

# Analysis and optimisation through innovative driving strategy of high power IGBT performances/EMI reduction trade-off for converter systems in railway applications

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## Abstract

In railway applications possible interaction between power train and signalling system requires efforts to Electro Magnetic Compatibility (EMC) problems. With the progress of power device technology in recent years, it has become feasible to improve performances of power electronics systems; however EMI noise, caused by fast switching commutations in power converters, has to be managed. EMC control has, therefore, become a worldwide topic, and requests for EMI noise reduction have become very strong.

In the paper, after a deep analysis of EMC features in railway applications, two innovative driving strategies have been introduced and characterized, in order to find a good trade-off between high power IGBT performances and EMI reduction constraints. Characterization and discussion are based on experimental basis.

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## 1. Introduction

Electric and electronic systems have to be *electromagnetic compatible (EMC)* in all application fields. Project criteria then have to consider at the same time the functional character of projected/realized products and legal requirements of EMC, fixed by the EC directive EN 50121-3-1, 2 and, in Italy, by the legislative decree n. 476 dated 4/12/1992.

In particular, in railway applications, guaranteeing system electromagnetic compatibility is a very critical task, even more difficult, for some aspects, than in other industrial sectors. In fact, in a railroad, many highly integrated equipment categories but with different characteristics have to coexist, and a lot of different noise sources, both external and internal to railway, are present.

The recent progress of power device technology, particularly by the appearance of IGBT, has made possible to improve performances of power electronic sys-

tems, in terms of weight, volume, and power losses [1, 2]. However, contrary to the progress of IGBTs, EMI noise, caused by high dv/dt and high di/dt switching gradients, has got worse [3, 4]. As a matter of fact by increasing switching speed, power dissipation of a power device is reduced, but level of EMI is increased, so that a reasonable compromise between device features, power losses and EMI must be found in the design of any power converter. In this paper we have focused our attention, in particular, on radiated EMI noise generated by converter systems.

The compromise between the improvement of switching performances and the reduction of EMI noise can be achieved by optimizing the parameters of the driving circuit as it is shown in [5]. The results reported there refer to medium voltage IGBTs and were obtained by means of the standard experimental procedure not simply applicable to high voltage and currents IGBTs used in railway applications.

The objective of this paper is to present the ex-

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perimental characterization of two innovative driving strategies with regard to both their switching performances and EMI emission. The two strategies have been applied to last generation of high voltage/current IGBT modules. The two techniques are discussed, in order to understand the best trade-off between switching losses and EMI noise. The analysis has been experimentally performed by an original experimental procedure to measure the EMI noise radiated by high voltage/high current dc-ac converter.

## 2. Electro-Magnetic Compatibility (EMC) in railway applications

A railway system is both a noise source and a noise susceptible element toward/by external environment and itself. So that its Electro-Magnetic-Compatibility must be guaranteed both in reducing its radiated noise and in limiting the effects of unwanted disturbances coming from electro-magnetic noisy external devices.

In order to guarantee system electromagnetic compatibility different international standards are available for fixing the maximum acceptable noise generated by the apparatus in each frequency band.

The railway systems in the European Community are regulated by the directive EN 50121-3-1, 2 that imposes EMI measurements to be performed on the entire train system. These measurements are intended to the train homologation so that they represent the final step of the train development. Obviously, the designer to achieve the train homologation has to consider that a train is a very complex system where many equipments and devices coexist into a relatively small space. Most of these equipment have to be considered both as noise sources and noise susceptible elements. So that the designer has to separately study the single apparatuses and has to guarantee that each of them does not generate excessive electromagnetic noise [6].

In modern trains power electronics converters are widely used and among the disparate parts of a train system they result to be the most electro-magnetic noisy. In fact because of the converters downsizing and the enhancement of switching performances, particularly after the introduction of IGBTs, EMI noise has got worse. Moreover, the heterogeneity of a power electronic converter, where switches, chopper, inverter, motors operating at high currents, have to coexist with control devices that use microprocessors, enhances the problems of EMC. Therefore their control has become

a very important topic [7÷9] and requests for EMI noise reduction have become very strong.

Switching converters generate both conducted and radiated noise toward the external environment. In particular they introduce harmonics with multiple intensities and frequencies in the absorbed line current. Such harmonics often extend to audible frequencies and have such an intensity that can cause noise and interferences both to telephonic and signalling lines parallel to the contact line [6].

On the other side the very fast devices commutation often generate high frequency oscillations into the converter components that can become quite efficient antennas and radiate electromagnetic noise. These emissions can compromise both the correct operation of converter internal parts, like for example its control circuits, and/or external equipments, like the signalling radio system used in some high speed lines.

In the following sections our attention will be only focused on converter systems radiated noise with the objective of experimentally characterizing the electromagnetic noise radiated by an inverter where optimized IGBT driving strategies have been used.

## 3. Innovative driving strategies

Gate drive circuit in power converters is the interface between power IGBT switches and logic level signals in the modulator. It can be optimised to achieve the best performance that can be obtained from the power semiconductor devices. So a gate driver should switch the IGBT at high speed, while limiting  $di/dt$  and  $dv/dt$  gradients and associated noise generated during the switching transient. The simultaneous requirement to minimize switching losses, the peak of reverse recovery current during turn on and the peak over-voltage during turn-off together with low EMI emission make gate driver design a challenging task.

In previous works [10, 11, 12], two innovative driving strategies were presented from the point of view of optimizing switching performances while respecting devices Safe Operating Areas. In the following sections for each of them a suitable experimental analysis of radiated noise is reported for turn-on converters operations.

### 3.1 Experimental set-up

The proposed innovative driver circuits have been assembled in an inverter leg breadboard mounted

commutated on pure inductive load, using 3.3kV, 1.2 kA IGBT. The system has been set in a semi-anechoic chamber and its radiated noise during turn-on transient has been received through a wideband antenna. In order not to disturb measurement operations, links between subsystems and instruments have been realized with optical fibres. A single shot test procedure has been pointed out in order to avoid the large power dissipation involved in high power converters. Signals from antenna have been acquired through a wideband oscilloscope, and then they have been elaborated in order to calculate their amplitude spectrum. Measurements have been performed in the range 1÷250 MHz.

In order to acquire only the turn-on generated noise, the wideband oscilloscope connected to the receiver antenna, has been synchronized with the same on pulse sent to the IGBT driver through optical fibres taking into account the propagation delay. The direction of maximum radiated noise has been found by a 360° inverter rotation. Moreover, we have individuated that the maximum electric field is radiated in vertical polarization. A photograph of the converter system in the anechoic chamber is shown in the Fig. 1.

### 3.2. First proposed strategy: reduction of switching losses and EMI noise

Switching transients generate electromagnetic interference with amplitudes directly related to the time variation of collector current and voltage gradient [5]. As known,  $di/dt$  gradient can be controlled by the gate resistance value, that, however, has to match two divergent goals: low power losses require a low gate resistance, while low EMI generation requires a high value of  $R_g$ .

The first proposed strategy allows us to reduce turn-on transient times, switching energy dissipation [10], without increasing significantly EMI noise because it separately controls collector voltage and current gradients. In fact this approach consists in reducing switching times right after collector current peak is reached; in such a way, it is possible to accelerate the final part of the voltage collector variation, and thus the switching speed, without increasing collector current slope. The strategy requires two different driving resistance values during turn-on: the commutation starts with a gate resistance, whose value is set to the value suggested by the data sheet, and then continues, as collector current peak is reached, with a resistance, whose value is reduced to an optimum one [10]. An energy reduction up to 14% was obtained, in comparison with

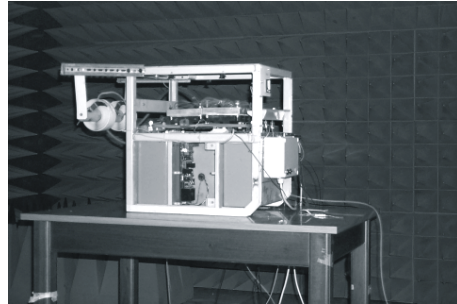


Fig. 1. Inverter phase leg in anechoic chamber.

the conventional R-C driver. In Fig. 2 turn-on dissipated energy and losses reduction are reported.

In a typical switching converter the generated noise can be attributed to the resonant interaction between the circuit stray inductance and the diode output capacity [7]. If we apply this result to our experimental set-up we can conclude that our driving technique does not increase significantly radiated emission, because it changes diode  $dv/dt$  gradient only in the final part of the commutation. In Fig 3 the spectrum of the turn-on radiated signal is presented in the two cases, for a supply voltage of 1500 V and a load current of 1200 A: it is clear that a small EMI increase (see Fig. 3.a) is observed for the proposed low-loss strategy with reference to the conventional one (see Fig. 3.b).

The main spectral components are observed at the frequencies: 3.6, 19, 35, 75 MHz. In Fig. 4 the amplitude of the emitted component at 3.6 MHz is reported as a function of the load current for optimized and conventional driver: the proposed strategy does not increase harmonic content. Analogous results are still valid for other frequencies.

### 3.3. Second proposed strategy: trade-off between high losses reduction and EMI noise

Another driving strategy [11] has been also studied, and its performances have been analysed. It is based on the idea that commutations can be made faster by reducing gate resistance. In particular load current range has been divided into four sets and for each one it has been found the gate resistance value that allows us to accelerate turn-on transient without damaging the device (i.e. DIODE SOA constraints are respected as it is shown in Fig. 5 where diode switching locus is reported on its SOA).

In such a way this technique allows us to reduce turn-on energy up to 37 % [11], as shown in Fig. 6.

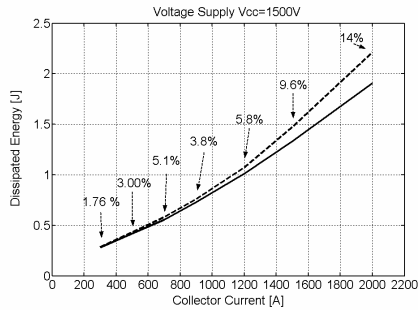


Fig. 2. Turn-on dissipated energy and losses reduction for the first optimized driving strategy

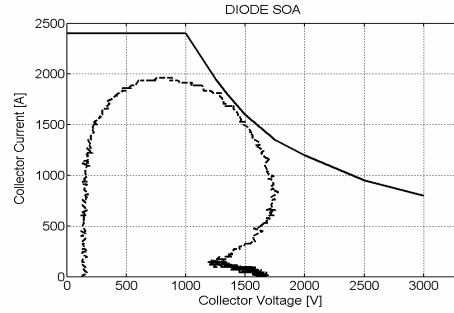
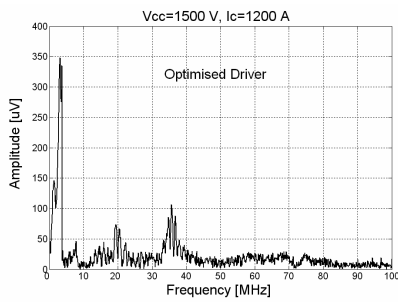
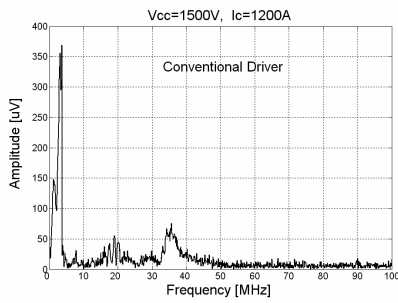


Fig. 5. Switching locus reported on Diode SOA



a)



b)

Fig. 3. Radiated signal spectrum for the first proposed driver (a) and the conventional one (b)

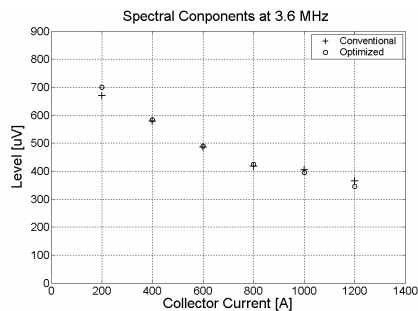


Fig. 4. Spectral component amplitude as function of collector current @  $f=3.6$  MHz,  $V_s=1500$  V

Obviously such gate resistance reduction causes the increase of EMI radiated noise. Fig. 7 shows, as an

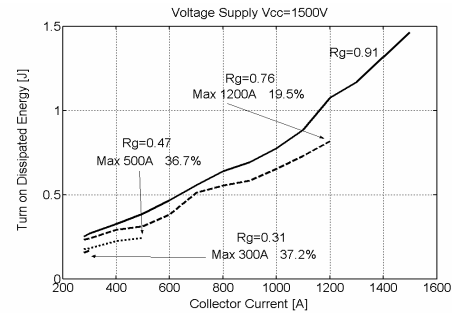


Fig. 6. Turn on dissipated energy reduction for different driving resistance

example, the noise spectrum for three different gate resistance values at  $I_c=250$  A and  $V_{cc}=1500$  V: harmonic amplitude rises as gate resistance decreases from  $0.91 \Omega$  down to  $0.31 \Omega$ .

In Fig. 8, instead, noise level at  $3.6$  MHz versus collector current is reported for several gate resistance values; it can be observed that levels are highly dependant on gate resistance and that they show a higher value above all for low load currents.

### 3.4. Comparison between the two strategies

A comparison between the two innovative strategies can be done.

Both of them have got the following advantages [10, 11, 12]:

- they reduce turn-on energy,
- they do not affect delay time,
- they respect diode SOA,
- they respect the limited driving current.

The second method allows obtaining a larger energy reduction (up to 37%) if compared with the first one. However this advantage has to be paid, first of all, in terms of EMI noise, in fact the second technique only increases radiated emission. Moreover it has to be

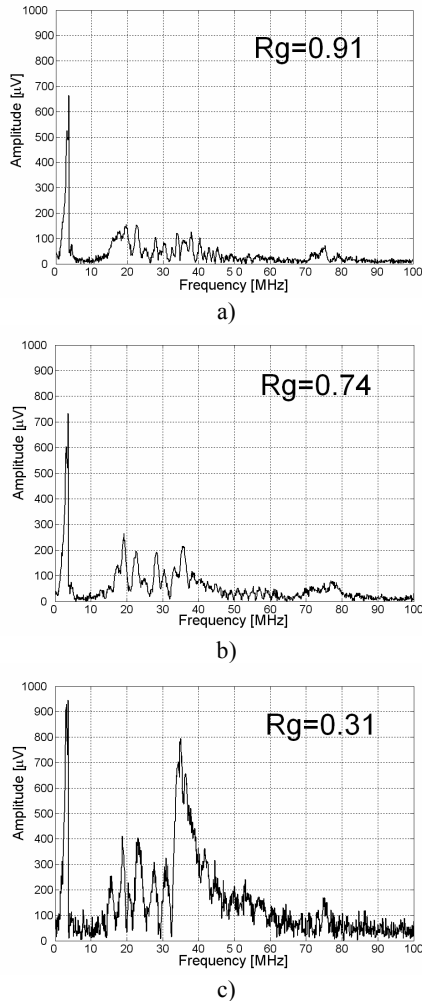


Fig. 7. Radiated signal spectrum at  $I_c=250A$  for gate resistance values equal to  $0.91 \Omega$ , a)  $0.74 \Omega$ , b) and  $0.31 \Omega$ , c)

paid in terms of driver complexity: the first driving strategy only requires an accurate resistance variation, while the second one requires that gate resistance has to be changed at least four times, as a function of collector current.

At the end, it can be said that the second proposed method could be utilized when

- turn-on losses are predominant compared with total inverter ones, due to implementation complexity;
- when an EMI noise increase can be accepted, due to higher radiated emission, and then, probably, not in railroad applications.

In other cases it could be more convenient to use the first driving strategy. Regarding the second driving

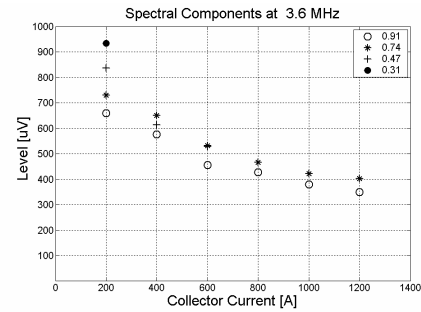


Fig. 8. Spectral component amplitude as a function of collector current, for several gate resistance values, @  $f=3.6 \text{ MHz}$

strategy, the radiated noise could be reduced through a specific bus-bar layout optimisation.

### 3.5. Rating of the two proposed strategies referred to European Standard requirements

All the results obtained in the previous sections have been compared with the in force European Standard for apparatus used in railway applications (CEI EN 50121-3-1,2).

According to this standard traction converters over 50 kVA have not to be tested individually but when the vehicle is tested as a whole; moreover emission have to be measured in the range between 30 MHz and 1 GHz, and its maximum allowed limit is of 190 dB $\mu$ V/m, measured at 10 m distance.

In order to verify the radiated limits, traction converter emission noise has been measured in the semi-anechoic chamber. Electric field has been calculated during turn-on commutation, taking into account the antenna factor and the cable attenuation, in the same experimental conditions used in the previous paragraphs. In Fig. 9 and 10 electric field has been reported for conventional driver and the two proposed ones: it can be noticed that, in all cases, the field value is lower that the maximum acceptable one. However it is important to underline that the standard limit is related to the entire vehicle [EN 50121-3-1], while we have only tested an inverter leg.

## 4. Conclusions

Electromagnetic compatibility in railway system has been analysed. Particular attention has been given to radiational EMI problems generated by IGBT converter systems. Two innovative driving strategies have been considered and experimentally tested in order to

find the best trade-off between EMI noise and high power IGBT performances. The first proposed technique allows reducing transient times, switching energy dissipation (up to 14%), without significantly increasing EMI noise, by controlling separately voltage and current gradients. The second one, instead, allows reducing highly power dissipation (up to 37%) but causes an increase of EMI noise.

Considerations about the two strategies allows us to sustain that the choice between them depends on the weight of turn-on losses on the total inverter ones, and by the maximum admitted EMI level. Probably the best choice for railway applications is represented by the first proposed strategy.

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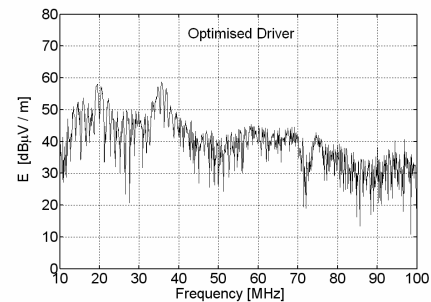
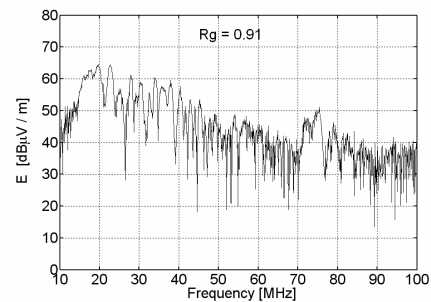
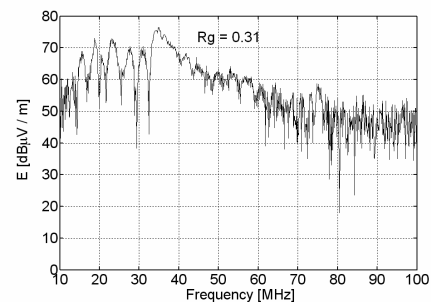


Fig. 9. Electric field for the first optimised drive



a)



b)

Fig. 10. Electric field for  $R_g=0.91 \Omega$ , a) and  $R_g=0.31 \Omega$ , b)

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