles

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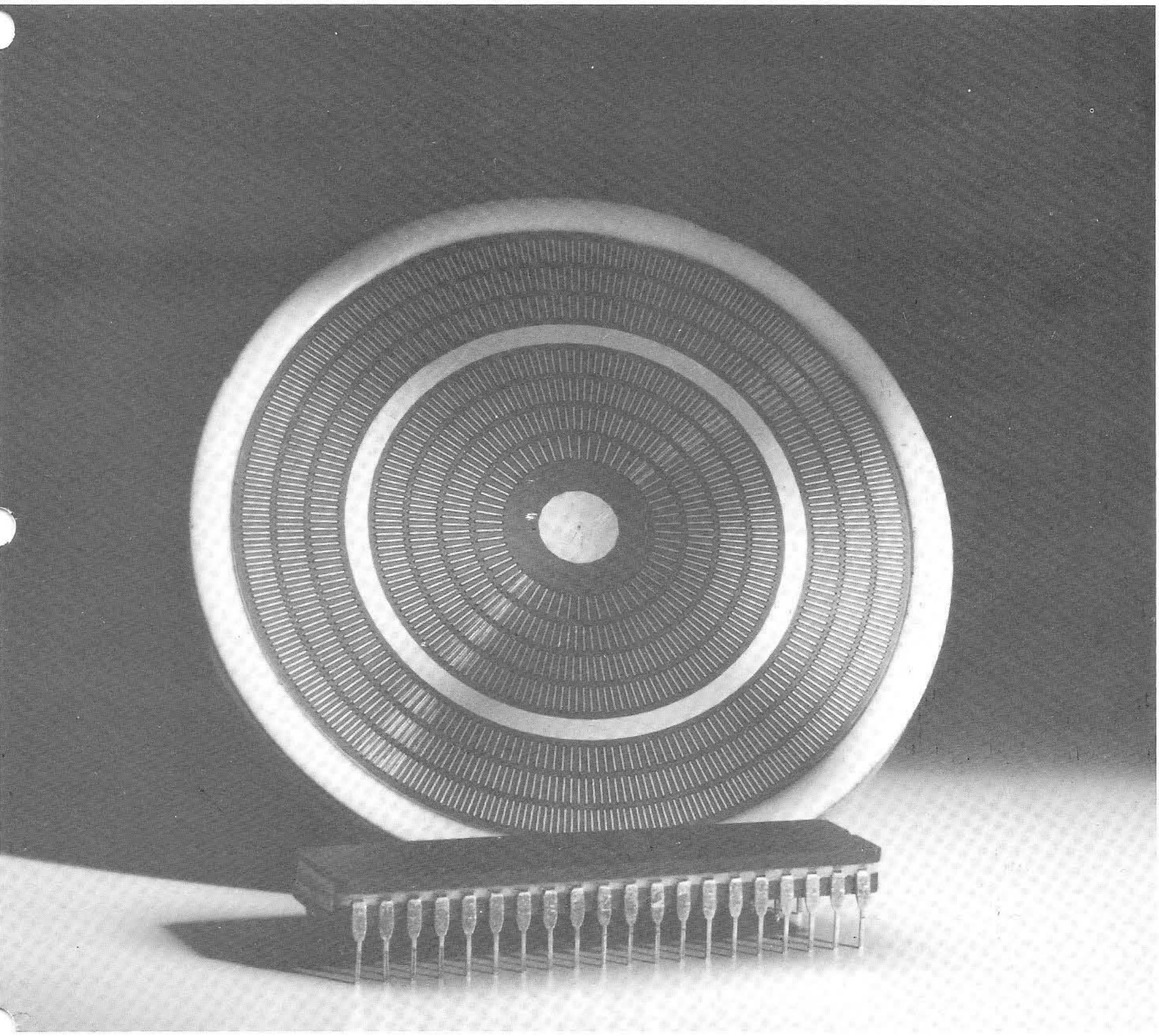

RECENT ADVANCES IN THE APPLICATION OF GTO THYRISTORS IN RAPID TRANSIT VEHICLES

Until 1982, all DC choppers used conventional thristors. These required heavy and bulky commutation components. The availability of high-power GTO's has changed the technology available to system designers and new light-weight choppers are thus available. The paper will discuss the microprocessor controlled GTO choppers that have been supplied to the London Underground, the Hong Kong Mass Transit Railways, the Danish State Railways, British Rail and other administrations. Until the advent of high powered GTO's, three phase drives were more complicated and expensive than DC drives. The simplification of power circuits that is now possible has made the 3 phase-drive more cost competitive. The paper will also discuss a new design of three-phase that has recently been delivered to British Rail. This incorporates a sophisticated modulation strategy to eliminate interference at signalling frequencies and parallel control loops that optimise motor flux without the need for accurate measurement.

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GTO Choppers for Rail Vehicles

This paper discusses seven recent designs of choppers using Gate Turn Off (GTO) thyristors. Details are given of three designs that are being introduced into fleet operation on British Rail, Hong Kong MRTC and the London Docklands Light Railway.

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Introduction

The railway industry is one of the major users of power semiconductor devices. During the electrification of the West Coast Main Line in the early 1960s the latest designs of germanium diodes, and then silicon diodes, were used as soon as they were available to replace the unreliable mercury-arc rectifiers of the earlier classes of locomotives and electric multiple units (EMUs).[1]

During the 1970s the U.K. railway operators were less adventurous; although prototype phase-angle controlled EMUs using thyristors were demonstrated in 1967, orders for fleet operation were not placed for another 10 years. Prototype thyristor choppers were demonstrated overseas in 1970 but production orders were never placed by U.K. railways and GEC's first major orders for choppers were for Dublin[2] and Seoul.[3] These were "three thyristor" choppers with analogue control systems and over 300 units were commissioned between 1983 and 1986. Part of the reluctance to invest in chopper controlled units can be attributed to fears of signalling interference but this issue is now well understood[4] and is no longer seen as a reason to avoid chopper control.

High power GTOs only started to become available around 1983;[5] in the following five years they have totally replaced conventional thyristors for EMU choppers and are beginning to be widely used in locomotives. This period has coincided with the introduction of 16-bit microprocessors and the two technologies have inevitably become associated. Digitally controlled GTO choppers are now the norm for all new D.C. EMU equipment. This change represents a revolution in the design of propulsion equipment as dramatic as the introduction of power semiconductor devices in the 1960s.

1500V Choppers for Hong Kong

A prototype GTO chopper was commissioned and put into service in mid-1987. A further 19 units are in course on manufacture. Hong Kong MTRC is a high performance mass transit underground system with vehicles as large as U.K. main line coaches. All previous cars have been camshaft/resistor controlled.

A simplified circuit diagram of the chopper is shown in figure 1. Two adjacent cars, each with four motors, are fed from one pantograph. The power is taken through a high speed circuit breaker (HSCB) into a filter consisting of a 6mH inductor (L1) and a 3.5mF capacitor (C1). This has a natural frequency of 35Hz which is below the critical 50Hz frequency that might be excited by substation phase unbalance. An additional shunt filter (L2 and C2) is used to increase the input impedance at signalling frequencies.

During motoring the motor/brake switch (MBS) connects the motor armatures to the line as shown, the current then passes through the fields and is controlled by a single GTO (GTO2). The diode (D2) provides a freewheel path when the GTO is not conducting and the rate of change of current through the GTO is limited by the di/dt choke (L4).

When braking is selected, the motor/brake switch (MBS) connects the fields to the top of the motor string and GTO2 controls the field current. The field resistor (R2) limits the current to allow a wide control range without an excessively short minimum on-time. The armature resistor (R3) is inserted in the circuit by opening a contactor (not shown) when the maximum motor back EMF is less than the line voltage.

When the regenerated voltage exceeds the filter capacitor voltage, the braking diode (D3) conducts and the regenerated energy goes back into the line. If the capacitor voltage rises to too high a value, the braking chopper (GTO1, D1 and L3) draws current through the braking resistor (R1). This resistor is not rated for continuous use on a non-receptive line and air brakes are blended in over a short period to maintain the braking effort.

The chopper uses a forced air cooled 4.5kV, 2.5kA GTO (MEDL DG758SX45 or equivalent) which carries a maximum accelerating current of around 800A; the RMS current over the worst case specified route is just less than 300A. Each chopper operates at 260Hz and the two adjacent

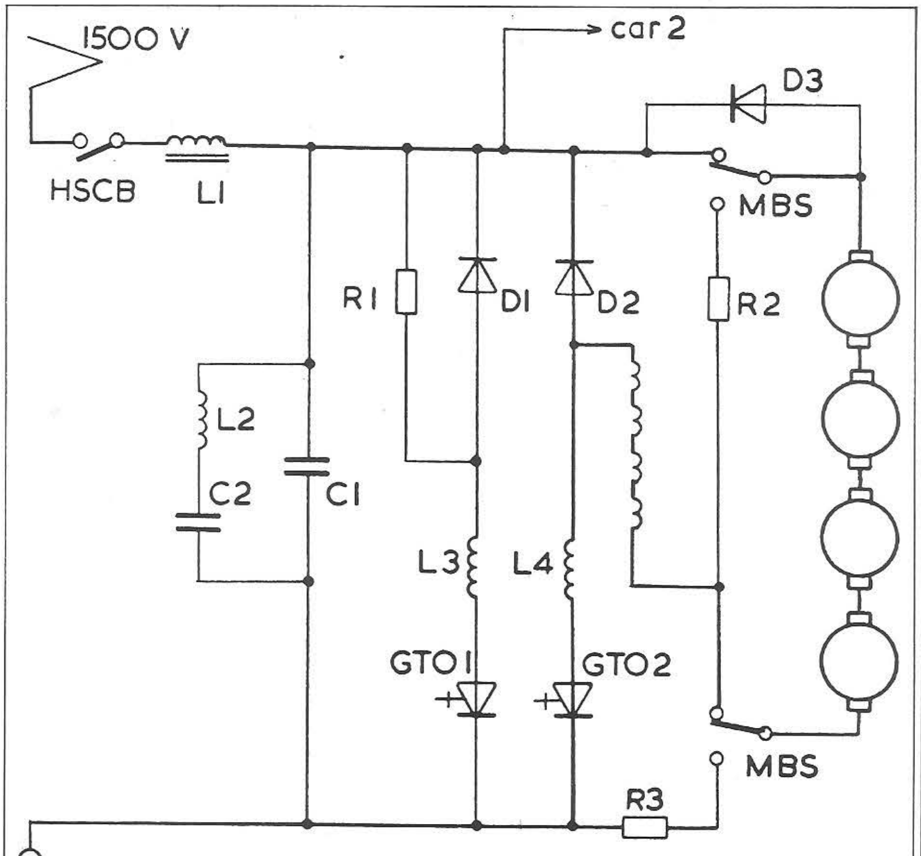


Figure 1. Hong Kong MTRC Circuit Diagram.

cars, which use the same line filter, are interlaced to give a line current ripple of 520Hz. When the motor is operating at full voltage the chopper GTO is permanently "on" which reduces switching losses.

Danish State Railways (DSB)

A prototype chopper very similar to the HKMTRC chopper described above has been supplied to DSB for a 1500V suburban EMU. The major differences are that the main GTO is duplicated, as described below, to increase the motor current and the rheostatic brake is fully rated. The circuit has been rearranged to cater for the DSB supply (overhead line at – 1500V relative to the rails). The prototype was commissioned in mid-1987 and has been in service since January 1988.

British Rail Class 319

The Class 319 EMU is (Figure 2) specified for operation on the 25kV lines north of London and on the 750V electrification under the city and in the South. The first Class 319 units were commissioned in 1987, full passenger service commenced in May 1988 and the fleet of 60 EMUs will be in service during 1988.

Each power car has four motors and each motor is individually controlled by a motoring-only GTO chopper. The power circuit is shown in Figure 3. A transformer followed by a single diode bridge provides a rectified supply for the choppers. The line filter inductor is designed to function both as a smoothing reactor, for operation on A.C. lines, and as a line filter, for operation on D.C.

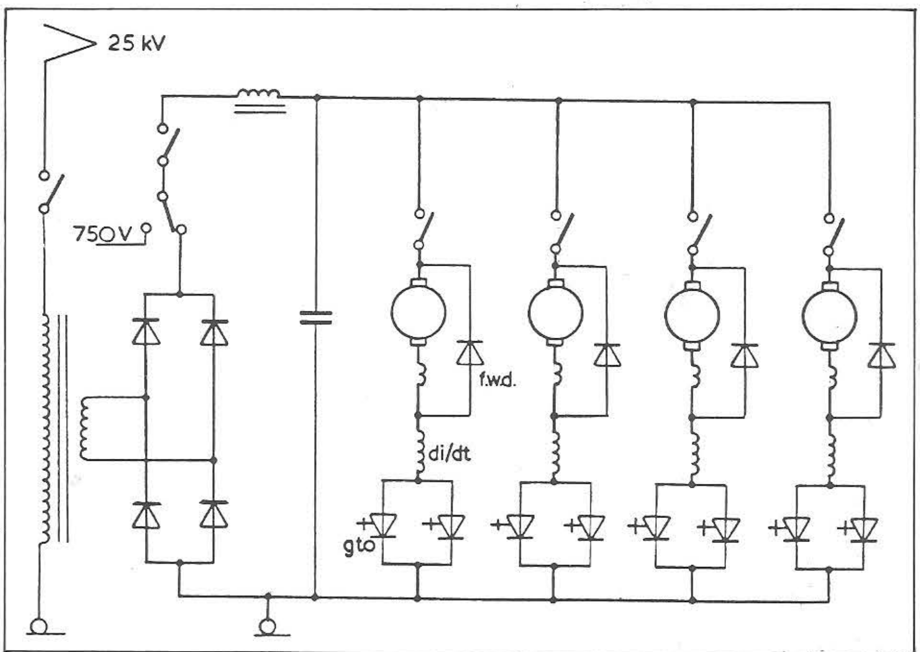
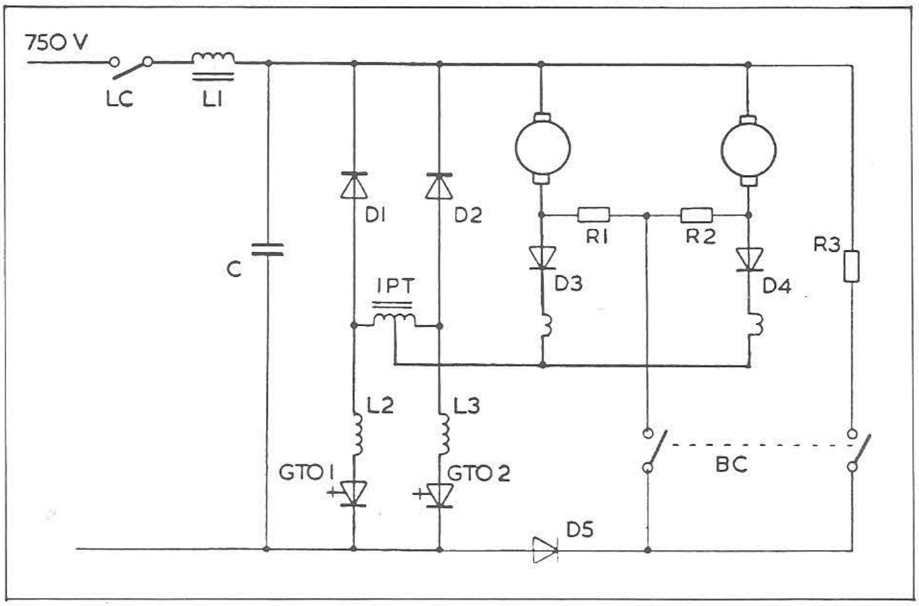


Figure 2. BR Class 319 EMU (above) and Figure 3. BR Class 319 EMU Circuit Diagram (below).

Two MEDL 2.5kV 1.4kA GTOs are used to take the current for each motor. They are controlled to operate alternatively and "timeshare". The mean current through each device is half the total and the switching losses are also shared. Because the devices are not switched on at the same time they can share the same surge suppression network and di/dt inductor. A freewheel diode (fwd) is connected across each motor. The firing pulses for motors 1 and 3 are in phase and the effective frequency of each chopper is 300Hz.

Figure 4. The Docklands Light Railway passing new developments in London (top) and Figure 5. Docklands Light Railway Vehicle Power Circuit Diagram (right).



Docklands Light Railway

The London Docklands Light Railway (DLR) is a fully automatic railway in the East of London[6] (Figure 4). A fleet of 11 microprocessor controlled articulated units have been in passenger services since August, 1987. A further 10 units have been ordered for the extension to Bank in the City of London.

Each unit has two powered monomotor bogies and one trailer bogie. The power circuit diagram is shown in Figure 5 below. When motoring the line contactor (LC) is closed and the braking contactor (BC) is open. There are two choppers (one comprises GTO1, L2 and D1 the other comprises GTO2, L3 and D2). These are switched in anti-phase at a frequency of 264Hz giving a line ripple frequency of 528Hz. Unlike the chopper on the Class 319, the two GTOs can be on at the same time and therefore they have individual di/dt chokes and snubbers. The interphase transformer (IPT) ensures that the two phases of the chopper run independently.

The trains are designed with rheostatic braking and not regenerative braking. When braking is selected LC opens and BC closes. The armature current is circulated through the armature resistors (R1 and R2) and the braking resistor (R3). The voltage across R1 and R2 is available to drive the current through the fields and is controlled by the 2-phase chopper.

Other GTO Chopper Developments

Three different types of GTO chopper have been described: four motors in series fed by a single chopper and with regenerative braking, four motors each with an individual chopper with no electric braking and a two-phase chopper feeding two motors in parallel. Two options have been described for sharing current between devices; timesharing and the use of anti-phase choppers and an interphase transformer.

In addition to these designs GEC has delivered a prototype unit to London Underground Limited that uses a single chopper to provide the power for eight traction motors arranged in 4 parallel strings of series pairs.[7] These motors are separately excited from an independent chopper. The main chopper uses two 1.4kA devices in each phase of a two-phase circuit. A prototype regenerative chopper has also been commissioned on a BR 750V Class 455 EMU.

GTO choppers have also been used on two types of locomotive. The British Rail Class 91 25kV locomotive, which first ran on the main line in February 1988, was specified to have a rheostatic brake capable of operation without an overhead supply. This has been achieved by the use of a two stage field supply circuit: the first stage provides a fixed direct voltage, across which a battery is floated, and the second stage consists of a GTO chopper to control the motor field.

The South African Transport Services (SATS) 10E1 locomotive is a heavy freight 3000V Co-Co. An order for 50 locomotives was received in 1984 and the first were handed over in 1987. This design used conventional thyristors in the armature choppers but GTO choppers for the separately excited fields.

The Future

In a period of less than five years the microprocessor controlled GTO chopper has become established as the "industry standard" for the control of motors on DC systems. Development work has been completed to allow the use of GTOs in series for armature choppers or 3kV systems. □

Acknowledgement

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BR 150V Class 455 EMU (top), BR Class 91 25kV Locomotive (middle) and SATS 10E1 locomotive (below).

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