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Drive systems for high speed trains

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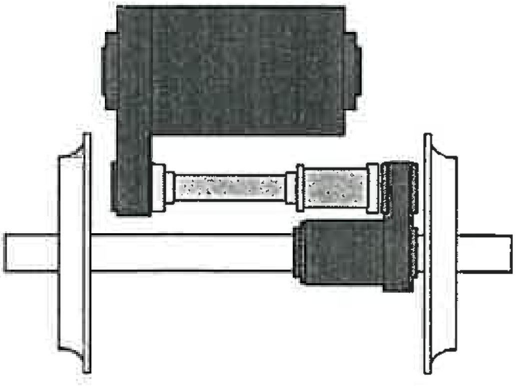
Introduction

The railway industry has been strongly influenced by the development of power semiconductor devices. The principles of GTOs and IGBTs have been known for many years but it was only in the 1980s that the power semiconductor industry started to exploit these inventions which have made a major change to the design of traction systems. In the past 20 years there have been at least nine generations of equipment - phase-angle controlled thyristor rectifiers (for ac electrified routes), thyristor choppers (for dc routes), synchronous drives using thyristors, gate turn off thyristor (GTO) choppers, current source inverters (CSI) or voltage source inverters (VSI) using thyristors, GTO inverters, insulated gate bi-polar transistor (IGBT) inverters and force commutated converters using either GTOs or IGBTs.

TGV Paris - South-East (TGV-PSE)

The first very high speed trains introduced in the early 1980s, the 270 km/h TGVs operating between Paris and Lyon, used dc motors. The power was limited to 535 kW per axle by the space available for the traction motors. To achieve low track forces and good dynamic stability the bogie frame mass is kept as low as possible by body mounting the motors, as shown in the following sketch: [1]



The motor, although in the centre of the bogie, is resiliently mounted on the underside of the power car floor and is directly coupled to a first-stage reduction gearbox (with an intermediate gearwheel to achieve adequate separation of the centrelines of the motor and drive shaft). Between this gearbox and the second-stage gearbox is a cardan shaft with tripode transmission. The second stage reduction box is supported from the powered axle. This scheme has proved satisfactory and has been repeated on subsequent builds of TGV trainsets.

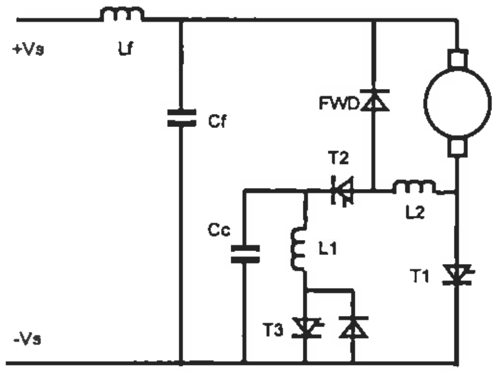
The high speed lines in France use 25kV 50Hz but many of the "classical" lines use 1500V dc. The electrical drive system for the TGV-PSE has to accommodate both supply voltages and therefore uses an input ac to dc converter followed by a thyristor chopper. All devices are mounted on forced-air cooled heatsinks. To achieve the necessary installed power, there are two Bo-Bo power cars at each end of a rake of eight articulated coaches and, in addition, the end bogies of the passenger vehicles are motored by the same type of drive system.

The choice of synchronous drive systems

Following the success of the TGV-PSE it was decided to extend the high speed network by building a new line to Le Mans to join with upgraded lines serving the Atlantic coast of France. The new design of train for this project was named the TGV Atlantique (TGV-A).

The dc drives on the 100 TGV-PSE trainsets worked well but, because of the low motor power, necessitated a total of 24 powered axles for a "full length" train of 16 passenger cars. The proportion of the train devoted to power equipment was higher than desirable and the maintenance workload imposed by the large numbers of power devices was expensive. At the end of the 1970s, French Railways (SNCF) started looking for a technology to replace dc drives. The key requirement was to find a more powerful motor that would fit within the space constraints of the dc motor and its transmission system described above.

At the time GTO thyristors were not available and choppers or inverters required large numbers of fast turn-off thyristors. The circuits were complicated and required many ancillary semiconductor devices and passive components. The following simplified circuit shows the "standard 3-thyristor chopper" used by ALSTOM for applications as diverse as metro cars on Seoul Subway and heavy freight locomotives in South Africa: [2]



The components L_f and C_f form an input filter with a resonant frequency of around 35Hz to isolate the equipment from the supply and to provide a low impedance source for the chopper. The motor current is switched on by T_1 . To turn off the current T_2 is fired which diverts the load current through the inductor L_2 into the commutation capacitor C_c thus allowing T_1 to turn off. When the capacitor charges to line voltage, the current is diverted through the free-wheel diode FWD. The capacitor is recharged to a negative voltage by firing thyristor T_3 . The resonant circuit of C_c and L_1 causes a voltage overswing leaving the capacitor fully charged and ready for the next commutation cycle.

Such a chopper circuit was bulky, heavy and had a high component count. The inductors carried high pulse currents with fast rising edges and thus equipment was prone to radiate RF interference. A force-commutated 3-phase inverter (basically six choppers in a bridge) based on the same technology was even more complicated.

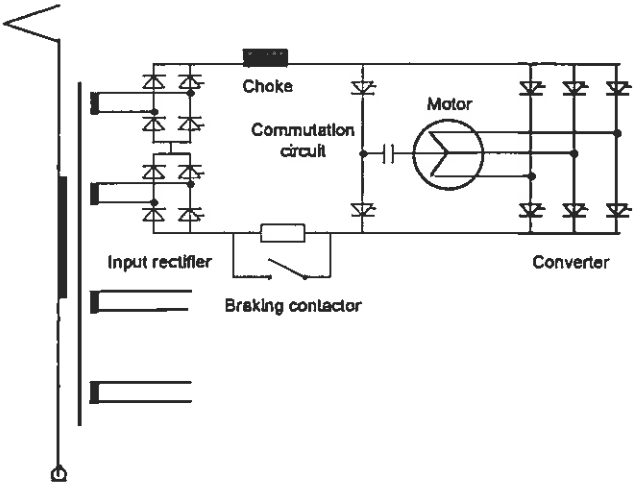
Towards the end of the 1970s SNCF organised a "competition" between the asynchronous drive and the synchronous drive. Two old locomotives, BB10003 and BB10004, were converted, the former to asynchronous and the latter to synchronous drive.[3] A comparison of the numbers of power devices used by these two projects with other locomotives of a comparable generation (i.e. pre-GTO) is shown in the following table:

Locomotive	Drive	Year	Devices
SNCF BB15000	dc (phase angle)	1971	136
BR 87.101	dc (phase angle)	1973	128
BR APT-P	dc (phase angle)	1974	40
SNCF BB10004	***synchronous***	***1982***	***132***
DB Class E120	asynchronous	1983	450
SNCF BB10003	***asynchronous***	***1983***	***320***
SNCF BB26000	synchronous	1987	96
BR Class 91	dc (phase angle)	1988	28

The comparison is not completely fair as the locomotives are of different power ratings and have different input circuits. However it can be seen that, in general, the dc drives use fewest devices followed by the synchronous drives and then asynchronous drives. Asynchronous thyristor drives are three or four times as complicated as the dc drives they replaced. On this basis SNCF decided to adopt the synchronous drive for its TGV-A fleet.[4] The overall complexity is not much worse than a dc drive but the motor is substantially lighter. Calculations showed that the total mass of a 1,100kW synchronous motor plus its self-commutated inverter at 1.5 tonnes was within a few percent of that for a 535kW dc motor.[5]

TGV- Atlantique

A much simplified power circuit diagram of TGV-A is shown below:



There is an input rectifier, controlled to give a constant current through the line choke. When the drive is running above 10 km/h the EMF of the synchronous motor is sufficient to naturally commutate the converter. At low speeds, auxiliary commutation is provided by the pair of thyristors connected to the motor star-point. Rheostatic braking is provided by opening the braking contactor and allowing the motor to drive current through the resistor and the diodes in the input converter. The motor field is weakened as the speed increases to deflux the machine. (Not shown on the above diagram are the separate rotor field supply and the arrangement to reconfigure part of the input converter to accommodate 1,500 Vdc input.)

The power semiconductors are enclosed in tanks of Freon; this boils in contact with heat exchangers close to the devices and then condenses it the top of the tanks where the heat is transferred to air-cooled heat sinks. Recent designs use a new fluid, FC72, in place of the Freon (a CFC) that is being phased-out under the Montreal protocol.

The benefits of the synchronous drive are that it gives a constant and controllable torque, it uses few large (and relatively slow) power semiconductor devices and the converters do not need forced commutation circuits. Some disadvantage are that the salient-pole rotor of the traction motor is more complicated than the squirrel cage rotor of an induction motor, there are sliprings to carry the field power and a position feedback is needed from the motor to control the converter. By the nature of the drive a separate converter is required for each motor.

The synchronous motor has been very successful in 300 km/h high speed trains. A fleet of 105 trains was built for TGV-A, this has been followed by 18 for the Spanish Railways AVE fleet, 50 for the "Network TGV" (TGV-R) that connects many provincial towns and cities in France, 30 double-deck TGVs, 17 multi-voltage trains for international services to Germany and the Netherlands and, most recently, the first of the 46 Korean TGV trainsets has just been delivered. The world rail speed record of 515 km/h was established by a TGV-A with synchronous drives.

Eurostar - London to Paris and Brussels

Thirty eight trains were built for high speed services through the Channel Tunnel. Mechanically *Eurostar* is based on the *TGV Atlantique*. However, many changes have been incorporated to make it suitable for running through the Tunnel to London; the most obvious is that, because the British loading gauge is smaller than the UIC gauge used in mainland Europe, the train has had to be redesigned to reduce the width. This has affected not only the body but also the bogies and the doors and steps to accommodate the higher platforms in the UK. To maximise the amount of traffic through the Tunnel a very long train was required. The *TGV-Atlantique* trains have 10 coaches between a pair of power cars. *Eurostar* has 18 intermediate coaches making it a much heavier train requiring more power to maintain its full speed.

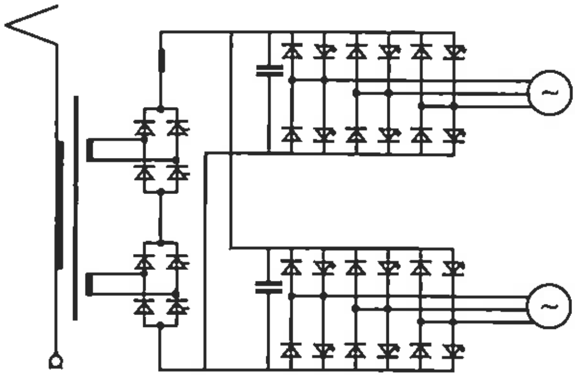
The challenge to the *Eurostar* power equipment designers was to squeeze more power into a smaller vehicle cross section than TGV-A while continuing to meet the same axleload limits. The task was made even more difficult by the need to adapt to three different supply voltages, to provide the system redundancy dictated by the Tunnel rules and to accommodate the signalling, communications and control systems needed by the four railway administrations. It was the availability of 4,500V 2,500A GTOs that made this design practicable.

The power equipment on *Eurostar* was completely redesigned in comparison with the previous generation of TGVs. *Eurostar* has to cope with three different supply voltages - 25kV in France, 3000V dc in Belgium and 750V dc on the Network South East lines in the UK. The 750V supply is a radically new feature for TGVs as it requires pick-up shoes that collect current from a third rail and not a pantograph operating from an overhead line. These collector shoes have to be retracted on other lines, to prevent fouling the gauge, and earthed for safety reasons.

Like TGV-A, *Eurostar* uses 3-phase motors. Unlike TGV-A they are asynchronous motors fed by GTO inverters rather than synchronous motors fed from thyristor converters. The inverters for each bogie are independent - even to the extent of having a separate control battery and charger - and are fed from the "common bloc" which is, in effect, a mobile substation converting the three incoming supplies to a clean dc supply suitable for the inverters.

The common blocs are the largest components in the power cars. The include a thyristor converter to convert the ac supply from the transformer to 1.8 kVdc suitable for the inverters, a GTO chopper to convert 3 kVdc to 1.8kVdc (when running on BR the dc link voltage is 750 V), another chopper to convert 1.8 kV to 500 Vdc for the train auxiliaries, various L-C filters to improve power factor, reduce line current ripple and provide smoothing for the motor blocs and a number of contactors, isolators and circuit breakers to configure the above components for the different supply voltages.

A much simplified power circuit diagram, when connected to run on 25kV 50Hz, is shown below:

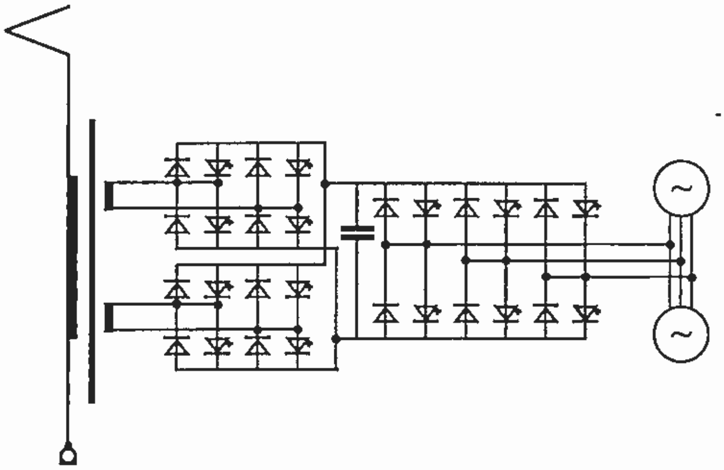


There are two input rectifiers in series to produce the 1800V dc link and a separate inverter for each motor. The inverters each consist of three (non-flammable) oil-cooled semiconductor stacks. The heat is dissipated in a radiator mounted in the same airstream as the main transformer.

Force commutated input converters

Eurostar uses the same half-controlled bridge input converter as thyristor-controlled locomotives with dc motors. Consequently the "natural" power factor is, at best 0.85 and there are high levels of low-order harmonic currents. Regeneration (i.e. returning braking power into the overhead line) is not possible. With the increasing appreciation of the cost of energy, concern over voltage distortion at the point of common coupling with the public power supply and the need to run more trains over a route without strengthening the power supply, railway administrations are asking for a train that draws a close approximation to a sine wave at unity power factor and that is capable of regenerative braking.

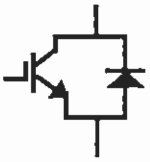
For historical reasons, the German railways (DB) generate their own supply at 16.6Hz and therefore, with a low-capacity power supply without the back-up of a national power grid, were one of the first to be faced with the need for such a drive system. The locomotive E120, referred to earlier, was one of the first to use force commutated converters. Other European railways considered the idea but, due to the complexity of the thyristor converters, rejected it. This design has been continued in the 270 km/h ICE trains, now using GTOs rather than fast thyristors.[6] A simplified power schematic of the drives for one bogie of the ICE2 is shown below:



ALSTOM has produced similar drives for multiple-unit trains, including for the Kwachon Line in the suburbs of Seoul in Korea. The American Flyer train for the NE Corridor will use this technology as do the BB36000 series of locomotives for SNCF which use a novel design of water-cooled heatsinks.

IGBT drives

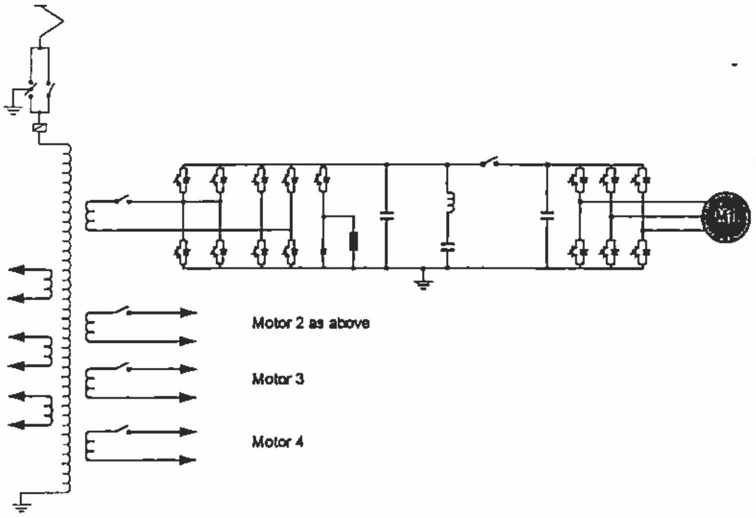
The Insulated Gate Bi-polar Transistor (IGBT) has revolutionised the design of traction systems by a greatly reduced space requirement in comparison with GTOs and a much lower gate drive requirement. Whereas a large GTO requires a negative gate pulse at turn-off of 500A or more, the IGBT is a voltage-controlled device and thus the control signal has to charge the internal capacitance but not provide a fraction of load current, as with the GTO.



The GTO has a maximum limit of dI/dt dictated by the speed at which carriers (i.e. electron holes) can spread across the silicon wafer. If this limit is exceeded the device suffers local overheating leading to failure. The IGBT does not suffer from this limitation and therefore can operate with much higher dI/dt levels. The switching losses of the IGBT are lower and the device can be operated economically at a much higher frequency (around 2kHz compared with 300Hz for the GTO). Because of the higher frequency of operation and the need to avoid parasitic oscillations and voltage "overswing" during switching, the physical layout of an IGBT inverter is very critical. Input reservoir capacitors have to be very close to the power devices and the inductance of the connections has to be very low. ALSTOM achieves this by using a laminated busbar arrangement (similar in concept to a multi-layer printed circuit board) with the capacitors mounted very close to the power devices. IGBTs are provided with anti-parallel diodes, connected as shown on the above diagram, which limit damaging reverse voltages.

A great benefit of the IGBT to the equipment designer is that it incorporates electrical insulation within the device packaging. The thyristor or GTO requires insulation within the cooling system either by using air, oil or some other insulating liquid as the cooling medium. This imposes limits of creepage and clearance distances that make it difficult to build very compact equipment. The IGBT, on the other hand, does not require external insulation and can thus be cooled by water (with appropriate corrosion inhibitors and antifreeze), making for a very compact mechanical design.

Using 3.3kV 1.2kA IGBTs it is possible to produce a drive systems with a dc link voltage of 2.1kV which allows a complete water-cooled 1MW inverter to be packaged into a space 600 x 600 x 100mm. The diagram below shows a simplified power circuit of a new generation of locomotives being designed by ALSTOM. Each motor has a separate force-commutated input converter, braking chopper and three-phase inverter housed in three such modules.



A similar design of power equipment has been produced for the refurbishment and conversion to ac drives of the Amtrak AEM7 locomotives. This uses 3.3kV IGBTs in the force-commutated input converters, four of which, in parallel, feed a common dc bus. Independent inverters are provided for each bogie group and two auxiliary inverters provide a 440V 60Hz supply for the locomotive loads and the train air-conditioning supply. The transformers are tapped to cater for the different input voltages of 25kV 60Hz, 12.5kV 60Hz and 11kV 25Hz found on the Amtrak network.

Conclusions

The paper has described some of the changes that have taken place over the past 20 years in the design of electrical drive systems for high speed trains. The development of the GTO and IGBT has dramatically changed the types of circuit that are used. Circuits such as force commutated converters and inverters have been known for several years but have been uneconomic and, because of the high component count, unreliable before the advent of these new power semiconductors.

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