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# CAPACITOR FOR THE VOLTAGE-SURGE SUPPRESSION IN A SIC-MOSFET HALF-BRIDGE INVERTER

**Rini Nur Hasanah**
*Corresponding author*
Doctor of Engineering Sciences, Professor*
E-mail: rini.hasanah@ub.ac.id
**Waru Djuriatno**
Master of Engineering, Assistant Professor*
**Lunde Ardhenta**
Master of Engineering Sciences, Lecturer*
**Hadi Suyono**
Doctor of Philosophy, Professor*
**Febry Pandu Wijaya**
Doctor of Engineering,
Senior Manager of Product and Technology
PT. INKA (Persero)
Yos Sudarso str., 71, Madiun, Indonesia, 63122
**Hazlie Mokhlis**
Doctor of Philosophy, Professor
Department of Electrical Engineering
Universiti Malaya Power and Energy System Research Group
University of Malaya
Kuala Lumpur, Malaysia, 50603
*Department of Electrical Engineering
Brawijaya University
MT Haryono str., 167, Malang, Indonesia, 65145

***This paper explores some efforts to suppress the voltage surge appearing during the operation of a SiC-MOSFET-based half-bridge circuit in an inverter topology. The study is important to carry out, as the voltage surge problem does not come up when a Si-IGBT is used as the switching component in the half-bridge; however, some applications demand certain properties like what is found in a SiC-MOSFET. Compared to Si-IGBT with rise-time/fall-time larger than 100 ns in general, the use of SiC-MOSFET is preferable due to its much shorter switching time, less than 50 ns, which brings about a much lower switching loss and lower operating temperature. However, the choice of the usual electrolytic capacitor in the dc-link would produce an undesired voltage surge during the half-bridge operation. The origin of the surge is sometimes assigned to the inductance parasitic effect of the SiC-MOSFET high frequency. This research proves the benefit of a film capacitor to suppress the surge due to its lower equivalent series resistance (ESR) than that of the electrolytic capacitor. The results contribute to the consideration to take during the circuit realization in various applications, as there are not many papers yet found discussing the use of film capacitor in the dc-link of a SiC-MOSFET half-bridge inverter. This study also reveals the importance of the film capacitor placement during the design stage of SiC-MOSFET applications; moreover, motor controllers being equipped with an inverter such as described in this study have not been found yet in the market. The efforts investigated in this work would help to control the undesirable voltage spikes that frequently occur when applying a SiC-MOSFET to a half-bridge inverter design***

***Keywords: dc link, equivalent series resistance, fall-time, film capacitor, half-bridge, inverter, rise-time, SiC-MOSFET, switching loss, voltage surge***

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## 1. Introduction

Electronic-based equipment is indispensable in modern daily life as well as industry. However, none of the equipment works without the technology to deliver power to them [1]. Newly developed equipment is becoming smaller, faster in their operation, and tougher to face applications in harsh environments than the ones previously existing. The continuously increasing awareness of energy saving and environmental protection also requires better and better efficiency of the equipment.

To date, silicon (Si) has been becoming the main material to be used in power electronic components. Various power devices rely on the characteristics of silicon to accomplish their functions in electrical power conversion to supply much electronic equipment. However, new application requirements have directed the evolution of power electronics technology toward higher efficiency, higher power density, and more integrated systems. The mature technology of Si power devices has been approaching their performance limitations [2]. Operation in a much higher level of voltage, frequency, as well as temperature, cannot be fulfilled anymore by Si-based power devices.

A breakthrough has been found in the use of wide-bandgap materials, which are dotted with higher-energy electronic band gaps. Among some wide-bandgap materials, Silicon-Carbide (SiC) is the readiest to use for various applications [2]. It also has a much wider bandgap than other semiconductor materials such as Si or GaAs, offering some critical advantages like the ability to handle higher voltages and power, higher operating temperatures, faster switching, better efficiency, and a significantly smaller form factor.

In general, both Si-based MOSFETs (Metal-Oxide-Semiconductor Field Effect Transistors) and IGBTs (Insulated-Gate Bipolar Transistors) are used in many different types of power applications, including automotive and transportation, aerospace, renewable energy, test and measurement, and telecommunications. MOSFETs are generally applied for lower voltages and power equipment, while IGBTs are well adapted to higher voltages and power.

The coming of SiC-based MOSFET offers excellent advantages compared to their Si-based counterparts. SiC-MOSFET is a switching component made of wide bandgap semiconductor material [2]. It outperforms the IGBT for high-voltage and high-frequency applications. This component is capable of operating at a very high switching frequency (switching time <50 ns). This property results in smaller switching losses, which in turn will lead to higher efficiency. Higher efficiency would require reduced thermal management components, which are indispensable for smaller-size and lower-weight applications, like aerospace applications or electric transportation in general [3], as well as in renewable energy applications [4].

Many advantages offered by SiC-MOSFETs can be obtained provided that some challenges are to be overcome. The research on various problems related to the SiC-MOSFET applications is still widely open. It may cover starting from topics related to modeling [5] up to problems during fabrication [6]. It may also touch the problems tied to the SiC-MOSFET functioning [7] as well as its interaction with the surrounding equipment [8]. Therefore, studies that are devoted to exploring the efforts to reduce losses related to applications of high switching-frequency power converters are of scientific relevance.

## 2. Literature review and problem statement

High-voltage, high-power applications normally include the use of Si-IGBTs as the power-switching component. However, because of certain requirements to fulfill, SiC-MOSFETs start to supplant the role of Si-IGBTs [2]. The use of SiC-MOSFET succeeded in reducing power losses in the inverter for traction application [9]. However, the success was seen in a global view. The details of the functioning circuits as well as the possible surge appearance because of high frequency switching were not specifically explored. The modern rail traction power system also relies on the wideband gap-based switching component. It requires a converter with a smaller size and a lighter weight, while at the same time demanding higher efficiency, power density, operation temperatures, and frequency [10]. The advantages of high speed and high current of SiC-MOSFET in pulsed power application were also confirmed in [11]. The higher current surge produced as a result of the SiC-MOSFET usage was shown, and the influence of dc-link capacitance was explored. However, there was no further exploration on the appearance of voltage surge as well as the importance of capacitance trade-off in replacing Si-IGBT with SiC-MOSFET. The reduced losses make the production of smaller equipment possible; however, some other problems may come up during the printed-circuit board layout design [12]. The importance of the components' layout to avoid the undesired EMI issues was emphasized. The choice of components' types also determines the dimensional consideration in its placement on the board.

It is known that the use of SiC-MOSFETs will result in a voltage surge in the half-bridge circuit. In [13], the cause of the phenomenon was assigned to the parasitic effect of high-speed component switching. The influence of parasitic inductance has also been much investigated to envisage the problem solution. However, changing the inductance is not easy to do. The influence of inductance and its placement variation has been examined in [14]. It was concluded that the severity of oscillation during switching had been due to the lower ratio of device capacitance over inductance.

A dc-link capacitor is commonly used to handle the voltage fluctuation in a converter topology [5]. It acts to filter out the ripple voltage and current, while also becoming an important energy storage device [15]. Various types of capacitor technology may be used. An electrolytic capacitor is found in the dc-link of many converter topologies, for example in the converter for electric vehicles [16]. It has a small dimension, but a high capacity. It has an equivalent series resistance (ESR) in the order of tens to thousands of milliohms. It was stated in [16] that the dc-link capacitor was still bulky enough. A smaller and lighter device would require a smaller dimension of the capacitor. A film capacitor may fulfill the requirements [17].

Replacement of the Si-IGBT switching component with SiC-MOSFET does not imply that direct replacement of the electrolytic capacitor with a film capacitor is possible. On the other hand, film capacitors, which can work at a much higher voltage, normally have smaller capacitance with an ESR value of less than tens of milliohms. The low equivalent series resistance allows the film capacitors to handle ripple-current as well as high surge-voltage ratings better. Unlike electrolytic capacitors, the non-polarized property of film capacitors makes them more immune to reverse-connection errors and withstand exposure to a much higher voltage. The better self-healing property also ensures a safer response to occasional stresses, as typically encountered in real-world applications [17]. These all characteristics make the film capacitors good candidates for many power-conditioning duties in important applications like electric transportation, renewable energy, and industrial drives.

Compared to Si IGBT, the use of SiC-MOSFET is much more preferable for high switching-speed applications. SiC-MOSFET has a much shorter switching time (less than 50 ns) than Si IGBT, which in general has a rise time/fall time larger than 100 ns. The high-frequency switching as a result of the short switching time will cause a parasitic inductance effect on the long dc-link used [14]. Combined with the relatively high value of electrolytic capacitor ESR, the parasitic effect would cause a negative voltage surge on the active leg of the half-bridge circuit [18]. Turning-on on the switching component on the alternate leg will result in the opposite polarity of the voltage surge. A lot of research has been carried out to overcome the surge problem, for example by using a digital active driver. In [19], the use of an active driver was proven to suppress voltage surge during SiC-MOSFET turn-off, whereas in [20] the surge suppression was done by optimizing the gate-driving waveform and no necessary use of a snubber capacitor has been proven.

Considering the continuously increasing use of SiC-based power converters, especially SiC-MOSFET in high switching-speed applications, the efforts to minimize or even eliminate the undesired surge problems as a consequence of high-frequency switching and its interaction with various factors are still open to investigation.

## 3. The aim and objectives of the study

The aim of the study is to identify a method to suppress the voltage surge in a SiC-MOSFET-based half-bridge inverter application. The research results would become a recommendation to consider and to refer to during the application of SiC-MOSFETs in power converters in general, especially those demanding compact dimensions, high efficiency, as well as high operating speeds.

To achieve this aim, the following objectives are to accomplish:

– to investigate the voltage-surge characteristics of a half-bridge inverter that uses a Si-IGBT or a SiC-MOSFET as the switching components;

– to investigate the role of capacitor in the dc-link of the Si-IGBT-based and SiC-MOSFET-based half-bridge inverters;

– to investigate the influence of gate resistor on the transient characteristics of a SiC-MOSFET half-bridge inverter;

– to compare the voltage surge simulation results to experiment results;

– to investigate the influence of capacitor placement on voltage-surge characteristics of a SiC-MOSFET half-bridge inverter.

## 4. Materials and Methods

### 4. 1. Object and hypothesis of the study

The object of the research in this paper is the undesired voltage surge emerging during the use of SiC-MOSFET power switching component to replace Si-IGBT in the half-bridge inverter applications. The surge is thought to be caused by the high switching frequency of this wideband gap-based component, as well as the combined effects of parasitic inductance, electromagnetic interference, as well as the equivalent series resistance of the capacitor used in the dc link.

It is predicted that the severity of voltage surge can be minimized through the trade-off of the various influencing parameters. In this paper, it is assumed that the influencing factors are the choice of capacitor in the dc link, the capacitor placement, as well as the gate resistor.

An electrolytic capacitor is commonly used in the dc-link of the Si-IGBT-based half-bridge inverter circuit. The voltage surge is still appearing when SiC-MOSFET is used to replace the Si IGBT switching component. A film capacitor is going to be explored to provide a high value of dc-link capacitance. The film capacitor has some properties like low capacitance density, relatively high operating voltage, and low ESR value, but it is normally much more expensive than the electrolytic capacitor. On the other hand, high capacitance density, relatively low operating voltage, high ESR, and low cost are some of the important properties of an electrolytic capacitor.

### 4. 2. Methods

The study is performed by first investigating the characteristics of surge produced in a half-bridge inverter, by observing the voltage surge in the dc-link. Starting-on transient simulations are to be performed using the half-bridge inverter circuit, before finally being validated using laboratory experiments.

A half-bridge inverter with Si-IGBT as the main switching component and an electrolytic capacitor in the dc-link is taken as the base case. It is to be improved by adding a film capacitor in parallel with an electrolytic capacitor in the dc-link. A further step is done by using a SiC-MOSFET instead of Si-IGBT as the main switching component, while still using an electrolytic capacitor in the dc-link. Improvement is then investigated by using an additional parallel film capacitor, and finally by using only a film capacitor in the dc link.

An important observation is also conducted to examine the influence of gate resistors on the transient characteristics of the inverter. Special care is taken when placing the capacitor in the circuit. It is placed as close as possible to the position of the switching component of the SiC-MOSFET half-bridge inverter. The aim is to reduce the parasitic inductance between the film capacitor and the SiC-MOSFET.

To obtain a comprehensive comparison, some special configuration cases of the half-bridge inverter are considered as follows:

– case I: Si-IGBT half-bridge inverter with an electrolytic capacitor in the dc link;

– case II: Si-IGBT half-bridge inverter with an electrolytic capacitor and additional parallel film capacitor in the dc link;

– case III: SiC-MOSFET half-bridge inverter with an electrolytic capacitor in the dc link;

– case IV: SiC-MOSFET half-bridge inverter with an electrolytic capacitor and additional parallel film capacitor in the dc link;

– case V: SiC-MOSFET half-bridge inverter with a film capacitor in the dc link.

### 4. 3. Circuit configurations

The simulation circuits for Case I until Case V are given in Fig. 1–5.

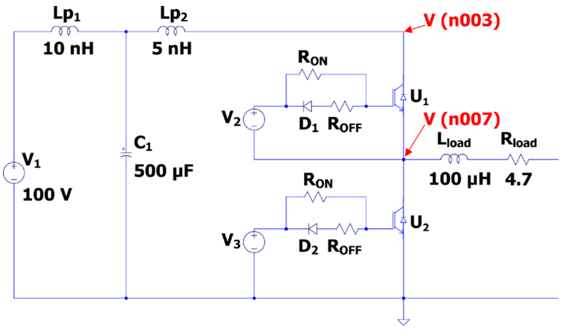


Fig. 1. Simulation circuit of a Si-IGBT half-bridge inverter using an electrolytic capacitor in the dc-link

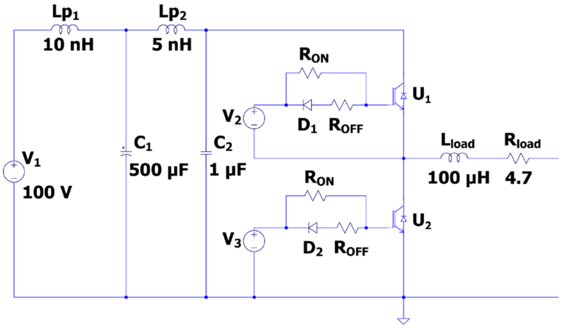


Fig. 2. Simulation circuit of a Si-IGBT half-bridge inverter using an electrolytic capacitor with an additional parallel film capacitor in the dc-link

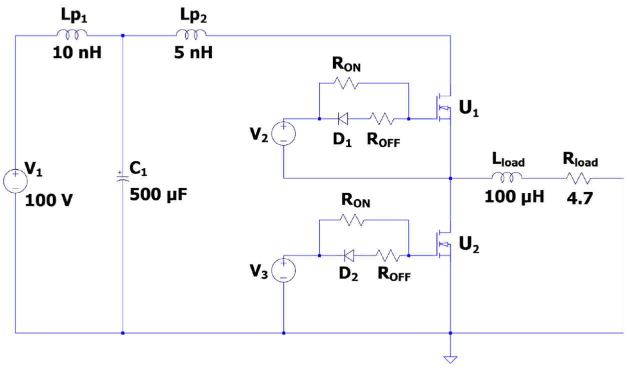


Fig. 3. Simulation circuit of a SiC-MOSFET half-bridge inverter using an electrolytic capacitor in the dc-link

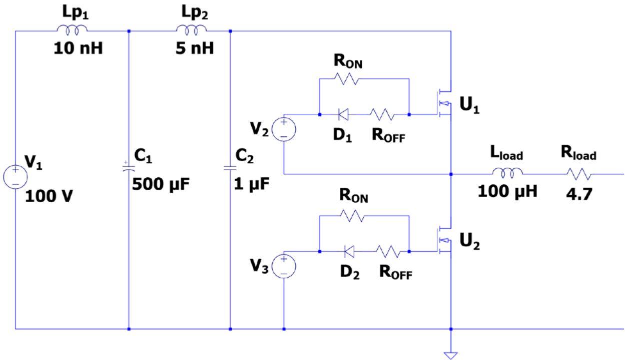


Fig. 4. Simulation circuit of a SiC-MOSFET half-bridge inverter using an electrolytic capacitor in the dc-link with the parallel addition of a film capacitor

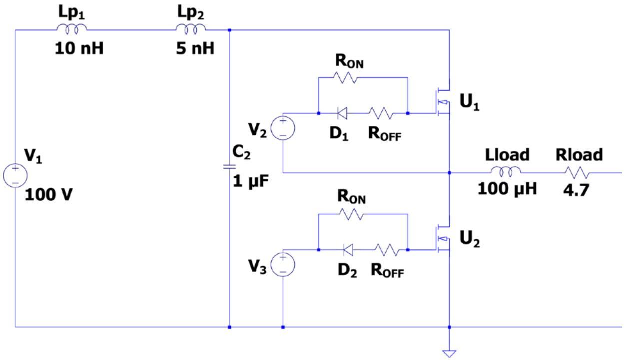


Fig. 5. Simulation circuit of a SiC-MOSFET half-bridge inverter using a film capacitor in the dc-link

Fig. 1–5 represent the half-bridge inverter circuits to be used during the simulation. The differences among all circuits are determined by the switching components used, which are Si-IGBT and SiC-MOSFET, as well as the types of capacitors used in the dc link. Three cases are considered: using only an electrolyte capacitor, using an electrolyte capacitor with an additional parallel film capacitor, and using only a film capacitor in the dc link.

### 4. 4. Circuit parameters

Simulations have been conducted by using the LTSpiceIV software. The LTSpiceIV software was chosen as it is widely used in industry. Although free, it is practically not restricted to limit its capabilities. The model of SiC-MOSFET is taken from Onsemi products, which is the type NTC020N120SC1: Silicon Carbide MOSFET, N-Channel, 1,200 V, 20 mΩ, Bare Die, with 3 pins. The model of Si-IGBT is also taken from Onsemi products, which is the type FGY75T120SQDN: IGBT, Ultra Field Stop, –1,200 V, 75 A. The considered electrolytic capacitor of the dc-link is the default polar capacitor model with 500 µF capacitance and 100 milliohms ESR. The default capacitor model is also used as a film capacitor by setting the capacitance value of 1 µF and ESR value of 10 milliohms. DC-link inductances are represented using two default inductor models, $Lp_1$ and $Lp_2$, which values are 10 and 5 nanohenries, respectively. A 10-ohm resistor is selected as $R_{ON}$ and a 1-ohm resistor is selected as $R_{OFF}$. A series $R$-$L$ of a resistor and an inductor is used as the load of the circuit, with a resistance value of 4.7 ohms and an inductance value of 100 µH. The gate-driver signal of the MOSFET is a square signal with rise-time $t_{rise}$ and fall-time $t_{fall}$ of 10 ns, $t_{ON}$ of 100 ns, and a period of 250 ns [6, 13].

## 5. Results of the Study on the Voltage-Surge suppression in a SIC-MOSFET Half-Bridge Inverter

### 5. 1. Results of investigation on the voltage-surge characteristics of a half-bridge inverter

The results of the simulation on the voltage performance of the half-bridge inverter are presented in Fig. 6, 7, respectively. In Fig. 6, an electrolytic capacitor is used in the dc link of a Si-IGBT inverter (Case I), whereas in Fig. 7, an electrolytic capacitor is used in the dc link of a SiC-MOSFET inverter (Case III).

As can be observed in Fig. 6, 7, the voltage performance of half-bridge inverters, either using Si-IGBT or SiC-MOSFET as the switching components, both are containing undesired voltage spikes. However, a comparison of Fig. 7 and Fig. 6 indicates that for some applications requiring fast switching, replacing the Si-IGBT with the wideband gap-based SiC-MOSFET component will just worsen the voltage surge conditions both in the dc link and the output of the inverter.

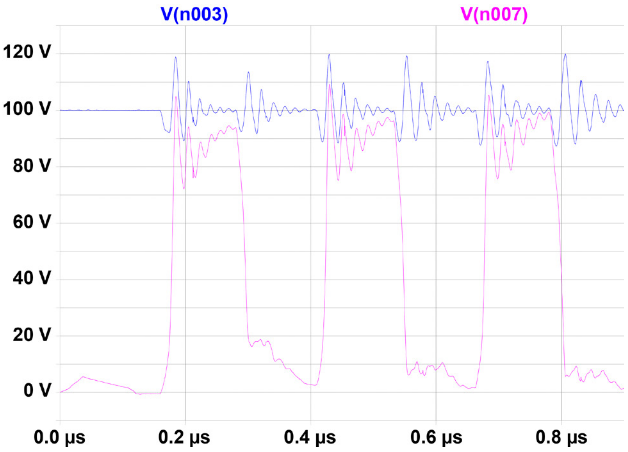


Fig. 6. Surge characteristic simulation results of a Si-IGBT half-bridge inverter using an electrolytic capacitor in the dc-link (Case I), where the blue line indicates the dc-link voltage, while the violet line indicates the output voltage of the half-bridge inverter

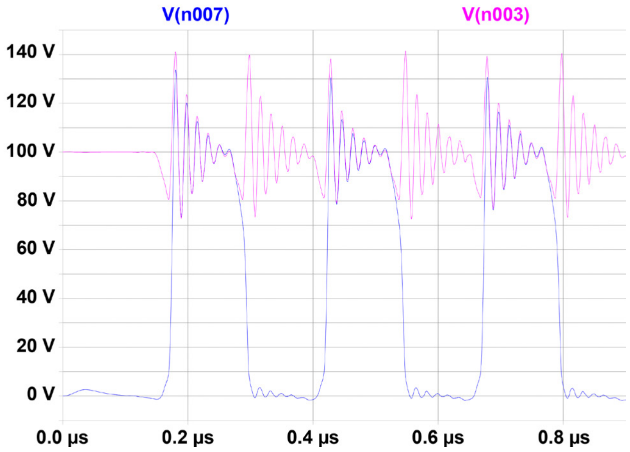


Fig. 7. Surge characteristic simulation results of a SiC-MOSFET half-bridge inverter using an electrolytic capacitor in the dc-link (Case III), where the blue line indicates the dc-link voltage, while the violet line indicates the output voltage of the half-bridge inverter

### 5. 2. Results of investigation on the role of capacitor in the dc-link of a half-bridge inverter

The investigation on the role of capacitor in the dc-link of a half-bridge inverter can be based on Fig. 8, 9 consecutively. Fig. 8 indicates a parallel structure of an electrolytic capacitor and a film capacitor is used in a Si-IGBT half-bridge inverter (Case II), whereas in Fig. 9 the Si-IGBT component is replaced with SiC-MOSFET (Case IV). In this way, the influence of an additional film capacitor can be observed.

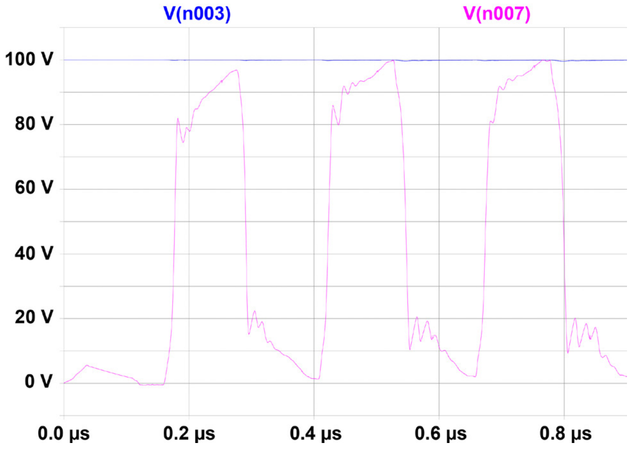


Fig. 8. Surge characteristic simulation results of a Si-IGBT half-bridge inverter using an electrolytic capacitor with an additional parallel film capacitor in the dc-link (Case II), where the blue line indicates the dc-link voltage, while the violet line indicates the output voltage of the half-bridge inverter

As can be observed in Fig. 8 and by comparing to Fig. 6, the addition of a film capacitor in parallel to the electrolytic capacitor could eliminate the surges on the dc-link voltage and also reduce those on the output voltage of the Si-IGBT half-bridge inverter.

Observation made on Fig. 9 and comparing it to Fig. 8 indicates that the addition of a film capacitor in parallel to the electrolytic capacitor in the dc link enables the reduction or even the elimination of the voltage surges or ringing in the SiC-MOSFET half-bridge inverter. Being compared to the surge reduction obtained in a Si-IGBT inverter shown in Fig. 8, the level of improvement obtained using the film capacitor is higher in the case of a SiC-MOSFET inverter (Fig. 9). Both voltage surges in the dc link as well as the output of the inverter are disappearing in the SiC-MOSFET inverter of Fig. 9, whereas some ringing is still appearing in the Si-IGBT inverter of Fig. 8.

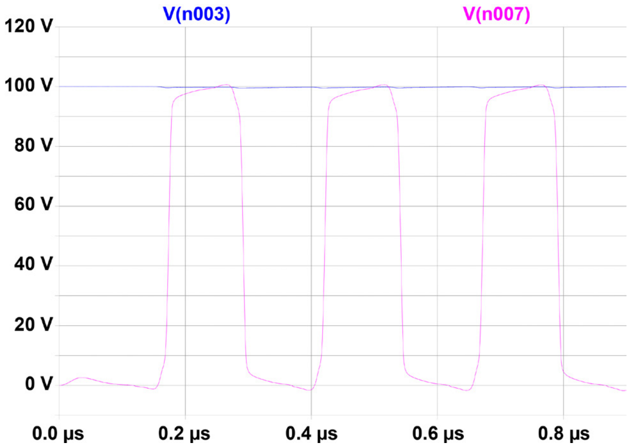


Fig. 9. Surge characteristic simulation results of a SiC-MOSFET half-bridge inverter using an electrolytic capacitor and an additional parallel film capacitor in the dc-link (Case IV), where the blue line indicates the dc-link voltage, while the violet line indicates the output voltage of the half-bridge inverter

The simulation results displaying the surge characteristics of a SiC-MOSFET half-bridge inverter when there is only a film capacitor in the dc-link (Case V) are presented in Fig. 10.

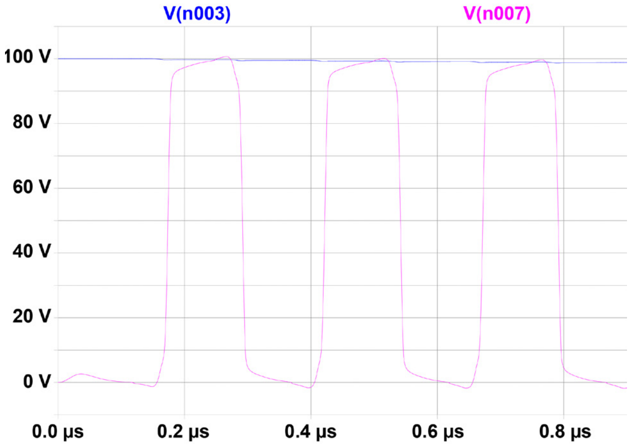


Fig. 10. Surge characteristic simulation results of a SiC-MOSFET half-bridge inverter using only a film capacitor in the dc-link (Case V), where the blue line indicates the dc-link voltage, while the violet line indicates the output voltage of the half-bridge inverter

When there is only a film capacitor used in the dc link (Case V), as seen in Fig. 10, there are no surges appearing both in the dc link voltage as well as in the output voltage of the inverter. The results shown in Fig. 10 are not too different from those shown in Fig. 9 (Case IV). It means that replacing the Si-IGBT with SiC-MOSFET accompanied by the replacement of the electrolytic capacitor with a film capacitor offers a promising elimination of voltage surges both in the dc link and in the output of the inverter.

### 5. 3. Results of investigation on the influence of gate resistor on the surge

The voltage surge caused by the high switching frequency of SiC-MOSFET may produce high switching losses and even harm the SiC-MOSFET itself. There must be an optimization of the voltage surge and the switching speed, as it is hard to obtain the favorable condition of both: low voltage surge and fast switching speed. In [6], the turn-off transient was improved by optimizing a gate driver with a switched capacitor.

Another influencing factor is the gate resistor. The results of an investigation on the gate resistor influence are given in Fig. 11, 12 subsequently. Fig. 11 indicates the simulation circuit, whereas Fig. 12 displays the simulation results. The considered values for simulation were the gate resistor $R_{ON}$ of 2 ohms and $R_{OFF}$ of 1 ohm, with a series inductive resistive load with $L_{load}$ of 100 µH and $R_{load}$ of 4.7 ohms.

The circuit shown in Fig. 11 is the same as the circuit used in the previous sections (Fig. 1–10), except that the gate resistor $R_{ON}$ is reduced from 10 ohms to 2 ohms while maintaining the $R_{OFF}$ of 1 ohm.

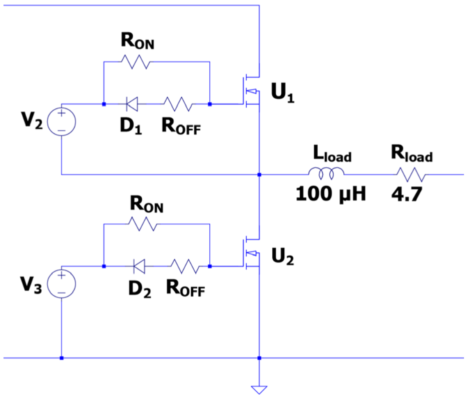


Fig. 11. Simulation circuit to examine the influence of the gate resistor $R_{ON}$ of 2 ohms and $R_{OFF}$ of 1 ohm on the SiC-MOSFET output voltage with a series inductive resistive load with $L_{load}$ of 100 µH and $R_{load}$ of 4.7 ohms

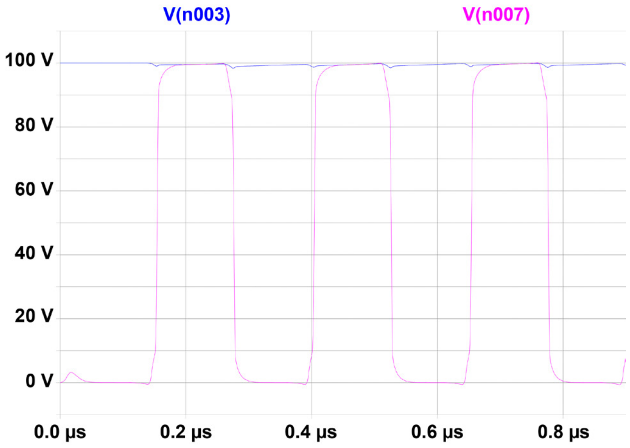


Fig. 12. Simulation result to examine the influence of the gate resistor $R_{ON}$ of 2 ohms and $R_{OFF}$ of 1 ohm on the SiC-MOSFET output voltage with a series inductive resistive load with $L_{load}$ of 100 µH and $R_{load}$ of 4.7 ohms

As presented in Fig. 11 and Fig. 12, $R_{ON}$ value reduction, from 10 to 2 ohms, gives an insignificant effect, although observable, on the dc-link voltage. As shown in Fig. 12, the dc-link voltage is dipped only by a small amount, about 2 volts, during the MOSFET transition. The $R_{ON}$ reduction produces the decrease in the switching or transition time of the MOSFET, and consequently the dipping of the dc-link voltage. If the voltage dip is sufficiently large, the voltage ringing in the dc link may appear.

### 5. 4. Results of the experiment on the voltage-surge characteristics of a SiC-MOSFET half-bridge inverter

The experiment set-up of this research is presented in Fig. 13, whereas the picture of the SiC-MOSFET half-bridge inverter board used in the experiment is displayed more clearly in Fig. 14.

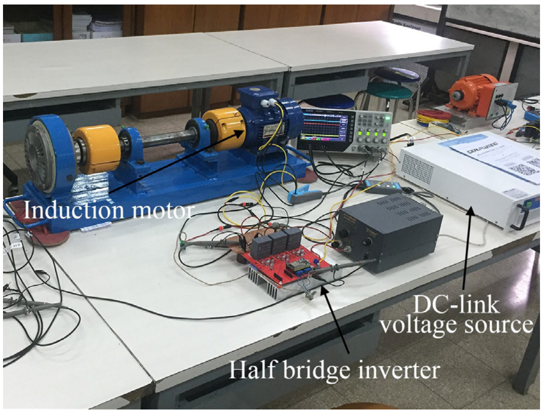


Fig. 13. The experiment set-up of the SiC-MOSFET half-bridge inverter

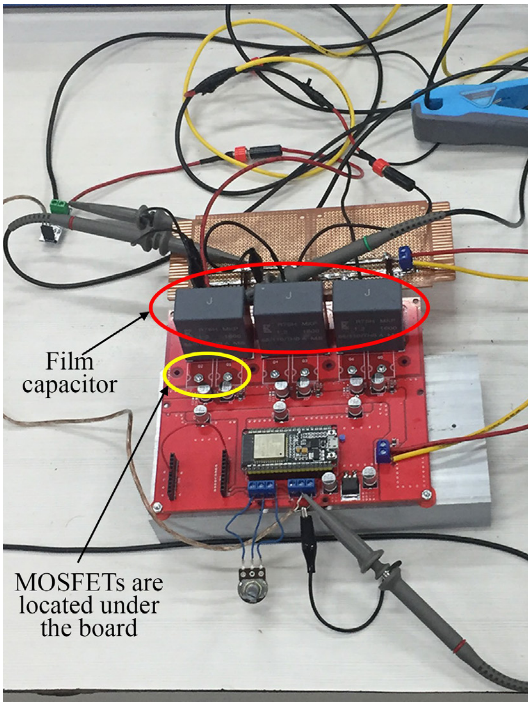


Fig. 14. The SiC-MOSFET half-bridge inverter board

The experiment results of the SiC-MOSFET half-bridge inverter using an electrolytic capacitor in the dc-link are presented in Fig. 15, whereas those with the addition of a film capacitor in parallel are presented in Fig. 16.

Fig. 15. Experiment results on the voltage in a half-bridge circuit with an electrolytic capacitor in the dc-link (red curve: dc-link voltage, yellow curve: half-bridge output voltage)

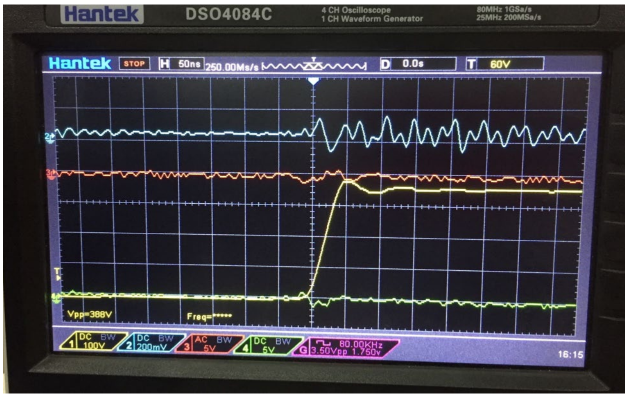


Fig. 16. Experiment results on the voltage in a half-bridge circuit with a parallel addition of the film capacitor to the electrolytic capacitor used in the dc-link (red curve: dc-link voltage, yellow curve: half-bridge output voltage)

As seen on the oscilloscope display, the yellow curve represents the half-bridge output voltage, the red curve represents the dc-link voltage, whereas the blue curve and green curve consecutively indicate the output current of the half-bridge and the negative voltage of the dc-link.

Fig. 15 shows the resulted voltage ringing in the dc-link (indicated with the red curve), which was caused by the very fast (about 50 ns) MOSFET transition being combined with a low-frequency response, high ESR electrolytic capacitor, and high dc-link inductance value. To solve the voltage surge or ringing problem, a film capacitor with small capacitance value, high-frequency response, and low ESR was placed in the dc-link as close as possible to the SiC-MOSFET half-bridge inverter. It was aimed to reduce the conductor inductance. The related experiment results using the film capacitor addition are shown in Fig. 16. It can be seen from the red curve in Fig. 16 that the dc-link voltage ringing is eliminated while the MOSFETs transition time is not affected.

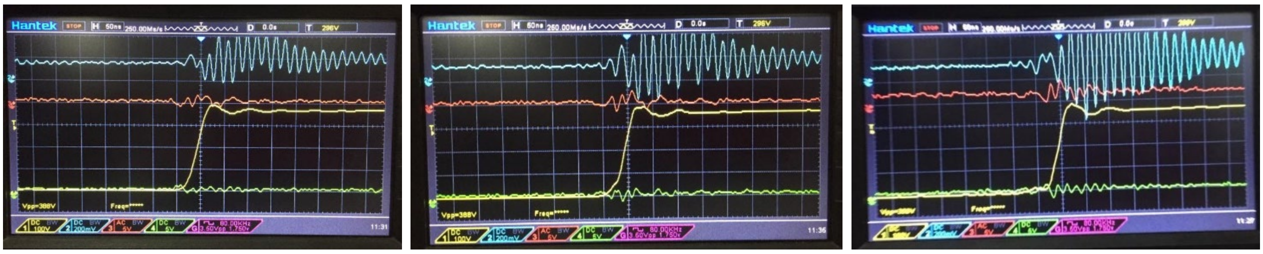
A comparison of the experiment results shown in Fig. 15 to the simulation results shown in Fig. 7 confirms that the replacement of Si-IGB with SiC-MOSFET in the half-bridge inverter using an electrolytic capacitor in the dc-link would just aggravate the voltage surge condition. A special measure needs to be taken to suppress it, which is confirmed by the experiment results shown in Fig. 16. The measure taken was the addition of a film capacitor in parallel to the electrolytic capacitor. Fig. 16 confirms the simulation results shown in Fig. 9.

### 5. 5. Results of the experiment on the capacitor placement in a SiC-MOSFET half-bridge inverter

The final board layout of a SiC-MOSFET application prototype should be designed carefully to avoid undesired effects like parasitic effects, ringing, electromagnetic interference, etc. The dimension as well as placement of all components involved in the printed-circuit board (PCB) must be meticulously considered. It is an optimization challenge by itself. In this study, the capacitor placement was represented using the dc-link cable length. Three cases of dc-link cable length were considered, which were 25 cm, 50 cm, and 100 cm. The related inductance values of the cable were 2.36 μH for the 100-cm cable, 1.28 μH for the 50-cm cable, and 0.72 μH for the 25-cm cable.

Fig. 17, 18 show the influence of the dc-link length on the transient characteristics of the SiC-MOSFET half-bridge inverter under consideration. Fig. 17 describes the result of the experiment to observe the influence of the dc-link length on the voltage surge of the inverter board with a film capacitor, whereas the result without a film capacitor is given in Fig. 18.

In Fig. 17, the influence of film capacitor addition can be seen on the resulted surge suppression during the switching transient period. It is also shown that the longer the dc-link, which means the larger the distance of the capacitor to the switching component, the higher the dc-link positive voltage oscillation (indicated with the red curve). It can also be observed that the most remarkable influence is on the output current of the half-bridge (indicated with the blue curve). The shorter the dc-link is, the smaller the half-bridge output current oscillation.



*a* *b* *c*

Fig. 17. Experiment results on the influence of the dc-link length on the voltage surge of the inverter board with a film capacitor: *a* – dc-link length of 25 cm; *b* – dc-link length of 50 cm; *c* – dc-link length of 100 cm (red curve: dc-link positive voltage, green curve: dc-link negative voltage, yellow curve: half-bridge output voltage, blue curve: half-bridge output current)


*a* *b* *c*

Fig. 18. Experiment results on the influence of the dc-link length on the voltage surge of the inverter board without a film capacitor: *a* — dc-link length of 25 cm; *b* — dc-link length of 50 cm; *c* — dc-link length of 100 cm (red curve: dc-link positive voltage, green curve: dc-link negative voltage, yellow curve: half-bridge output voltage, blue curve: half-bridge output current)

As presented in Fig. 18, if the film capacitor is not added to the dc link, the ringing or surge appears clearly in all presented characteristic curves. Comparison with Fig. 17 clarifies the fact that voltage surge suppression is affected by both the dc-link capacitor and the dc-link length representing the capacitor placement.

## 6. Discussion of the Voltage-Surge Suppression in a SIC-MOSFET Half-Bridge Inverter

This study on the voltage suppression in a SiC-MOSFET half-bridge inverter is carried out by beginning with the investigation of the characteristics of surge or ringing often appearing on the Si-IGBT half-bride inverter. The Si-IGBT converters are so far used in many high-voltage and high-power applications with medium switching frequencies. Newly developed applications demand more stringent requirements like higher operation speed, smaller dimensions, and higher efficiency, which cannot be fulfilled anymore by Si-IGBT-based devices. The coming of SiC-MOSFET-based devices offers a promising solution. However, the replacement of Si-IGBT with SiC-MOSFET does not automatically ensure that the problem is solved. The high switching frequency of SiC-based components brings about various problems, including ringing and voltage surge problems.

In the Si-IGBT half-bridge inverter, an electrolytic capacitor is commonly used in the dc link to provide a more stable DC voltage and to limit fluctuations [17]. It also helps to buffer energy, decouple AC and DC systems, and stabilize the converter control [21]. However, as seen in Fig. 6, the simulation results show that the voltage surges are still appearing both in the dc-link voltage as well as in the inverter output voltage. The surge is often assigned to the combined effect of the parasitic inductance and the high equivalent series resistance (ESR) value of the electrolytic capacitor used, which was 100 milliohms.

When for certain applications it is required to use SiC-MOSFET to replace the Si-IGBT in the half-bridge inverter, as seen in Fig. 7 the simulation results still indicate the occurrence of voltage surges during the switching-on transient. The use of SiC-MOSFET as the switching component is preferable in certain applications with tight requirements of high switching frequency, small dimensions, and high efficiency. The high switching frequency of the SiC-MOSFET is responsible for the parasitic inductance effect causing the voltage surges.

It can also be noticed that the highest peaks of oscillation in Fig. 6, 7 reach even more than 40 % of the average oscillation wave value, being the potential to bring about the degradation of the device performance or even damage to it. A very high spike or surge in the voltage and current may give too high stress and harm the device. The devices must be designed to withstand high voltages or currents, which means higher costs, and it will also produce important losses.

It can also be observed in Fig. 6, 7 that the use of a SiC-MOSFET half-bridge inverter results in a higher amplitude of voltage surges in the dc link than the use of a Si-IGBT. It means that the use of a SiC-MOSFET to replace the Si-IGBT in the half-bridge inverter would require a special measure to take to reduce or even suppress the voltage surges in the dc link.

As consideration of dimension is sometimes demanding in some modern applications like transportation, renewable energy, automatization, etc., improvement of the function of the dc-link electrolytic capacitor cannot be accomplished just by enlarging the capacitance. The capacitor technology and type may bring an important influence. The electrolytic capacitor is the most common choice for the dc-link capacitor due to its high power density. However, with its resonant frequency of around 4 kHz, it is not sufficient to absorb the current ripple in the SiC-MOSFET-based inverter [17].

Another capacitor type of choice is the film capacitor, which is capable to handle high ripple current, though with lower capacitance. As seen in the simulation results in Fig. 8, the addition of a film capacitor in parallel to the electrolytic capacitor succeeded in eliminating the voltage surges in the dc link of the Si-IGBT-based inverter, although in the output voltage, there are still some small spikes. The addition of a film capacitor with a much lower ESR than that in an electrolytic capacitor takes the role of suppressing the voltage surges in the dc link. Much cleaner voltage waveforms are obtained in the case of the SiC-MOSFET-based inverter. Comparing Fig. 8 to Fig. 9 also shows that the difference between the dc-link voltage and the inverter output voltage in the SiC-MOSFET-based inverter is smaller than that in the Si-IGBT-based inverter. It indicates that with the same capacitor configurations in the dc link of both circuits, the voltage drop condition is better when a SiC-MOSFET is used as the switching component than a Si-IGBT. The SiC-MOSFET offers better efficiency.

Fig. 10 shows that the results shown in Fig. 9 could be obtained by using only a film capacitor in the dc link of a SiC-MOSFET inverter. It is reconfirmed to take the cautious measure to avoid the appearance of voltage surges both in the dc link and in the inverter output when using a SiC-MOSFET component. The type of capacitor used and the related value of ESR take an important role in this surge suppression.

The gate resistors, $R_{ON}$ and $R_{OFF}$, have also been examined to identify their influence on the voltage ringing occurrence. The value of $R_{ON}$ has been reduced from 10 ohms, as used in Fig. 1–10, to 2 ohms while maintaining the $R_{OFF}$ value of 1 ohm, as seen in Fig. 11, 12. It was found that the influence of the gate resistor reduction on the switching-on transient of the SiC-MOSFET half-bridge inverter was quite insignificant, although observable on the dc-link voltage. The ON resistance reduction produces the decrease in the switching or transition time of the MOSFET, and consequently the dipping of the dc-link voltage. However, if the voltage dip is sufficiently large, the voltage ringing in the dc link may occur.

In Fig. 15, a series of pronounced surges on the dc-link voltage (red curve) appears during the switching-on process. Being compared to the same curve in Fig. 16, it is indicated that the addition of a film capacitor can successfully dampen the occurring ringing in the dc-link voltage. The duration of the ringing occurrence can also be observed through the yellow curve, which represents the half-bridge output voltage. The transient period during the switching processes can be more easily examined. It can also be observed that the use of a film capacitor makes the positive and negative voltage of the dc link much more symmetrical during the switching-on transient period.

It should also be examined in the circuits shown in Fig. 2, 4 that the parallel connection of the film capacitor is done by putting it closer to the switching component. It is aimed to reduce the occurrence of parasitic inductance, as the longer the dc link, the higher will be the parasitic inductance.

During the simulation, the influence of the capacitor placement has been represented with the dc-link length. Three cases of dc-link length have been considered, which were 25 cm, 50 cm, and 100 cm. Fig. 17 presents the experiment results to observe the influence of dc-link length on the voltage surge of the SiC-MOSFET half-bridge inverter with a film capacitor, whereas Fig. 18 presents the case without a film capacitor.

In Fig. 17, the result *a* has been produced with a dc-link length of 25 cm, the result *b* with a length of 50 cm, and the result *c* with a link length of 100 cm. The red curve indicates the dc-link positive voltage, the green curve indicates the dc-link negative voltage, the yellow curve represents the half-bridge output voltage, whereas the blue curve represents the half-bridge output current. It can be observed that the most remarkable influence of capacitor placement is on the output current of the half-bridge. The longer the dc-link, the more obvious the half-bridge output current oscillation.

The same experiment on the circuit without a film capacitor shown in Fig. 18 indicates a similar phenomenon, except that the voltage surges of the half-bridge are very significant. Without a film capacitor, surges are found in all positive and negative dc-link voltage as well as the half-bridge output voltage and current during the switching-on transient. The placement of film capacitors is very important in voltage surge suppression. The closer the film capacitor to the switching component, the lower will be the surge amplitude due to the lower value of parasitic inductance produced.

The type of capacitor used is also very important. A film capacitor can be used to suppress the surge owing to its low value of ESR. The surge itself is caused by the parasitic inductance and the high switching frequency. The parasitic inductance depends on the conductor length used in the dc link.

Besides the conductor length, the shape of the conduction path also influences the severity of the parasitic inductance effect. Consequently, during the design of the printed circuit board layout, efforts must be made so that the power lines connecting the dc-link components are designed as straight as possible.

Very often long dc-link paths have to be considered because the large dimensions of the dc-link capacitor make it difficult to place it close to the switching components. Considering that many factors are influencing in the occurrence of voltage spikes, a trade-off is challenging to do during application designs.

In general, the simulation and experiment results emphasize the importance of the correct choice of dc-link capacitor type and size as well as its associated placement on the circuit board layout. Optimization of all these factors needs more elaborate investigation and development.

## 7. Conclusions

1. The use of either Si-IGBT or SiC-MOSFET as the switching components in a half-bridge inverter has the potential to produce a voltage surge in the dc link. The sharp change in voltage can be attributed to the stray inductance related to the components. The use of SiC-MOSFET produces a smaller difference between the dc-link voltage and the inverter output voltage, meaning lower losses.
2. The role of the capacitor in the dc-link may help to reduce the severity of voltage surge, however, the right choice of capacitor type influences the surge suppression efforts. An electrolytic capacitor is the right choice for the dc-link of a Si-IGBT half-bridge inverter, whereas a film capacitor is a right choice for the dc-link of a SiC-MOSFET half-bridge inverter.
3. The gate resistor influences more the decrease of the switching or transition time of the SiC-MOSFET. Its influence on the voltage ringing occurrence is quite insignificant, although observable on the dc-link voltage.
4. Simulation on the characteristics of voltage surge brings benefits before the device realization. Experiment results confirm the benefit of voltage-surge suppression using a film capacitor in the dc-link of a SiC-MOSFET half-bridge inverter.
5. The occurrence of parasitic inductance is also influenced by capacitor placement in the circuit board of the device. The parasitic inductance can be lowered by putting the film capacitor as close as possible to the switching component.

## Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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## Data availability

The manuscript has no associated data.

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