Power Electronics Technologies for Railway Vehicles

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Abstract—**This paper describes the current range of advanced IGBT propulsion inverters used in railways from Light Rail Vehicles to High Speed Trains & Locomotives. The second part of the paper describes future trends in IGBT railway propulsion drives. One such trend is the concept of power integration which leads to weight, volume and cost reduction . Finally for systems with an AC input supply, a concept for reducing the weight of the main input transformer is also described. This uses a configuration of resonant converter and a medium frequency transformer , the so called e-Transformer, and could be particularly targeted for 15kV, 16.7Hz supplied systems.**

Index Terms—**Railway, Propulsion, Inverter, IGBT.**

I. Introduction

By 2015 the number of cities with one million inhabitants is set to increase from 300 to 560, ie an increase of 87%. 350 million people will live in mega cities of over 10 million inhabitants. Against this background of increasing urbanization, the importance of railway systems as the chosen means of transport within and between cities is set to increase.

A key driver for railway rolling stock is the associated power electronics propulsion technology. This paper will describe the modern range of IGBT propulsion drives in use today on the different types of rolling stock as well as future trends for smaller, lighter and cheaper propulsion drives.

II. Line Up Of IGBT Propulsion Drives

ALSTOM has been a major supplier of IGBT propulsion inverters using its ONIX® range of products. First orders for such equipment were received in 1993. Today such propulsion drives are used as standard for all types of rolling stock from Light Rail Vehicle (LRV) through to High Speed Train (HST) and also Locomotives. The propulsion technology is largely based on the 2 level IGBT inverter with ratings from 150kVA for LRV to 1.8MVA for Locomotives, the latter using 6.5kV IGBTs.

The heart of the propulsion inverter consists of the power module which houses the IGBTs. For railway application these power modules are usually natural cooled, forced air cooled or water cooled. Given below are the market requirements that impact on the design of the power module and propulsion inverter.

A. Typical Market Requirements

1) Increase of useful load (ie passenger load) without increase of axle load. This requirement leads to the need to reduce the weight of the propulsion inverter and in particular the power module.

2) Low floor to improve accessibility. Generally the propulsion inverter must be as flexible as possible to be installed in various locations in the car. This requirement leads to reduce the volume of the propulsion inverter and increase the flexibility of the arrangement, for instance reduced height so that it can be placed under the low floor.

3) The reliability of the propulsion inverter must always increase. Today a 150khrs MTBF for the power module is a must.

4) Operating lifetime is a key aspect, with the requirement today being 15 to 30 years depending on the project. Often there is an emphasis on life cycle cost, where the objective is to minimize the maintenance operation during the whole life cycle of the train.

5) Preventive maintenance is also to be minimized. Water cooled traction inverters require more preventive maintenance than static cooling systems (ie cooling systems with no rotating devices)

6) The constraint of EMC and new motor technology require improvement of the motor current form factor. This leads to optimize the switching frequency of the IGBTs in the power module

7) Cost reduction of the power module whilst ensuring that all the above requirements are met is a key market requirement.

B. Range of Power Modules

Fig. 1 shows the range of IGBT power modules currently used in ALSTOM. For propulsion inverters used in LRV and some metro applications natural air cooling is the preferred method of cooling. For the high power end water cooling is the standard. The latest water cooled power module houses eight 6.5kV IGBTs and has a rating of around 1.8MVA. This is used in the propulsion inverter for recent high speed trains and

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locomotives with a DC link voltage of 3kV nominal and 4.4kV maximum. This power module can be configured as one inverter (ie 3 legs and the rheostatic brake chopper) or a PWM converter (either 2 PWM converters in parallel or a PWM converter with parallel IGBTs)

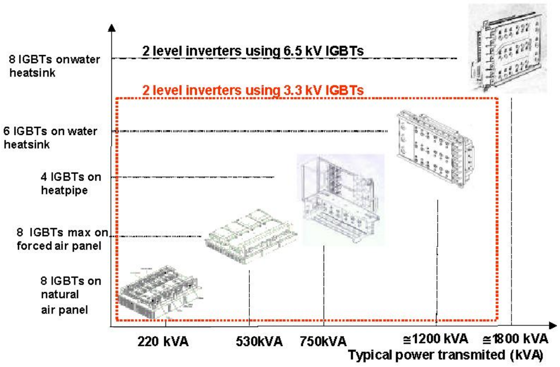

Fig. 1. Line up of 2 level IGBT propulsion inverters.

Recent improved designs of IGBT propulsion inverter have resulted in the maximum power with natural air cooling to be increased. Fig. 2 shows the comparison of this new design. The new design uses an improved thermal design as well as a modular design approach with the target of reducing manufacturing cost. This new design is rated at 800kW compared with 400kW for the previous IGBT inverter it replaced. Additional to this doubling of power, the weight was reduced by 20% and volume by 30%.

Fig. 2. New 800kW IGBT propulsion inverter (left) compared with previous 400kW version.

C. Propulsion System for High Speed Trains

Since its creation, 25 years ago, the TGV (Train à Grande Vitesse, or High Speed Train) continues to stay ahead of its time, as can be seen with the TGV-Est, the most recent addition to the family. It benefits from technological knowledge acquired from preceding versions and can run at 320 km/h, thus placing the journey from Strasbourg to Paris at just 2 hours 20 minutes under optimum comfort and safety conditions.

At the heart of the future high speed train development is a new range of IGBT based asynchronous traction drive in a power car able to run on 4 voltages and at 320km/h, a significant advance on earlier generations of TGV.

The new range of traction drive will comply with the latest technical specifications for interoperability issued by the European authorities. Other advantages will include reduced power consumption, both regenerative and rheostatic braking as well as better power to weight and power to volume ratios. For example, the new traction motors on TGV-Est will provide 1200kW for a much smaller motor weighing just 1350kg. This is a significant change compared with the large 535kW, 1515kg motors used on the original Paris-Sud Est TGVs

Additionally, ALSTOM is already planning for the future. Further improvements in very high speed trains are envisaged, enhancing speed, improving the quality of life on board, passenger comfort and protection, all without forgetting environmental preservation.

Tomorrow's concepts are already in the production phase. They articulate around two technological platforms, based on proven design principles and on new reasonable choices in terms of motorisation and optimisation of train architecture. The first, with a double deck, meets the requirements of the market for more capacity. It is designed to upgrade the existing TGV Duplex, while preserving the concentrated motorisation, towards a "Jumbo" capacity. This train will be capable of providing, over a length of 400 m, a capacity of 1200 seats, more than two TGV Duplex trains assembled together.

The second new concept, called AGV ("ALSTOM Grande Vitesse" or "ALSTOM High Speed"), with a single-deck, is developed along a new architecture and technology, designed to complete the range on offer to our customers. This fourth generation of very high speed trains, designed for inter-region rail links between cities, will carry up to 600 seated passengers at a speed that could reach 350 km/h. This performance will be achieved thanks to the advances in the fields of power electronics and electrical engineering, the use of composite materials to make light-weight trains and to aerodynamic testing. Thanks to this new technology a journey from Paris to Toulouse in France covered in 5 hours today will take only 2 hours 30 minutes. The concept design of the AGV lead car is shown in Fig. 3.

Fig. 3. Concept design of AGV lead car.

The compact 6.5kV IGBT based traction drive for the AGV enables a floor height above rail top of just 980mm, compared with 1200mm on other high speed trains. Additionally, the use of Permanent Magnet Motors (PMM) leads to lower energy consumption and reduced mass, with the motor weighing around 750kg. This leads to reduced bogie weight resulting in greater economy of operation.

D. Catenary free solutions for LRVs

Environment friendly design is not just about noise, pollution and sustainable development. It also requires full visual harmony with the city backdrop.

A traditional LRV running in a city center section requires an overhead catenary. Such a system can result in unattractive visual pollution as shown in Fig. 4. Some cities with historic architecture require a different solution of catenary free LRV in selected sensitive sections. Depending on the length of the required catenary free section, different technologies can be used as will be explained later in this section. All such solutions have an impact on the design of the power electronics technology for such vehicles. The great visual improvement in a catenary free solution is clearly seen in Fig. 5.

Fig. 4 Some examples of catenary based LRV city center sections.

Bordeaux Nice

Fig. 5 Some examples of catenary free LRV city Center sections.

Depending on the length of the catenary free section, different technologies are offered on ALSTOM Citadis LRVs as explained below:

1) Battery for short sections, in catenary free sections of limited length, such as crossing a historic square in a city center. The project in Nice, south-east France calls for catenary free operation in two historic squares; the Place Masséna and Place Garibaldi covering a distance of 440m and 470m respectively. To meet this need the city chose 20 Citadis LRVs which will be delivered in 2007. They will carry NiMH batteries, which offer a good compromise between performance, weight, volume and life cycle cost. This allows the LRVs to cross the two catenary free squares at lower speed.

2) APS for longer sections, the first application of which was in Bordeaux, south-west France. APS ("Alimentation Par le Sol" or "Ground Level Power"), which is exclusive to ALSTOM, is a system to power LRVs without overhead catenary, thus allowing the LRV to operate "wire free" over any distance and hence blend into the urban environment.

Power is supplied to the LRV through a third rail embedded in the track. It is made up of 8m long conducting section which can be powered and which are separated by 3m long insulating sections. Power is supplied to the conducting sections by underground boxes located every 22m.

Switching between the APS section and the catenary section is controlled from the driver's cab. When the LRV is stopped, the pantograph is lowered and the pick-up shoes are lowered for the transition from one system to the other.

The inner bogie of each LRV has two current pick-up shoes and antennas. The distance between the two pick-up shoes is longer than the length of the insulating section, thus ensuring continuity of power feeding as the LRV moves from one section to the next. The powering of a section is controlled by coded radio dialogue between the LRV and the APS system and only occurs when the conducting section has been covered by the LRV, thus ensuring total safety for pedestrians.

Outside of the LRV body or "footprint" all accessible sections are grounded as shown in Fig. 6. Consequently, they do not present any electrical danger to the public. Only sections that are entirely covered by the LRV footprint can be energized to power the LRV. The system is completely buried within the right-of-way surface and only the distribution strip appears at the surface level. There are no obstacles or equipment protruding, allowing for seamless integration to the urban right-of-way. There is no dangerous area to be protected, allowing all of the LRV right-of-way to be shared with any other user of the urban space.

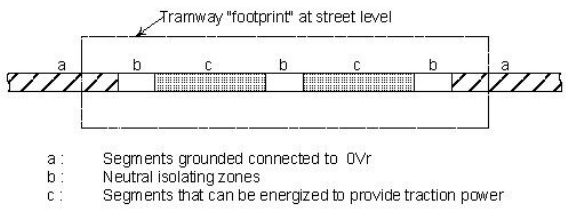

Fig. 6 Power distribution in APS scheme.

With this APS scheme only one or two conducting sections are powered at any one time. Conducting sections are energized by switchgear in the underground boxes, which today is the more economic and reliable solution compared with IGBT based power electronic switches. With further evolutions in IGBT technology, it could be possible to use such devices in this type of application.

The world's first application of APS technology is in Bordeaux, where 14km out of the 44km LRV network uses APS with operation since end 2003. Other cities which have chosen the APS system are Angers (17 LRVs, APS with 7.4% gradient in city center section of 12km new line) and Reims (APS in 2km of the 10km new line) in July 2006 and Orléans (Line 2 with 27LRVs) being the fourth city to choose APS in September 2006. The APS system is validated for full performance (acceleration and gradients) and is homologated for 60km/h operation.

In total more than 860 ALSTOM Citadis LRVs have been ordered by 24 urban communities, including 15 in France. They have transported more than 1 billion passengers and have traveled more than 76 million km.

3) Flywheel solution. The advantages of flywheels are better cycle life, power density, rapid charge rate and storage efficiency. The energy stored in the flywheel is proportional to Mv^2. Modern flywheels made of composites are enclosed in a safe vacuum container and have integrated power electronic controllers. They rotate at speeds above 20,000rpm providing a net energy storage of 4kWh and 325kW peak.

The flywheel stores energy generated during electrical braking and offers the following two advantages:

a) On catenary free sections, the LRV can run at reasonable speed with good acceleration. Due to its rapid charge rate, the flywheel can be 'replenished' while the LRV is standing at stops.

b) On sections with a catenary, the flywheel provides load leveling to reduce investment in ground infrastructure.

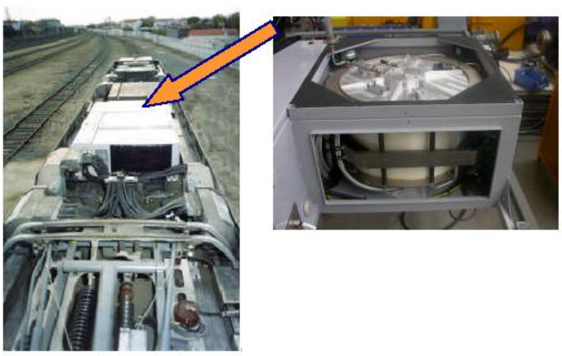

Fig. 7 Flywheel on Rotterdam Citadis roof.

Recent new technologies have led to significant reductions in flywheel size, allowing roof mounting as shown in Fig. 7. ALSTOM is carrying out demonstration tests using one of the 60 Citadis LRVs delivered to RET, the Rotterdam Operator in The Netherlands.

III. Future Trends In IGBT Propulsion Drives

A major requirement for future IGBT propulsion drives is the need to reduce cost, volume and weight whilst ensuring a maximum level of reliability and availability. Two particular examples of such future trend are described.

A. *Power Integration*

The current generation of propulsion drive power modules is based on the use of high voltage pack IGBTs available on the market. These IGBTS are used as single or parallel switches and cover a range of voltage (1700V, 3300V, 6500V) and nominal current (1600A-2400A, 1200A, 600A). The structure of the power module is a mechanical assembly of the following functional parts:

- Pack IGBTs
- Cooling device (convection heatsink, heatpipe, water plate)
- High power connection or bus bar
- Gate drivers
- Low voltage connection
- Capacitors (decoupling or filter)
- Mechanical parts for support and connectors
- Control board and current sensors can also be integrated in the power module

This current technology has the following limitations:

1) Thermo-mechanical limitation of the power module, due to the pack IGBT having many interfaces with non homogeneous materials as shown in Fig. 8.

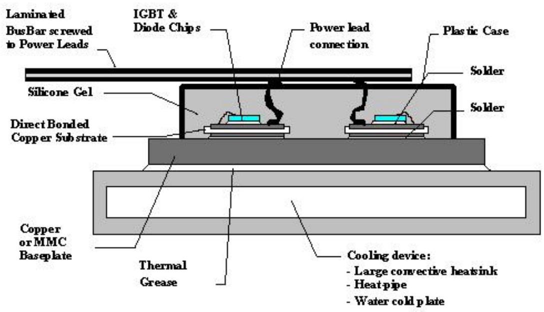

Fig. 8 Cross-section of standard power module.

The thermal grease between the pack IGBT and the heat-sink limits the thermal dissipation and induces temperature in-homogeneity.

Aluminum wire bonding limits the current capability and can fuse with high current.

2) Thermal limitation of the power module due to the structure of the pack IGBT. Today, power modules work with average heat dissipation of 30 to 80 W/cm2 on

silicon and the current density limitation mainly comes from this thermal aspect.

Power connections in the power module out of the pack IGBT allow ten time less current density than inside the pack IGBT. This is due to the fact that external connections are not actively cooled.

These two points induce over-cost of the power module for two reasons : more silicon needed and more metal needed for power connection.

3) Electrical limitation of the power module:
In many cases, paralleling of several pack IGBTs is needed to achieve the required power rating. Paralleling adds a limitation of the performance of the module:
- Current de-rating must be applied because of the discrepancies of thermal and electrical parameters of the IGBTs.
- Adding power connection gives additional parasitic inductances and increases the need for decoupling capacitors.

IGBT chip technology has dynamic losses that limits the switching frequency. For instance, 1500-2000 V_{DC} propulsion inverters with pack IGBTs are limited to a switching frequency of around 1kHz. New motor technology like permanent magnet motor requires better form factor and thus an increase in switching frequency.

The size of the power module and the arrangement of power components relatively to gate drives and control electronics can lead to long low voltage cabling. The management of this low voltage cabling is critical to avoid perturbation.

The principle of power integration is to include the maximum number of functions of the power module inside a macro-component. The final goal could be to have the full inverter with close control in a macro-component.

To illustrate this approach, a first generation of Power Integration propulsion inverter and related technologies has been developed based on the following concepts:

1) Improvement of IGBT and diode cooling by limiting the number of interfaces from silicon component to cooling fluid:
- This is done by integrating the cooling inside the component
- Heat generation rate of 200W/cm2 at chip level is possible with a temperature increase of 45K using water with 50% of ethylene glycol

2) Reduction of power connection and low voltage connection by implementing one leg or several legs in the component
- This design is possible by stacking chips and substrates
- Wire bonding is replaced by soldered connection (metal bumps)
- This architecture dramatically reduces the parasitic inductances

3) The parts (switches, cooling, power connection, low voltage connection) are packaged in a polymer component. Water tightness is ensured by silicone gasket.
- The suppression of many parts reduces the cost
- The replacement of metal by plastic reduces the weight.

An example of such a propulsion inverter leg using power integration is shown in Fig. 9.

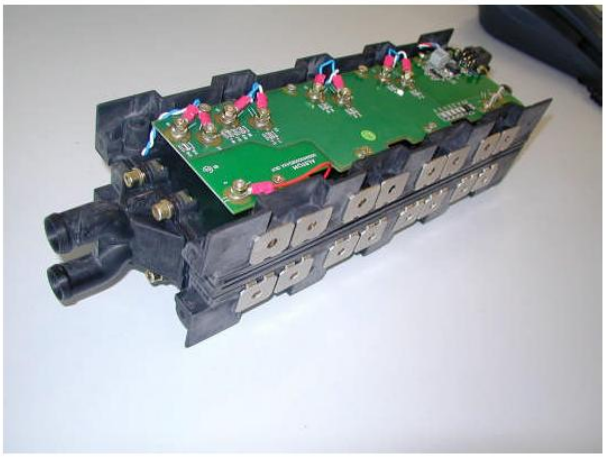

Fig. 9 Integrated leg (1500-2000V_{nom}, 3300V_{max}, 1200A_{nom}, 2400A_{max}) Size 396 x 107 x 88 mm

B. e-Transformer for 15kV 16.7Hz systems

In 15kV 16.7Hz supplied railway systems the integration of the propulsion drive can cause problems, particularly in low floor EMU designs, due to the high mass and volume of the drive system, largely due to the size of the input transformer. Several experimental systems have been developed based on the idea of replacing the conventional 16.7Hz transformer, one such system is described in this section.

The line side of the system consists of eight cascade modules with a 3.6kV intermediate DC circuit. The cascade modules consist of 6.5kV IGBTs and convert the 16.7Hz input frequency to a significantly higher transformer frequency of 5kHz. The chosen frequency of 5kHz results from a compromise between volume and weight of the transformer and switching losses in the IGBTs.

The basic configuration of this e-Transformer scheme is shown in Fig. 10. Each cascade module is connected to one primary winding of the new 5kHz transformer. The secondary winding of this transformer is connected to an output converter which uses 3.3kV IGBTs. This output converter produces a 1.65kV DC link which feeds the IGBT propulsion inverter. Redundancy is built into the input cascade modules so that full power operation can still be achieved with one out of the eight cascade modules removed from the circuit due to failure.

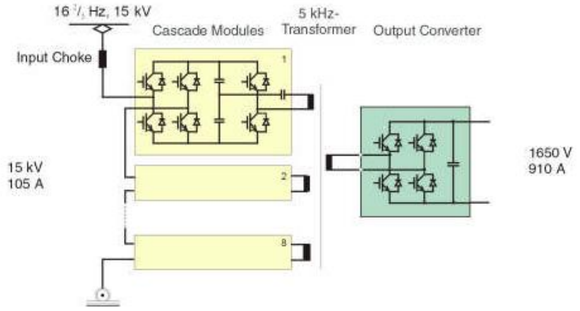

Fig. 10 e-Transformer topology.

In order to fully validate the performance of this new e-Transformer configuration, a 1.5MW prototype was designed, constructed and tested. Fig. 11 shows the prototype equipment.

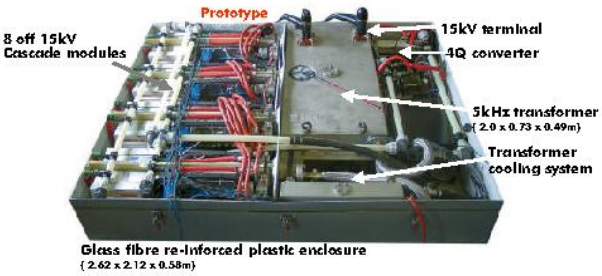

Fig. 11 Prototype 1.5MW e-Transformer.

The mass of the e-Transformer prototype was 3.1T compared with 6.8T for a conventional system using a 16.7Hz transformer. Although the mass reduction was more than 50% there still remains two major issues with this configuration:

1) Cost increase of around 50% compared with the conventional system. Although the cost differential can be reduced with improvements in design and mass production, the e-Transformer scheme will still remain more expensive on first cost basis.

2) Reliability is the major concern and challenge with the e-Transformer mainly due to the input cascade modules which have 48 IGBTs in total. With future advancements in high voltage IGBTs it could be possible that this issue is improved.

IV. Conclusions

ALSTOM offers a range of advanced IGBT propulsion drives for all types of railway vehicles as described in the paper. Short and medium term solutions for future power electronic technologies for railway vehicles are also under development so that future railway vehicles can be powered with advanced technology at optimum reliability and price.

References

[1] J. Taufiq, "Advanved energy efficient converters for locomotive and auxiliary power unit", IPEC Int. Power Electronics Conference, Tokyo, 2-7 April 2000.

[2] F. Lacôte, "Traction advances offer lower costs and higher capacity", Railway Gazette Int., April 2003, pp. 206-208.

[3] F. Lacôte, "Alstom-Future trends in railway transportation", Japan Railway & Transport Review No 42, Dec 2005, pp. 4-9.

[4] T. Ficat, P-J Vienney, "Wireless Tramway in Bordeaux", LRT Workshop, Kyoto, 2006.

[5] P. Lego, "Power converters for traction application", EPE 2003, Toulouse.

[6] M. Mermet-Guyennet, "New structure of power integrated module", CIPS 2006.

[7] B. Engel, M. Victor, G. Bachmann and A. Falk, "15kV/16.7Hz energy supply system with medium frequency transformer and 6.5kV IGBTs in resonant operation", EPE 2003, Toulouse.