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Series connection of IGBT

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Abstract—This article analyzes the effects of parasitic capacitances in the series connection of IGBT, which exist naturally due to gate driver and power circuit geometry. Two solutions, that can be combined, are proposed to minimize these effects in order to achieve a better voltage balancing. The first one is based on gate driver self-powering technique. The second one is based on a vertical structure assembly of IGBT connected in series. The performance offered by these two complementary solutions is investigated and validated on a series connection of three IGBT in a chopper converter. Both simulation and experimental results show the effectiveness of our approaches.

I. INTRODUCTION

The demand of high voltage switches is steadily growing, especially for applications in electric distribution system (FACTS), and railway traction (high speed train). However, the silicon IGBTs are limited to 6,5kV, with poor switching performances. The series connection of power switches allows to improve the switching performances (using switches with voltage ratings in the range of 4.5kV or lower) and to operate at higher voltage. Nevertheless, the series association of power IGBTs is very difficult; the main problem is to ensure an equal voltage sharing among the components during static and dynamic transient states.

Various voltage balancing methods have been suggested for IGBT connected in series. Several are based on active voltage control employed to limit the voltage during turning off time and to control the dynamic voltage sharing during switching transitions. In [1, 2, 3, 4, 5], numerous control strategies are proposed, including active voltage control and delay balancing. The active clamping circuit [6] is another technique which insures both protection and voltage balancing. In fact, series association of IGBT presents a structural voltage unbalance. All the previous solutions tried to equilibrate voltages among switches by performing complex controls on gate circuits. They lead to unequal gate driver signals to adjust voltage balance.

In this paper, we study the causes of this structural unbalance. In the next section, we explain the influence of parasitic capacitances on the voltage imbalance. Secondly, we show how to design both power and gate drive circuits to

guarantee a natural equal voltage sharing among all the IGBT connected in series. We proposed two solutions. The first one is based on the gate driver self-powering principle; it permits reducing the value of parasitic capacitances in each IGBT driver circuit. The second solution proposed allows reducing gradually the values and the effects of parasitic capacitances between each IGBT and the ground in power circuit, by placing series connected IGBT in a 3D vertical structure. Finally, we demonstrate the benefits of both solutions proposed in an experimental chopper with three IGBT connected in series. Experimental results and simulation results are compared and analyzed.

II. ANALYSIS OF VOLTAGE UNBALANCE CAUSES: EFFECT OF PARASITIC CAPACITANCES

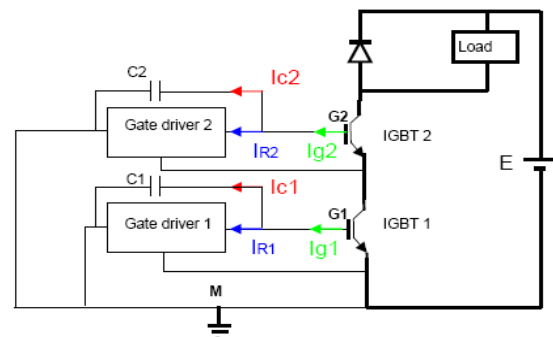


Figure 1. Parasitic capacitances in control circuits

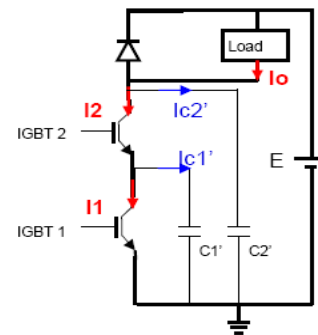


Figure 2. Parasitic capacitances in power circuit

Parasitic capacitances appear between different elements of the electric circuit and the ground. These capacitances have various origins: they can be inherent in the geometry of the circuit (e.g. capacitance between components and their heat sink connected to the ground, or capacitance between printed circuit board and ground...), or they are due to discrete components used to provide electrical isolation (optocouplers or transformers, floating power supplies...).

A. Parasitic capacitances in control circuit

Classical techniques are based on external supplies that are connected to gate drivers. This structure needs electrical isolators such as HF transformers and optical coupling, and thus it contains a parasitic capacitance. This capacitance has a certain influence on switching operation of the IGBT connected in series. In the case of a chopper with 2 IGBT connected in series, controlled by two gate drivers using external supplies (Fig. 1) C1 and C2 represent the two parasitic capacitances in both control circuits. They normally have the same values. I_{c1} , I_{c2} , I_{r1} , I_{r2} , I_{g1} and I_{g2} are successively the currents passing through these two parasitic capacitances, the gate drivers and the gates of the IGBTs. At the switching instant, we can demonstrate that:

$$\frac{dV_{G1M}}{dt} < \frac{dV_{G2M}}{dt}$$

The currents flowing through capacitances C1 and C2 are given by the following formula:

$$I_{ci} = C_i \frac{dV_{GiM}}{dt} \quad (1)$$

Thus, we deduce that: $I_{c1} < I_{c2}$

Besides, as a result of using identical components in both gate drivers, we normally have:

$$I_{r1} = I_{r2} \quad (2)$$

And:

$$I_{gi} = I_{ri} + I_{ci} \quad (3)$$

Therefore, the absolute value of the current in the gate of IGBT 2 is higher than the current in the gate of IGBT1:

$$I_{g1} < I_{g2}$$

Consequently, during switching transition, the voltage variation speed dV_{CE}/dt of IGBT 2 is higher than the one of IGBT 1. As a result, the V_{CE} voltage in steady state is higher across IGBT 2 than across IGBT1 [8].

We have shown that the parasitic capacitances between gate drivers and the ground modify the switching speed of IGBTs connected in series. If IGBTs are considered identical,

this is the main reason for the voltage unbalance in both dynamic and static state of these components.

B. Parasitic capacitances in power circuit

Since the collector of each IGBT must be isolated from the ground, there are several critical and additional parasitic capacitances in the power circuit. Fig. 2 illustrates two parasitic capacitances $C1'$, $C2'$ existing between the two IGBT and the ground in a chopper. During switching transient, the voltage V_{CE} of each IGBT changes rapidly, thus there are currents passing through these capacitances. They can be given by:

$$I_{C'i} = C'_i \sum_{i=1}^n \frac{dV_{CEi}}{dt} \quad (4)$$

Here I_0 , I_2 and I_1 are successively the currents going across the load, IGBT 2 and IGBT 1. We have:

$$I_0 = I_2 + I_{c2'} \quad (5)$$

$$I_2 = I_1 + I_{c1'} \quad (6)$$

Thus:

$$I_2 > I_1$$

Moreover, research has shown an analytical formula which calculates switching speed of MOSFET power device according to its current I_1 [8]:

$$\frac{dV_{DS}}{dt} = \frac{(I_1 + gm \cdot (V_{th} - U_t))}{(C_{GD} \cdot (1 + R_G \cdot gm) + C_{DS} + C_{DS_ext})} \quad (7)$$

According to the formula (7), the higher is the current passing through the MOSFET; the higher is the switching speed of MOSFET. Since the IGBT has a similar dynamic behaviour with the MOSFET, except for the tail current, thus by using the formula (7), we confirm that the switching speed of IGBT 2 is higher than that of IGBT 1. Therefore, the voltage across IGBT 2 is higher than that of IGBT 1 in static phase.

From the above analysis on the effects of parasitic capacitances, we can conclude that the higher is the rank of the IGBT in the series connection (IGBT 2 on Fig. 2), the higher is its switching speed, and higher is its voltage during the static phase. Therefore, in this paper we focus on solutions to minimize these effects of parasitic capacitances.

III. SOLUTIONS

A. Self-powering principle

We have explained the negative effect of parasitic capacitances connected between ground and control circuitry on the voltage balance among the power switches. These

parasitic elements are due to the external power supplies and the necessary insulation components. The self-powering technique has the advantage over the classical supply to eliminate these parasitic capacitances. This technique, presented in Fig.3, is based on five components [9]: an auxiliary high voltage MOSFET, a blocking diode, a bias diode, an avalanche diode and a storage capacitor. In fact, it takes advantage of converter's dv/dt , at every main power switch's turn OFF; it uses part of the energy flowing in the main power devices to recharge periodically the storage capacitor. The energy stored is then used to supply the gate driver while the main switch is turned ON and this until it turns OFF again. The capacitor size must be set accordingly to the gate driver consumption and the switching frequency of the converter. Since this gate driver powering technique has no connection or coupling to the ground, it does not add parasitic capacitance to the driving circuitry. Indeed, all elements are only connected to the power terminals of the main switches

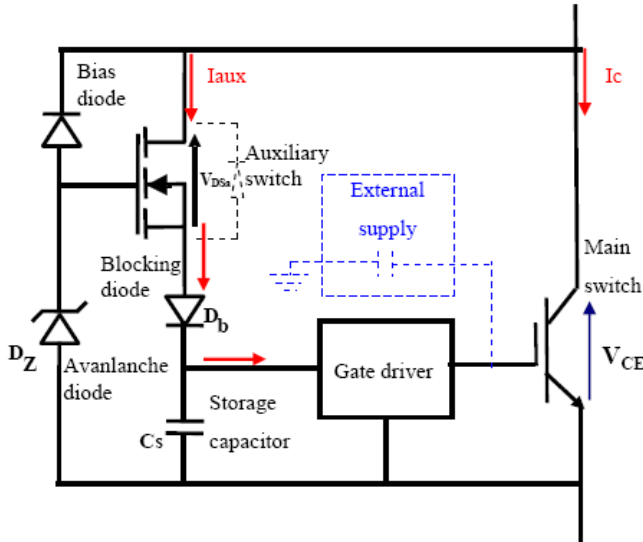


Figure 3. Self-powering topology around mains switch

B. Realization of a converter using a 3D structure

Equations 4, 5, 6 and 7 shows that the higher are the values of parasitic capacitances in the power circuit, the higher are the values of currents passing through these capacitances. This leads to greater differences between collector's currents of the IGBTs that are connected in series. Furthermore, the unequal IGBT's current affects the device's switching speed (formula 7), and consequently causes voltage unbalances across the series connected power devices. These parasitic capacitances are due to the power structure design and the safety requirements which impose to connect the heat sink to the ground; however, it would be interesting to minimize their value and influence. Hence, our approach aims to put IGBT connected in series in a vertical structure.

Fig. 4 presents a chopper with 3 IGBT connected in series, two realizations of this converter are then proposed: classical horizontal structure and 3D vertical structure.

In the first structure, the 3 IGBT are located in a same board so we deduce that $C'1=C'2=C'3$. In the second one, we can assume that $C'1>C'2>C'3$. This is due to the different distances between IGBT dies and the ground. Moreover, in the classical horizontal structure, we can see that the higher is the rank of the IGBT in the series connection, the faster its collector's potential changes. Therefore, T2 and T3 will be faster than T1. The solution of 3D vertical structure allows extracting less currents passing through parasitic capacitances of T2 and T3 (since $C'2$ and $C'3$ values are reduced), and it permits to obtain the better equality of switching speeds among the IGBTs.

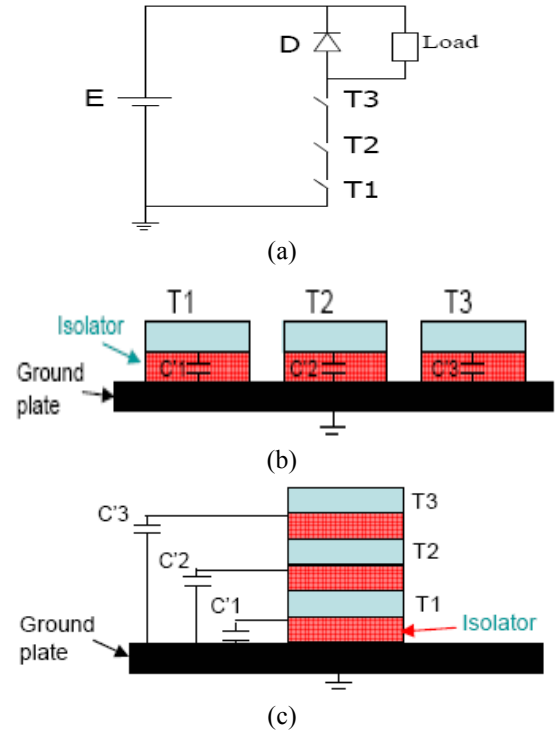


Figure 4. (a) Chopper (b) Horizontal structure (c) 3D Vertical structure.

IV. EXPERIMENTAL RESULTS

In order to validate our solutions for obtaining a good voltage balancing in IGBT series association, a chopper is considered for analysis and demonstration; Fig. 5 (a) shows the circuit diagram. The series-connected IGBT used in the test are HG TG30N60A (600V, 75A), the dc-bus voltage is set to 900V; the switching frequency is 20 kHz. On the gate driver, we have tested two supply techniques: the self-powering and an external supply (Fig.5 (b)), both of them will be implemented to prove advantage of the self-powering over the external supply in ensuring voltage balancing. Two power structures of this chopper (Fig. 5 (c, d)) have also been realized in order to validate the benefits of the 3D structure over the flat structure.

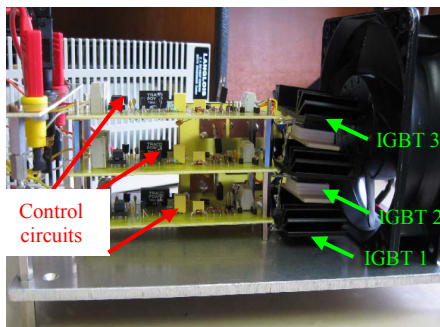
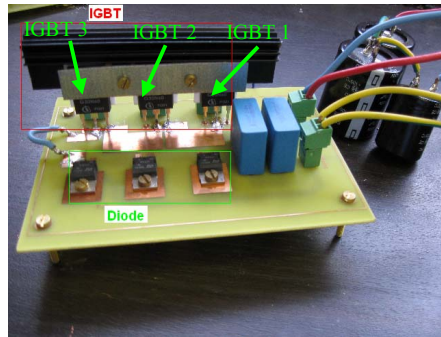
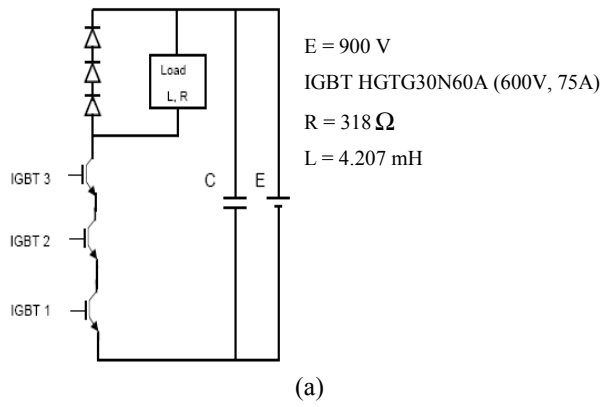


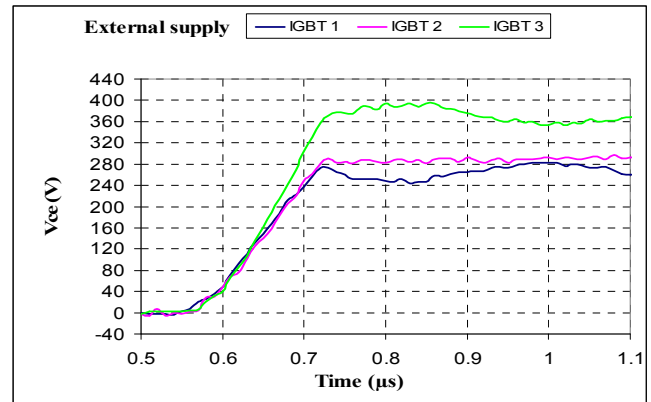
Figure 5. (a) Chopper (b) Control circuit (c) Horizontal structure (d) Vertical structure

A. Self-powering technique

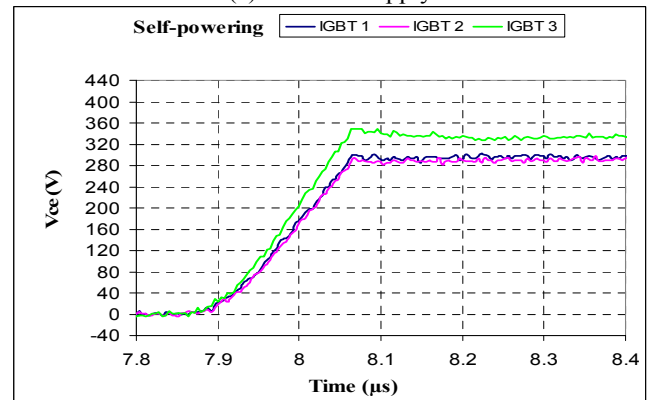
In this part, we use the self-powering and the external supplies for gate driver powering of the 3 IGBT in the horizontal structure of chopper. Fig. 6 shows the turn-off switching waveforms of 3 IGBT in both cases.

We can see that the delay times between the three waveforms are very short in both cases, approximately less than 10 ns. When the external supply is used to supply the control circuit, the switching speeds of 3 IGBT are very different; however, by using self-powering, this difference of switching speed is significantly reduced (Table 1). Therefore it confirms the effects induced by the parasitic capacitances existing in driver circuit in the case of external supply. As we explained in the previous section, the parasitic capacitances in gate driver produce an effect on accelerating switching speed of IGBT located at higher voltage levels in the series connection (IGBT1 on Fig. 5a). We can observe on Fig. 6a that the V_{CE} voltage of IGBT 3 raises faster than that of IGBT 2 and IGBT 1. When we compare the self-powering solution with, the classical external supply technique, a great improvement between the balances of the raising speeds of the Collector to Emitter voltage's IGBT can be observed.

We can notice that there is still some unbalance. It is due to the effect of other parasitic capacitances located in the optocoupler or between the PCB tracks and ground.



(a) External Supply



(b) Self-powering supply

Figure 6. Turn-off switching waveforms of 3 IGBTs connected in series (experimental waveforms).

TABLE I. SWITCHING SPEED IN TWO CASES

IGBT	IGBT 1	IGBT 2	IGBT 3
Switching speed (kV/ μ s)			
External supply	1.88	2	2.64
Self-powering	1.68	1.73	1.86

In order to show that parasitic capacitances are involved in voltage unbalance, we carried out some time domain simulations in Simplorer® software with both cases of external supply and self-powering. Fig. 7 shows the simulation schematic, in which C1', C2', C3' represent the parasitic capacitances between each IGBT collector terminal and the ground; C1, C2, C3 represent the parasitic capacitances in gate drivers while using external supply. They are considered negligible while using self-powering. The value of these capacitances is approximately calculated by using the formula for parallel-plate capacitor.

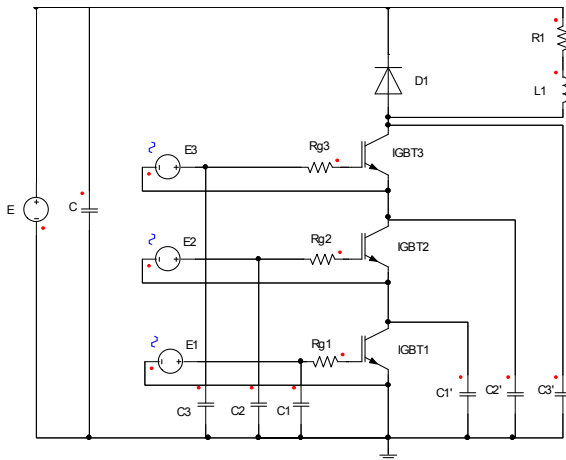
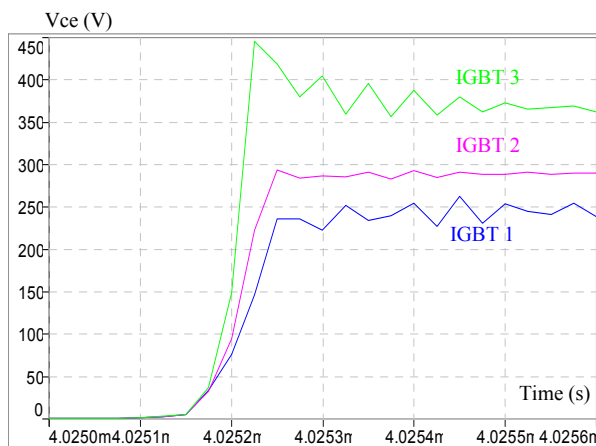
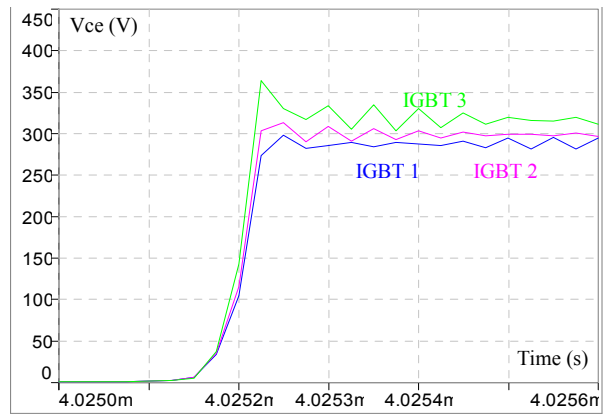


Figure 7. Simulation schematic in Simplorer



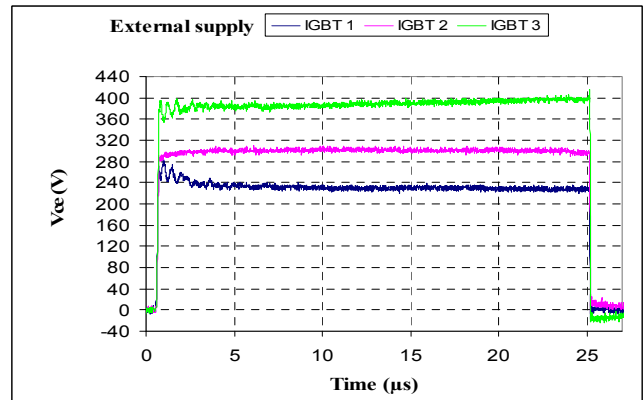
(a) External supply



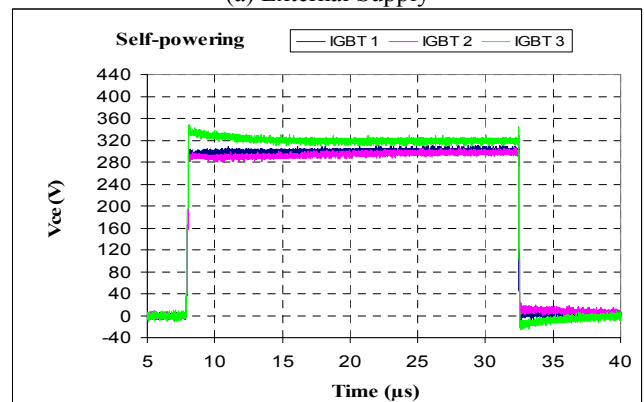
(b) Self-powering

Figure 8. Simulation results of switching operation of 3 IGBT connected in series (a) external supply and (b) self-powering.

The simulation results (Fig.8) show that the capacitances impact greatly on the voltage unbalance. On Fig. 8a the value of C1, C2 and C3 is 60 pF, and on fig 8-b theses capacitances does no longer exist. The value of C1', C2' and C3' are 8.4 pF in both cases.



(a) External Supply

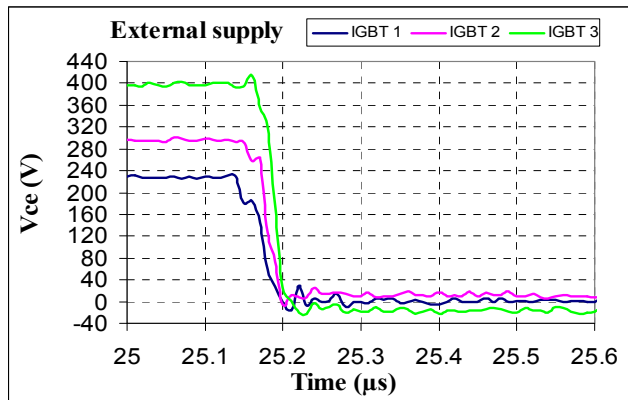


(b) Self-powering supply

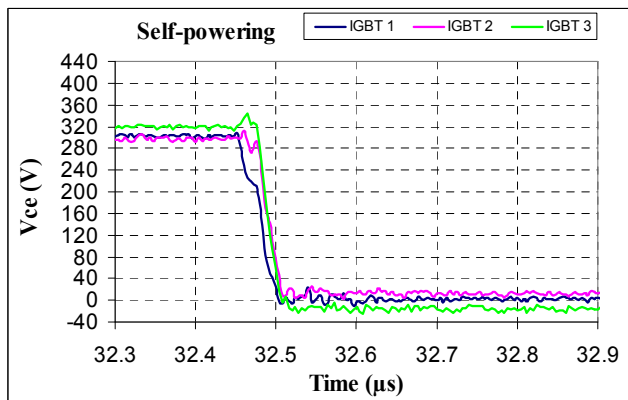
Figure 9. Voltage sharing of IGBT connected in series (experimental waveforms).

Fig. 9 presents the voltage sharing among these 3 IGBT in both cases. It can be seen that the self-powering technique improves significantly the balance voltage of the IGBT series connection in static phase. In fact, the dynamic operation decides the voltage sharing in static phase, more the IGBT's switching speed is fast, and more it supports a high voltage in steady state. The self-powering offers a better balance of switching speeds of IGBT connected in series, and it permit to obtain a better voltage balance in static phase: the V_{CE} of the IGBT 3 is approximately 20V more than that the one of IGBT 1 and 2. However, with external supply, there are about 90V and 60 V difference between IGBT 3 and IGBT 2, IGBT 2 and IGBT 1 respectively

Now we consider the turn-on transient of the 3 IGBT, the experimental results in Fig. 10 show in both cases that an over voltage happened on IGBT 3. This phenomenon is due to control signal's delay. If the 3 IGBT do not receive the gate signals at the same time an over voltage will appear. On figure 10, IGBT 1 and IGBT3 start the turn-on transient before the IGBT2, the consequence is an over voltage on IGBT3. To avoid this drawback, the synchronisation of the control signals must be improved.



(a) External Supply



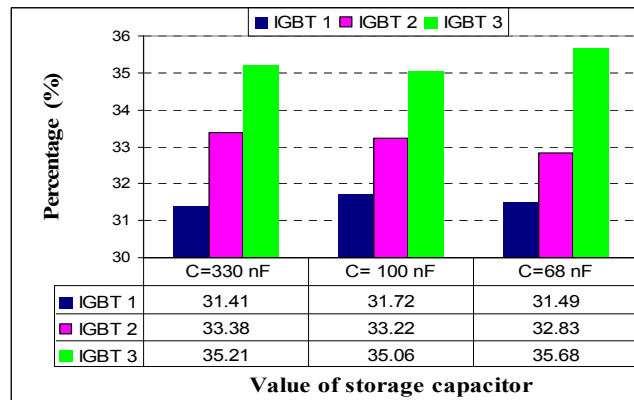
(b) Self-powering supply

Figure 10. Turning-on operation of IGBTs connected in series

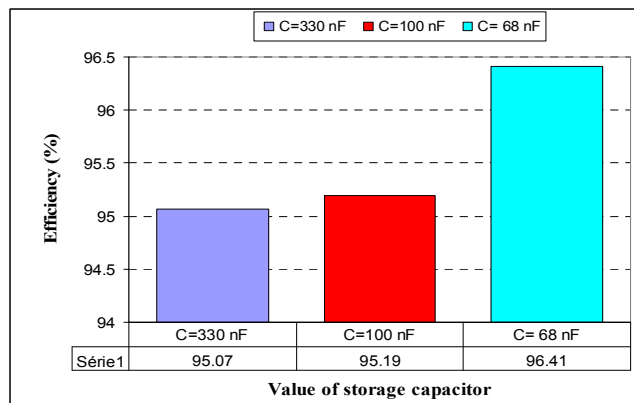
All previous results showed that the self-powering solution provides significant improvements versus the classical external supply in balancing the voltages of IGBTs connected in series. However, it would be interesting to take into account

how the parameters impact the efficiency in series association using the self-powering technique. We have observed the effects of the storage capacitor by changing its value; we have used successively three values 330 nF, 100 nF and 68 nF and measured the efficiency of the chopper according to these capacitors.

We measured the efficiency at switching frequency of 40 kHz; Fig. 11 shows that when the capacitance of storage capacitor (C_s on Fig. 3) decreases, the converter's efficiency increases slightly. Regarding to voltage balancing, we find that for the capacitance value of 100 nF and 330 nF, we obtain a better balance compared to that of case $C = 68$ nF. So we can conclude that the choice of storage capacity is always based on a compromise between voltage balancing and the overall efficiency of the converter.



(a) Voltage sharing



(b) Efficiency

Figure 11. Volatage balance and efficiency during turning-on operation of IGBT connected in series

B. Vertical structure 3D

In order to validate the performances of the 3D vertical structure solution, we used the self-powering technique for gate drivers; the voltage sharing in vertical structure will be compared with that of horizontal structure. Fig. 12 shows the turn-off waveforms in both structures. We can observe that with the vertical structure, the peak transient voltage experienced by IGBT 3 is less than that in the horizontal structure (338 V against 348 V); therefore, the voltage sharing after switching operation is better. According to the formula

(4), the parasitic capacitances $C'2$ and $C'3$ generate more capacitive current than $C'1$ due to the high value of the $\sum_{i=2,3}^3 \frac{dV_{CEi}}{dt}$. Therefore these capacitances $C'2$ and $C'3$ will greatly impact the voltage unbalances among the 3 IGBT. The proposed 3D structure reduces these capacitances. The values are $C'1=4.58$ pF; $C'2=0.79$ pF; $C'3=0.43$ pF in the 3D structure against $C'1=C'2=C'3=8.4$ pF in horizontal structure.

The 3D structure permits an improvement in turn-off switching of series association of IGBT.

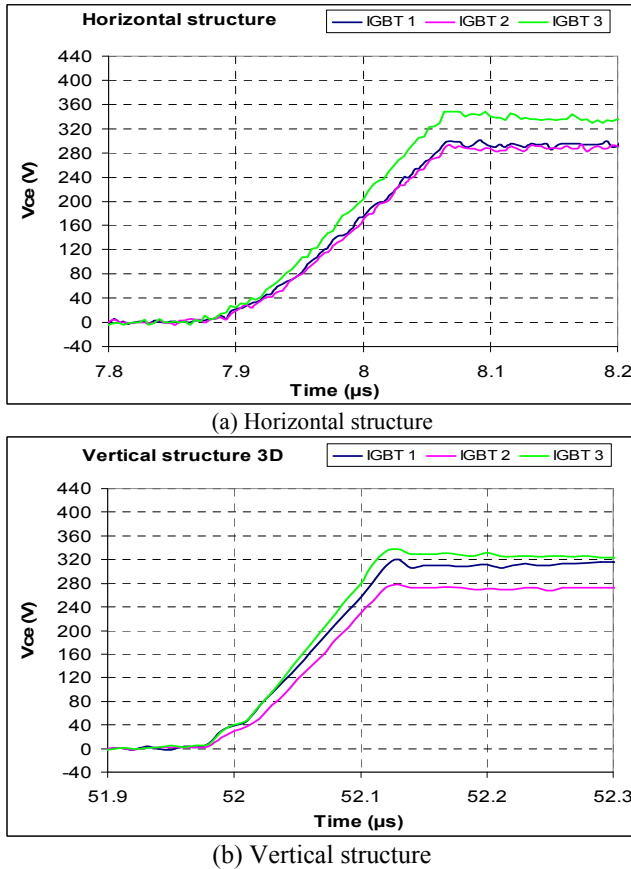


Figure 12. Turn-off waveforms of 3 IGBT connected in series (experimental waveforms).

V. CONCLUSION

This paper has presented, analyzed and validated two solutions proposed to improve the voltage sharing among IGBT connected in series. The main purpose of this article is to minimize the effects of the parasitic capacitances on voltage balancing by acting on design of the gate driver and the converter. The first solution, based on self-powering technology, offers a very good balancing voltage in steady state phase. The second solution is to minimize the value of parasitic capacitances in power circuit, by putting IGBT series association in a vertical structure; we demonstrated that this structure has advantages over the horizontal structure during the IGBT turn-off.

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