Switch Short-Circuit Fault Detection Algorithm based on Drain-to-Source Voltage Monitoring for a Fault Tolerant DC/DC Converter

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Abstract*—Switch Short-Circuit Fault (SSCF) is one of the most harmful failure mode in a DC-DC Converter. As a consequence, the earliest identification should be ensured in order to avoid the shutdown of the whole system. In this paper, a fast and simple method is introduced for detecting and identifying the faulty leg caused by a SSCF in a six-phase Interleaved Boost Converter (IBC) for Fuel Cell Vehicle application. The proposed detection technique is based on a comparison between the power MOSFET Drain-to-Source Voltage V_{DS} in ON state with an adjustable threshold voltage $V_{DS\text{-}ON\text{-}TH}$ by using only control pulses and driver information. After the fault detection, and its isolation, remedial actions by control reconfiguration methodology are applied to allow the DC-DC converter to operate in pre-fault conditions. To confirm the effectiveness of the suggested approach, simulation tests are reported using Matlab/Simulink© and ANSYS/Simplorer©. Also, comparative study between the developed voltage-based method and current-based method is provided by numerical simulations. The results obtained by the proposed method indicate that the SSCF can be detected not only in switch ON state but also in OFF state by adding some modifications to the proposed algorithm. In switch OFF state, the results prove similar behavior detection time for both the methods which detects fault occurrence in less than one switching period. By contrast, for the ON state, the proposed method detects the failure for a 100 kHz frequency using the voltage information provided by the driver. The advantage of this method is that the detections are valid in both states (ON and OFF), the suggested algorithm is simple, and easily configurable.

Keywords—Short-Circuit Fault, Switch Failure Diagnosis; Fault Tolerant Converter; Interleaved Boost Converter; Fuel Cell.

I. Introduction

DC-DC converters are widely used in many fuel cell decarbonized applications such as light transportations (vehicle), heavy transportations (trucks, train…), aeronautics, among others. In such applications a high level of reliability and efficiency is required. For that reason, fault diagnostic, control strategy and fault tolerant strategies must be integrated to protect the fuel cell (avoid current ripple, hydrogen overconsumption), the converter (break of the chip) and the load [1-3]. These systems typically contain more than a dozen of switching devices [4], and the probability of the semiconductor device failure is much higher than in other application areas with more than 30% of the dysfunctions [3]. Switch failures can be categorized into two major groups: Short-Circuit Fault (SCF) and Open-Circuit Fault (OCF). Compared to OCF, SCF causes more harmful effects on converter circuit. For this reason, earlier fault diagnosis remains the most important task that allows the SCF detection and identification of its location.

Recent researches have studied diagnosis and fault tolerance in case of switch failures. Authors in [5] propose a switch OCF and SCF detection method for boost converters based on the sign of the inductor slope. This method detects faults with a limitation law over the duty cycle (D) that must be considered to avoid false fault detection due to non-ideal behavior of power switches, delays and dead times. It needs one switching period to detect a fault in an OFF state. This fault detection criteria is used in some other works such as in [4], [6], and [7]. In [8] the detection technique proposed to identify the short circuited cell in a cascade H-bridge inverter is based on the comparison of the output voltage V_{out} with a reference value V_{ref} which is produced by using DC-link voltage and switching pulses. The difference between them is called “error” and according to its value a fault alarm ERROR is generated to indicate the presence or absence of a fault. The cracked cell is detected as faulty cell in 670µs that corresponds to less than four switching periods. However, few papers have proposed Switch Short Circuit Fault (SSCF) Diagnosis approach by sensing its Drain-to-Source voltage rise [9, 10]. In [9], the authors indicate that switch fault detection can be achieved by monitoring its gate-to-source voltage V_{GS} or its drain-to source voltage V_{DS}. In [10], a self-powered solid state circuit breaker (SSCB) concept was introduced using a normally-on SiC JFET as the main static switch and a fast-starting isolated DC-DC converter as the protection driver. The proposed SSCB detects short circuit faults by sensing its drain-source voltage rise and draws power from the fault condition to turn off the SiC JFET. It has been shown that this SSCB demonstrates a fault current interruption capability up to 180A at a DC bus voltage of 400V within 0.8µs.

This paper investigates a SCF diagnosis of power switches and proposes a Reconfiguration Strategy (RS) of the faulty 6-phase Interleaved Boost Converter (IBC) to recover its pre-fault operation. This converter topology, depicted in Fig. 1, is selected for the following advantages: reducing the fuel cell input current ripple to preserve its performance and lifetime, the volume of passive elements (inductors) and the cost. In addition, by paralleling the phases, the modularity of the converter could enable, if one of the phases becomes out of work, a continuity of service by using the N-1 healthy phases [6]. In the considered application, “fault tolerant” property means the DC/DC converter is able to operate with no interruption of the full power flow from the fuel cell source to the DC load, even when a fault occurs. This converter is considered fault tolerant because after short-circuit detection, identification and isolation, it can continue supplying power from the source to the load with a reduced phase number which is not the case for the conventional boost (one leg) converter that is sensitive to faults and leads to unavailability of the structure when a fault occurs. Fuses have been added to ensure the phase protection and fault tolerance (FT).

The objective is to propose a simple and non-intrusive SSCF diagnosis method which employs Drain-to-Source voltage V_{DS} waveform as a fault indicator. By using switching Pulse Width Modulation (PWM) control pulses, the developed algorithm compares the measured voltage V_{DS}, taken from the gate driver, with a parametrized threshold voltage value, noted by $V_{DS\text{-}ON\text{-}TH}$. The advantage of this fault detection algorithm is that it is assisted by the switch driver which detects an over-current using a fixed hardware threshold on the card, as an alarm to SSCF method. The specificity of developed method relies on the fact that the detection threshold $V_{DS\text{-}ON\text{-}TH}$ is adjustable according to the operating conditions and load power. After the fault identification and isolation, a FT Strategy for the 6-phase IBC is applied to ensure a continuity of service of the FC electric vehicle in healthy/degraded operation modes [3], [11].

In order to prove the effectiveness of the proposed fault detection method, a comparative test study between the actual voltage approach with the diagnosis methodology scheduled in [5] based on current criteria is provided by numerical co-simulation results coupling MATLAB/SIMULINK© (PWM control part implementation) and ANSYS/SIMPLORER (system implementation part: FC Source (70V, 300A) + IBC interface (100 kHz) + DC load (350V)). For this high switching frequency F_{SW} and low DS bus voltage, a MOSFET is chosen as a semiconductor power-switch for the studied IBC. To improve the system reliability and robustness, semiconductors based on Silicon Carbide (SiC) technology are used [12]. In fact, these components have shown better performances at extreme conditions compared to the Silicon (Si) ones. For example, a planar SiC MOSFET can withstand a short-circuit during 15 µs at V_{GS} = 18 V and only after 30 repeated events of the short-circuit test the degradation process begins and involves the ageing of the power switch [13]. The IBC has been designed using a CAS120M12BM2 SiC Half-Bridge Module (C2M MOSFET and Z-Rec Diode) of 1200V/120A ratings manufactured by CREE (Wolfspeed Group) [14].

This paper is organized as follows: Section2 explains in details the suggested SSCF for the 6-phase IBC operating in unidirectional power flow in Continuous Conduction Mode (CCM). Moreover, in this section, remedial actions allowing the converter to work in pre-fault operation condition are proposed. Section 3 details the simulation results which indicate the potentialities of the proposed method for ON and OFF states compared to an existing one. Conclusions and future works are presented in the last Section.

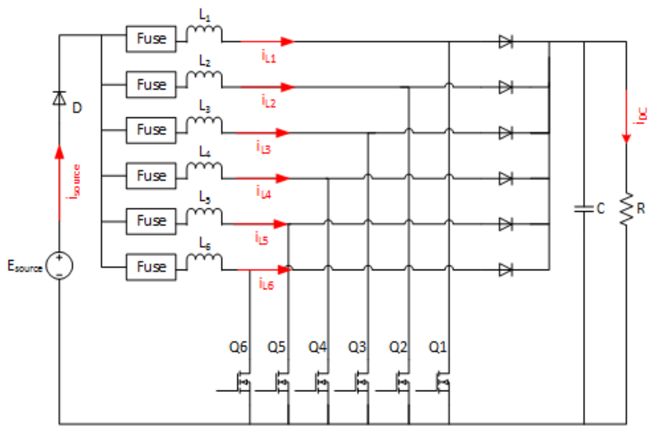

Fig. 1. Fault Tolerant IBC.

II. Switch Short Circuit Fault Detection Method

A. *Fault Diagnosis Methodology*

To achieve fault detection function in the proposed converter, one way is to monitor switch electrical characteristics. In the case of a MOSFET chip, there are two ways to identify the breakdown. The first way is to check the MOSFET switching action by inspecting its gate-to-source voltage V_{GS}. The second way is to measure the drain-to-source voltage V_{DS} [9]. The proposed fault detection method is based on the second one, especially the $V_{DS\text{-}ON}$ when the switch is ON, to detect fault occurrences. This method only needs the gate voltage V_{GS} imposed by the switching PWM command signal sensored V_{DS} and an imposed threshold voltage $V_{DS\text{-}ON\text{-}TH}$ to detect a faulty switch. The fault detection algorithm is performed online during system working, its instance named as T_{test} corresponds to the moment when the switch is in the middle of the ON state. This time is obtained periodically in the same way explained in Fig. 2. It is considered to be the most appropriate moment for diagnosis task because of the following reasons: ON states are well established, all types of delays are exceeded, so all false detections are avoided [15].

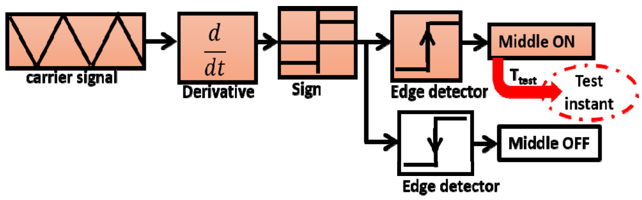

Fig. 2. Fault detection time generation.

In healthy converter operating mode, the value of V_{DS} is equal to $V_{DS\text{-}ON}$ when the switch is ON (Switch PWM Command =1 during [0, DT_{SW}]) and it is equal to the bus voltage V_{DC} when the switch is OFF (Switch PWM Command =0 during [DT_{SW}, T]) as shown in Fig. 2. In the case of SSCF, the V_{DS} signal waveform is distorted and its $V_{DS\text{-}ON}$ value continues rising as depicted in Fig.3 in dysfunction condition function part. Fault alarm BIN is generated by comparing the monitored signal $V_{DS\text{-}ON}$ (T_{test}) with the imposed threshold voltage $V_{DS\text{-}ON\text{-}TH}$; if no fault is determined BIN is equal to "0" or else it sends "1" to reveal a SSCF propagating and warn FT strategy to intervene in protecting the components of the faulty leg, the IBC, the FC source and the DC bus against harmful impact of this dangerous fail.

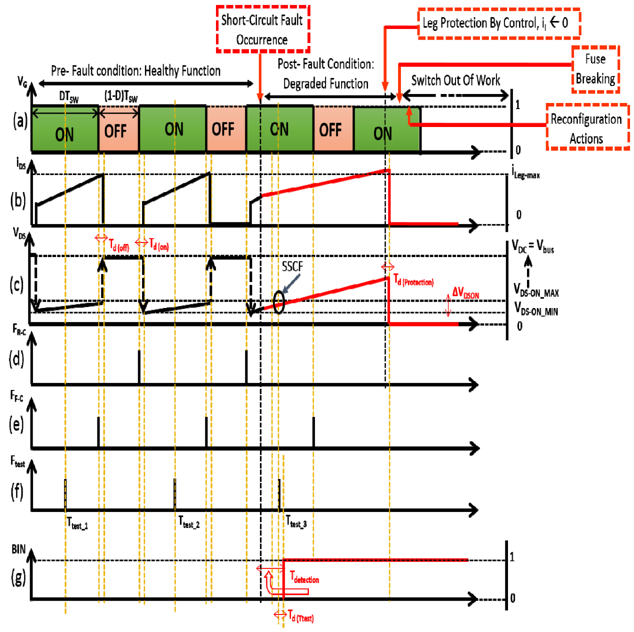

Fig. 3. Waveforms of the power switch before and after the short-circuit fault : (a) PWM switch command signal, (b) Drain-to-Source current i_{DS}, (c) Drain-to-Source voltage V_{DS}, (d) Rising edges of switch command, (e) Falling edges of switch command, (f) Diagnosis instants, (g) Fault alarm signal.

B. *Threshold voltage VDS-ON-TH calculation*

The fault detection algorithm needs the value of $V_{DS\text{-}ON\text{-}TH}$ to detect and identify the faulty switch. This parameter is imposed by taking into consideration the I_{DSrms} current amplitude and the ripple introduced by the PWM switching. The level of the $V_{DS\text{-}ON\text{-}TH}$ threshold is set taking into account a margin (gain) in order to avoid false fault detection, or alarm in particular also during load variation. The margin should be taken above the rated voltage ripple. The synoptic of the threshold definition is shown in Fig. 4. Hence, the threshold can be parameterized in function of the operating conditions. This strategy is more adjustable, following the application, in comparison to the driver monitoring for which the V_{DS} monitoring is fixed on the hardware card. In order to have an efficient detection strategy, the $V_{DS\text{-}ON\text{-}TH}$ threshold should be taken lower than the fixed driver threshold. It has been observed that for a value of 2V the implemented algorithm generates a fault. The proposed method for the calculation of $V_{DS\text{-}ON\text{-}TH}$ is explained in Fig. 4 and the Table 1 summarizes different parameters of an operating mode.

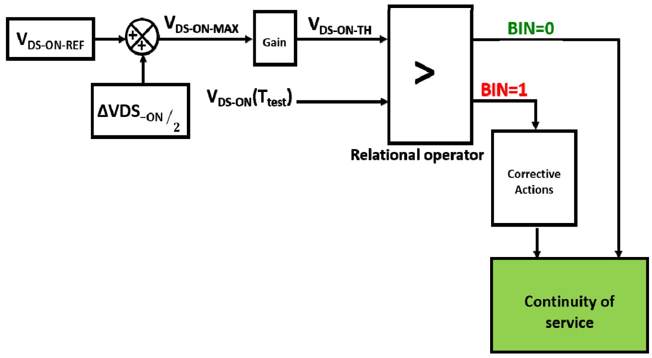

Fig. 4. Fault diagnosis diagram.

Table 1. Parameters of the proposed fault detection method

Parameters	Value
V_{GS}	20V
I_{DS}	50A
$V_{DS\text{-}ON\text{-}REF}$	0.65V
$\Delta V_{DS\text{-}ON}/2$	0.045/2V
$V_{DS\text{-}ON\text{-}MAX}$	0.672V
$V_{DS\text{-}ON\text{-}TH}$	2V

III. Fault Tolerant Strategy

After the fault detection and identification thanks to the implemented fault detection algorithm, a fault tolerant control is applied to enable a degraded operation mode even if a short-circuit on a power switch fault has been detected and isolated. This action consists in three steps; 1) Release the faulty phase by imposing a zero current, 2) Fault isolation by the switch-off control of a fuse at the instant of detection, 3) Reconfiguration of converter control algorithm in N-1 healthy phases. A chronological sequence of the methodology is shown in Fig. 5, the steps are explained hereafter.

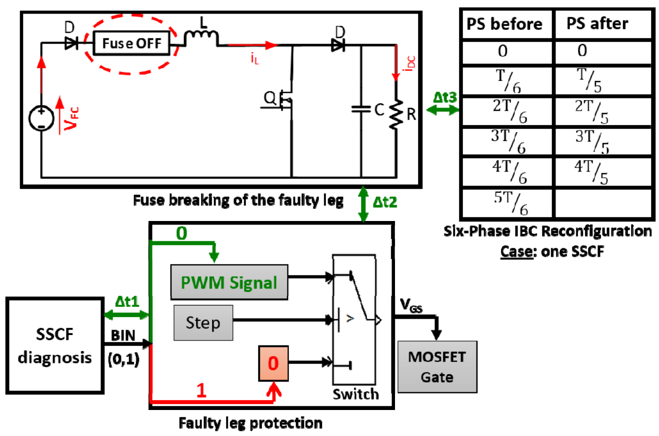

Fig. 5. Fault tolerant Strategy/Control.

A. *Release of the phase current constraint*

Once the fault is detected and localized, control regulation imposes a zero current for the defective leg and distributes the

FC current amplitude to the IBC healthy phases as depicted in Fig. 5. This is very beneficial in protecting different converter elements (inductor, diode, MOSFET) of the faulty phase and avoid component's stress before fuse melting. Without this technique, a spark may appear after a sudden fuse cut and damage the load, the converter and even the FC source.

B. Fault isolation and reconfiguration strategy

After the distribution of the current delivered by FC source for healthy phases and forcing current annulation of the faulty leg, the fault can be isolated properly [14] and [15]. This can be done by means of a fast-acting fuse with no time delay which has the capability to clear the electrical short-circuit by breaking the faulty leg without any observable damage or arcing events inside the pattern loop. Here, the fuse was installed in the input side of each leg to avoid costly damage on different circuit components. In Simplorer© software, the fuse was modeled by a normally ON ideal switch in healthy conditions and which turns OFF when an overcurrent is detected by the proposed fault detection method. In practice, the selection of an appropriate rating of a fuse is based on further features such as: the melting time, nominal fuse melting integral $I^2t_{Nom.Melt}$ (the amount of energy necessary to blow the fuse) and the fuse current rating (which must be lower than the switch current rating). In addition, for this DC application, the fuse has to withstand at least the applied DC source voltage at the current zero crossing [16], [17], and [18].

Once the fault is safely interrupted, the fault tolerant converter continues operating and supplying power to the load but with more ripple rate on FC current. This is due to the loss of faulty leg(s) and to nonsuitable phase-shift between the remaining healthy legs. Hence, to improve the fault tolerance behavior of the studied IBC, control must be readapted using only healthy legs as shown in Fig. 5 in order to maintain the same pre-fault ripple rate condition. Therefore, the fault tolerance capability of the IBC is enhanced by the fault tolerant action of PWM control without adding any additional components to the basic circuit.

IV. SIMULATION RESULTS

A. Fault detection algorithm validation

In previous sections the proposed fault detection algorithm was presented in a working model with a detailed analysis. A co-simulation results between Matlab/Simulink© and ANSYS/Simplorer© is carried out as shown in Fig. 6. Parameters of the studied system are given in Tab. 2.

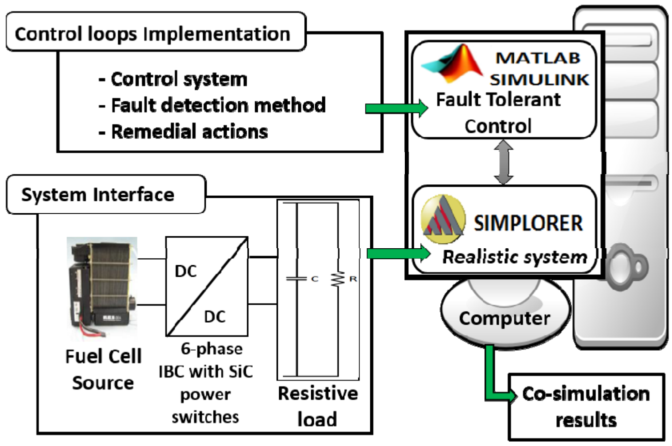

Fig. 6. Co-simulation principle between Matlab/Simulink© and ANSYS/Simplorer.

Table 2. Parameters of the SiC Boost Converter [19]

Elements	Value
L	200µH
C	500µF
R	6,4Ω
$R_{DS(ON)}$	0.013mΩ
F_{SW}	100kHz
D	80%

B. Fault detection method simulation results

This subsection details the different steps of the proposed fault detection method implemented in Matlab/Simulink©. First, the SSCF was created on the sixth power switch of the studied converter by connecting it in parallel with a normally-off ideal switch which switches-on at t_{fault} (fault occurrence instant) to create a fault. After the fault occurrence at t_{fault} = 12ms, the SSCF is detected through the fault detection algorithm in 200µs as depicted in Fig. 7, simultaneously control regulation releases the phase current constraint (imposes a zero current on the defective leg and $I_{FC}/5$ for healthy ones) and the controlled fuse melts before converter reconfiguration.

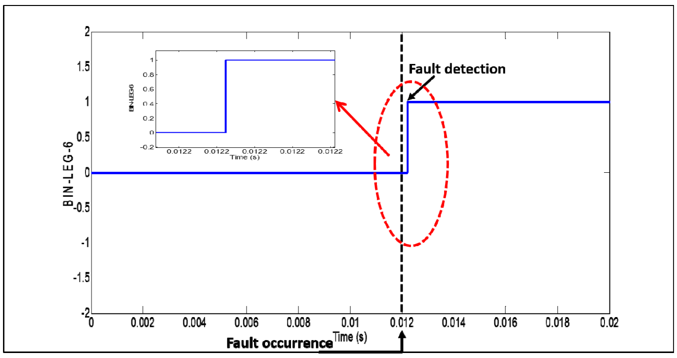

Fig. 7. Switch Short-Circuit fault detection with a duty cycle around 80%.

C. Fault impacts

The response of the system when a SSCF appears is given in Fig.8, Fig. 9 and Fig.10.

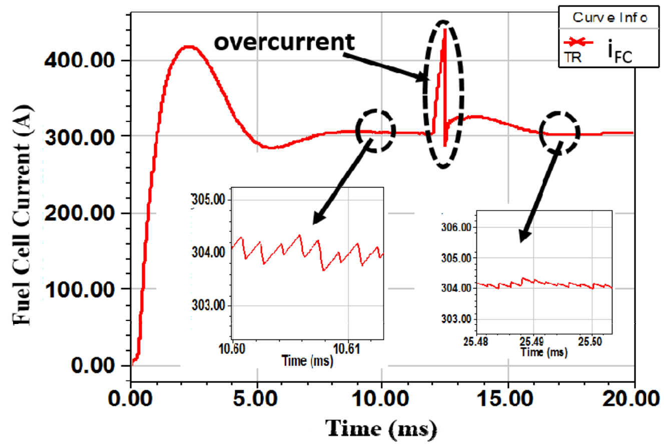

Fig. 8. Fuel Cell current (A).

In degraded mode, overcurrent and increase of fuel cell current ripples have been observed. For this reason, fault tolerant strategy is mandatory to reduce these effects. As shown in Fig. 8, current ripples get its initial state after fault diagnosis. In Fig.9 it can be seen that healthy MOSFETs are subjected to an electrical stress due to the fault occurrence. A transition from six legs (phase shifted by T/6) to five legs (phase shifted by T/5) after fault isolation and converter reconfiguration is performed to solve this problem.

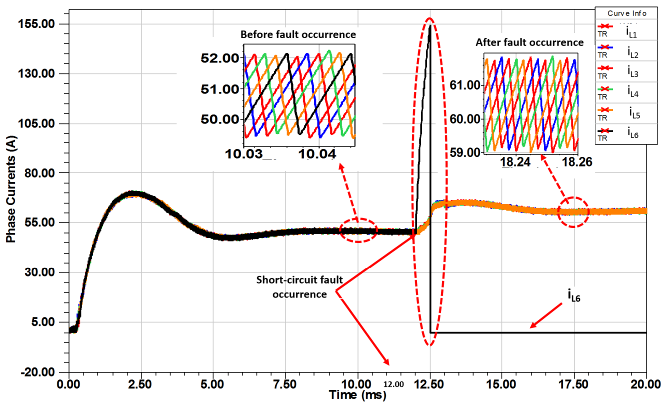

Fig. 9. Phase currents (A).

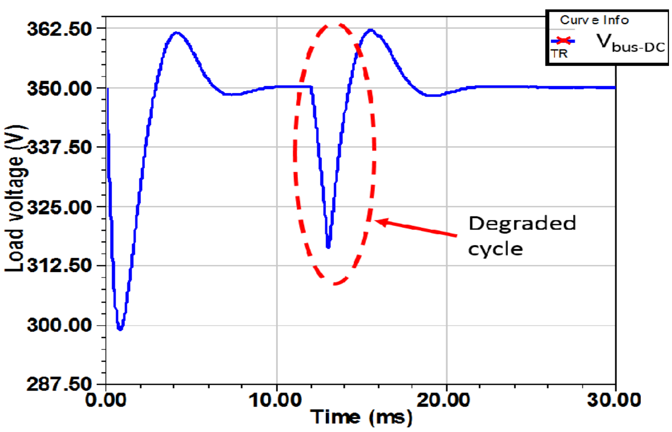

Fig. 10. DC load voltage (V).

In Fig. 10, it can be concluded that the implemented command controls the output load at a voltage value of 350V. In case of a fault occurrence, overvoltage is noted. After fault diagnosis, the command regulates the voltage on the nominal value.

D. Comparative Study By Simulation Tests

Comparative test is performed between the voltage-based detection method developed in this paper and another current-based method presented in [5]. The two detection approaches are applied on the same studied system for identical switching frequency (F_{SW} = 100 kHz) and test monitoring conditions (switch OFF state). The simulation result shown in Fig. 11 highlights dynamic behaviors of both methods when a fault occurs. It can be seen that both algorithms give the same fault detection time performance: fault alarm (BIN) changes its value from '0' to '1' in less than one switching period to indicates a fault occurrence. This result demonstrates the ability of the proposed method to detect a Short-Circuit fault not only in switch ON state but also in switch OFF state that is not the case of the current-based algorithm that diagnoses only in OFF switch state for a SSCF occurrence.

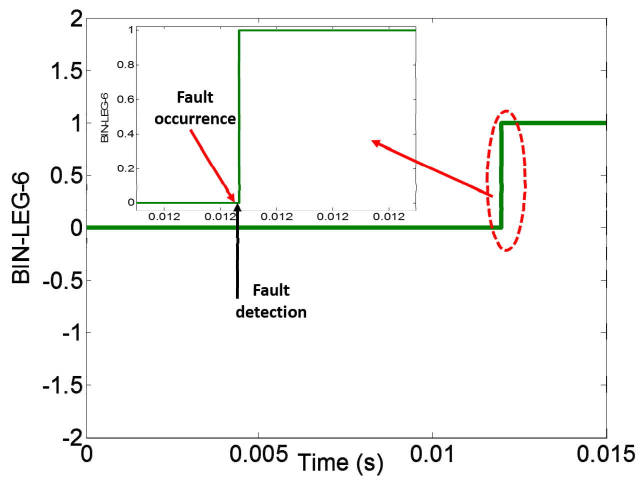

Fig. 11. Voltage-based method and Current-based method (diagnosis in an OFF switch state).

V. CONCLUSIONS

This paper has presented a study about the fault detection method and a fault tolerant control of a power switch short-circuit fault in 6-phase IBC. It has been seen, from simulation results, that the maximum required time to detect a switch failure by the proposed fault detection method in an ON switch state (without adding any extra sensors) is 200µs and less than one switching period for an OFF state. Also, a comparative study between the proposed detection algorithm and another one for switch OFF states demonstrates the interest of the suggested algorithm: the proposed method is adaptable for both ON and OFF switch state, and also the voltage threshold used is adjustable depending on the operating conditions and semiconductor technology.

In the future, the validity of this algorithm for small duty cycles will be studied. Also the validation of the detection method in the Discontinuous Conduction Mode (DCM) must be discussed. Indeed, for the DCM mode, the detection strategy should utilize the zero-current time intervals during the switching period, in order to switch-off the legs at reduced losses. Moreover, for low power flow, the DCM mode should be less current constraining for the SiC power transistors. Certainly the DCM mode should be the opportunity to investigate other specific detection and isolation strategies. In addition to prospective works, the control of the transients appearing in the SiC MOSFETs at high switching frequencies should also be investigated, and the possibility to replace the fuse by a controlled semiconductor already available in the switch packaging will be employed. Moreover, the MOSFET junction temperature increases with a short-circuit fault occurrence and so, it will be important to investigate if there is a swing of the threshold $V_{DS\text{-}ON\text{-}TH}$ with temperature.

VI. ACKNOWLEDGMENTS

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