Reliability improvement of multi-phase interleaved DC-DC converters for fuel cell electric vehicle applications

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ABSTRACT

This paper suggests a fast and low-cost method that can be applied in several DC/DC converter topologies for detecting open circuit faults (OCFs) and short circuit faults (SCFs). The suggested method may identify the faults of several power switches even if they occur simultaneously in multi-phase interleaved boost converter (MPh-IBC) by using just the sensors needed to control the converter. This fault detection method (FDM) is based mainly on comparing the measured inductor current and two fault detection thresholds, one for OCFs detection and the other for SCFs detection. This method combined with a corrective strategy to mitigate the negative impacts of OCFs, particularly the significant rise in the ripple of the DC bus voltage and the fuel cell (FC) current, which reduces FC aging and converter reliability. The simulation findings indicate the FDM's excellent performance and speed, as well as its usefulness in detecting defects of many power switches in the converter, with a fault detection time of up to 1.7 µs. The acquired findings further show the excellent effectiveness of the corrective strategy in reducing these ripples in the event of one or two faults.

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1. INTRODUCTION

Fuel cell electric vehicles (FCEVs) are the best future replacement for conventional cars to reduce pollution and fossil fuel shortages [1], [2]. In general, an FCEV powertrain consists of many components. This article considers only the fuel cell (FC) and power electronic converter interface. The FC fueled by hydrogen and air is a very environmentally friendly clean generator as it only produces electricity, heat, and water [3], [4]. The proton exchange membrane fuel cell (PEMFC) is one of the most favorable technologies available for FCEV applications [5]–[7] due to its solid electrolyte, high efficiency, low operating temperature, and relatively small size [8]–[10]. Indeed, PEMFC stacks generate relatively low voltages that need to be boosted to high voltage levels [11], which are between 270 and 540 V in electric vehicles (EVs) [12]. Typically, a DC/DC boost converter is used in this range [13]. However, these converters have some disadvantages for these applications, especially the reliability of maintaining their function in the event of a failure in the power switch. The most prevalent faults in these switches are the open circuit faults (OCFs) and the short circuit faults (SCFs) [14]. Both of these faults can damage other components in the power conversion system. Therefore, these faults must be treated quickly and carefully. The reliability of this converter is usually related to using dynamic redundancy by adding a redundant phase [15]–[17]. However, using this redundancy increases the converter's costs and complexity. Interleaved boost converter (IBC) topologies are regarded as efficient alternatives to avoid using this redundancy. FC applications benefit from this converter topology; it is modular, highly efficient, reliable, and reduces FC current ripple [18]–[20]. IBC topologies' main benefit is that they continue to provide power to the load even if OCFs are in switches. However, the degraded mode harms the FC and reduces converter reliability. This study proposes a corrective strategy to reduce these undesirable effects. Indeed, applying this strategy is related to the location of the faulty phases. So, developing a fast power switch fault detection (PSFD) method is necessary.

Few papers have proposed PSFD methods for IBCs. Research by Shahbazi *et al.* [21], the OCF detection method for 3-Ph IBC compares the inductor current slope with their estimated values is proposed, with identifying faults in 40 µs. Research by Ribeiro *et al.* [22] the same converter's OCF is detected using the input current derivative sign in defective and healthy modes with three switching periods for fault detection. However, no corrective strategy has been reported after locating defects in the previous two papers. Research by Yahyaoui *et al.* [23], drain-to-source voltage monitoring is used to detect SCFs in 6-Ph IBCs in 200 µs. Research by Guilbert *et al* [24], an OCF detection method based on Park's vectors joined with a remedial strategy for a 3-Ph IBC is proposed. Research by Guilbert *et al.* [25], a PSFD method with a reconfiguration strategy of operating degraded mode for 4-Phase Floating IBC is developed, where the fault detection method (FDM) is based on Park's vector. In contrast, the reconfiguration strategy eliminated another healthy phase in the non-defective part (floating or non-floating).

Although the FDMs in some of these papers are quick and inexpensive in others, most of these methods are used in specific types of converters or vary depending on the converter type or according to the number of phases in multi-phase IBC (MPh-IBC) topologies. Moreover, most of the FDMs reported in the previous articles cannot detect more than one PSF in the converter. Some of the corrective strategies presented in these papers can only deal with one faulty phase. This paper's main contribution is developing a quick and low-cost method for detecting both OCFs and SCFs for several switches in an MPh DC/DC converter. This method is suitable for several DC/DC converters. In addition, a corrective strategy is offered in this research to be used when these faults are detected to enhance FC performance, lengthen its lifespan, reduce hydrogen consumption, and improve the reliability of this converter.

2. MATERIALS AND METHOD

2.1. Four-phase interleaved DC/DC boost converter and roton exchange membrane fuel cell stack

In this study, the interface between the PEMFC stack and the load has been created using a 4-Ph IBC. Each phase consists of an inductor (Li), a diode (Di), and a power switch (Si). The four phases are linked in parallel with a filtering capacitor (C). To avoid SCF risks, simple switches (Sni) have been added to each phase to isolate the faulty phase when this fault occurs. To protect against these potential faults, we may also put a fuse (F) in series with the PEMFC stack.

Additionally, we link this stack in series with a diode (D) to shield it from feedback currents. The remainder of the FCEV power train has been considered a resistive load for simplification in this study. Figure 1 shows the 4-Ph IBC and PEMFC stack associated with this converter's controller, the FDM, and the corrective strategy. In this converter, the pulse-width modulation (PWM) gate control signals (GCSs) of the power switching devices have been successively phase-shifted by Ts/4. This shift lets reducing the input current ripple. The current delivered from the PEMFC stack is shared evenly between phases; this reduces the inductor's size by four times compared to the conventional boost converter and provides a smaller size of semiconductors. The inductor values are determined so the PEMFC current ripple ratio does not exceed 4% of the rated PEMFC. Besides, an electrical model of the PEMFC stack has been implemented in the MATLAB/Simulink environment and connected to this converter as a power source. Table 1 summarizes the system specifications.

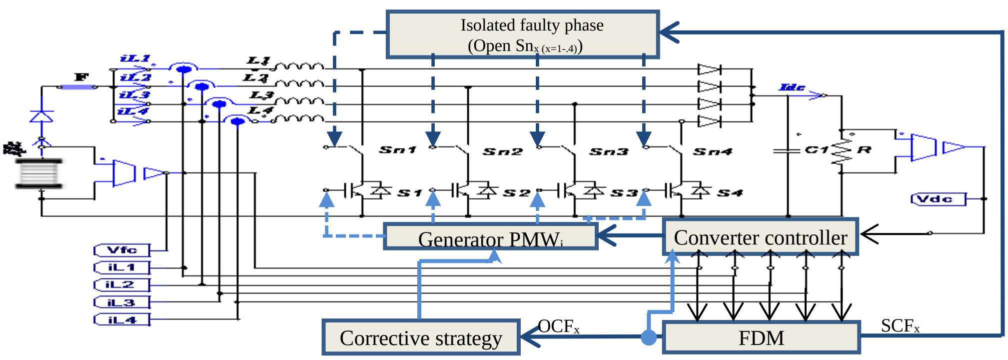


Figure 1. The 4-Ph IBC associated with the FC, the converter controller, and the FDM and the corrective strategy

Table 1. System specifications

Parameters	Variable
FC power, P_{FC}	21 KW
FC voltage, V_{FC}	70 V
FC current, I_{FC}	300 A
DC bus voltage, V_{dc}	360 V
Switching frequency, F_s	10 Khz
Inductor, L	130 µh
Capacitor, C	495 µf

2.2. Fault detection method and corrective strategy

2.2.1. Fault detection method

The FDM proposed can detect both the OCFs and the SCFs of multiple switches in MPh-IBC topologies. This method is low-cost and doesn't require additional sensors; it uses just the sensors already used to control the converter. The principle of the FDM is given in Figure 2.

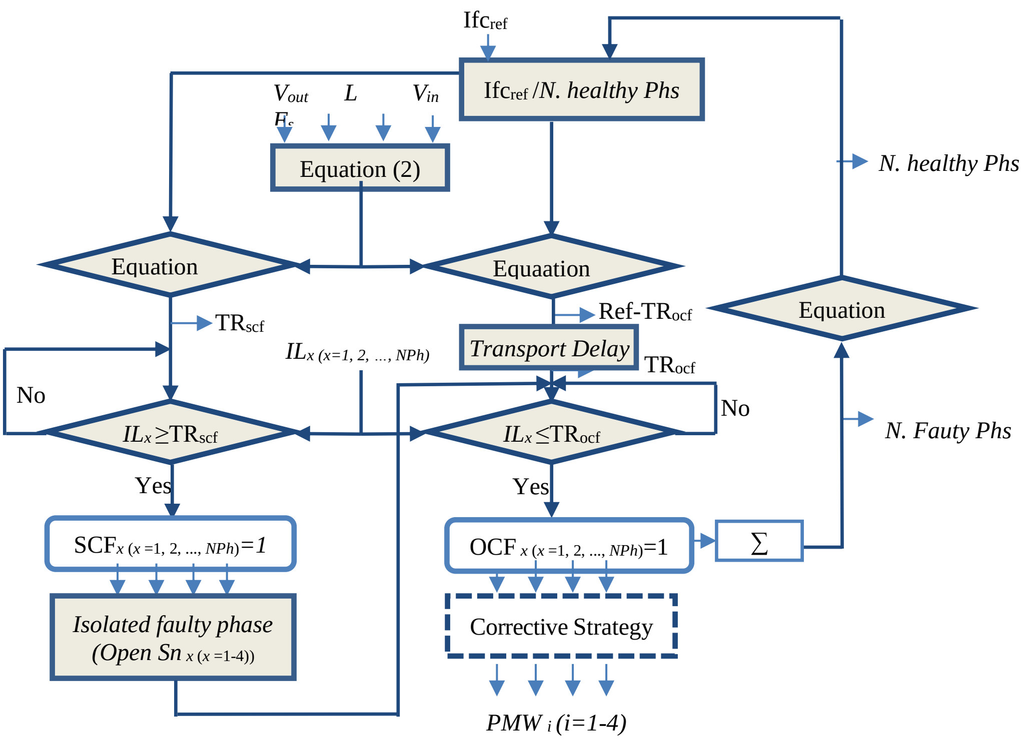


Figure 2. Schematic diagram of the suggested FDM and the corrective strategy

The basis for this method is principally to compare the inductor current measured for each phase (iLx) with two fault detection thresholds, one for OCFs detection (*TRocf*) and the other for SCFs detection (*TRscf*). These thresholds are determined by the total current reference (ifc_{ref}), the number of healthy phases (N. healthy Phs) of this converter, and the inductor current ripple (ΔiL). The ifcref is obtained from the outer loop of the converter control. In contrast, the N. healthy Phs are determined by subtracting the total number of phases in healthy mode (N. Ph *conv-healthy mode*) from the number of faulty phases (N. faulty Phs), which this latter is obtained through the sum of OCFs detection signals for each phase, which is '1' in the case of fault detection and '0' in the absence of a fault. The N. healthy Phs and the ΔiL can be respectively expressed as (1) and (2):

$$\text{N. healthy Phs} = N.Ph_{\ conv-healthy\ mode} - \sum OCSF_X \tag{1}$$

$$\Delta i_L = \frac{D.V_{in}}{L.F_s} \tag{2}$$

where *D* is the duty cycle, *Fs* is the switching frequency, and *L* is the inductor value.

To avoid the problem of misdiagnosing faults, 58% of the inductor current ripple has been adopted for the determination of the two fault detection thresholds, where the following expression determines the reference OCF detection threshold (*Ref-TRocf*):

$$Ref - TR_{ocf} = \frac{ifc_{ref}}{\text{N.healthy Phs}} - 58\%\ \Delta \mathrm{i}_L. \quad (3)$$

This reference threshold has been linked with transport delay to obtain the OCF detection threshold (*TRocf*) to avoid misdiagnosis of OCFs, especially when adjusting the N-healthy Phs after detecting OCFs, which rapidly changes the inductor current reference (iLref) and reference threshold. The following expression determines the SCF fault detection threshold (*TRscf*):

$$TR_{scf} = \frac{ifc_{ref}}{\text{N.healthy Phs}} + 58\%\ \Delta \mathrm{i}_L. \quad (4)$$

Finally, the OCFs are detected when the inductor current value for each phase is equal to or less than the *TRocf*, while the SCFs are detected when the inductor current equals or crosses the *TRscf*. Also noted is that when the FDM detects an SCF, the defective phase is isolated by opening the switch (Sni) of that phase, resulting in the fault becoming an OCF after this step. As a result, the FDM moves directly to the step that detects OCFs. In the end, when an OCF is detected, the signals are relayed to the corrective strategy, which then modifies the phase shift of the power switches' control signals between the remaining healthy phases.

2.2.2. The corrective strategy

Within this work, OCFs have been investigated. The loss of one or two phases in the 4-Ph IBC causes an increase in the ripple of the PEMFC and the DC bus voltage, which causes additional power losses and reduces the converter's reliability. This work provides a solution by offering a corrective strategy that doesn't require adding extra components to this converter to reduce these increases. This strategy depends on precisely adjusting the GCSs between the remaining healthy phases according to the faulty phases detected by the suggested FDM. Table 2 shows the corrective strategy that must apply to the 4-Ph IBC according to the defective phases provided by the FDM. If the switch is defective, this method sends logic "1" to the corrective strategy. As a result, the new GCS replaces the old GCS, taking the appropriate phase shift from the previous table into account. While the converter is in a healthy mode, this FDM sends the logic "0" to the corrective strategy. This strategy allows for managing the failure of one or two power switches. The faulty phase detection signals have been connected to gates and logic circuits to ensure the correct shifting of the remaining healthy phases.

Table 2. The corrective strategy applied according to defective phases

Faulty phases	Corrective strategy to apply
Phase 1	1) modify the Ph-shift of Ph 3 (from Ts/2 to 7Ts/12). 2) modify the Ph-shift of Ph 4 (from 3Ts/4 to 11Ts/12).
Phase 2	1) modify the Ph-shift of Ph 3 (from T/2 to T/3). 2) modify the Ph-shift of Ph 4 (from 3T/4 to 2T/3).
Phase 3	1) modify the Ph-shift of Ph 2 (from T/4 to T/3). 2) modify the Ph-shift of Ph 4 (from 3T/4 to 2T/3).
Phase 4	1) modify the Ph-shift of Ph2 (from T/4 to T/3). 2) modify the Ph-shift of Ph 3 (from T/2 to 2T/3).
Phases (1 and 2)	1) modify the Ph-shift of Ph3 (to T). 2) modify the Ph-shift of Ph 4 (to T/2).
Phases (1 and 3)	1) modify the Ph-shift of Ph2 (to T/2). 2) modify the Ph-shift of Ph 4 (to T).
Phases (1 and 4)	1) modify the Ph-shift of Ph2 (to T/2). 2) modify the Ph-shift of Ph 3 (to T).
Phases (2 and 3)	modify the Ph-shift of Ph 4 (from 2T/3 to T/2).
Phases (2 and 4)	modify the Ph-shift of Ph3 (to T/2).
Phases (3 and 4)	modify the Ph-shift of Ph2 (from T/3 to T/2).

3. RESULTS AND DISCUSSION

To verify the proposed FDM's performance and speed, as well as its ability to detect faults in several power switches in the MPh-IBC, and demonstrate the efficacy of the proposed corrective strategy in reducing the negative impacts caused by these faults. Numerical simulations with and without applying this strategy have been performed. The FDM, the corrective strategy, the electrical model of the PEMFC stack, the power circuits of a 4-Ph IBC, and its control have all been implemented in MATLAB/Simulink.

3.1. Effects of faults without applying the corrective strategy

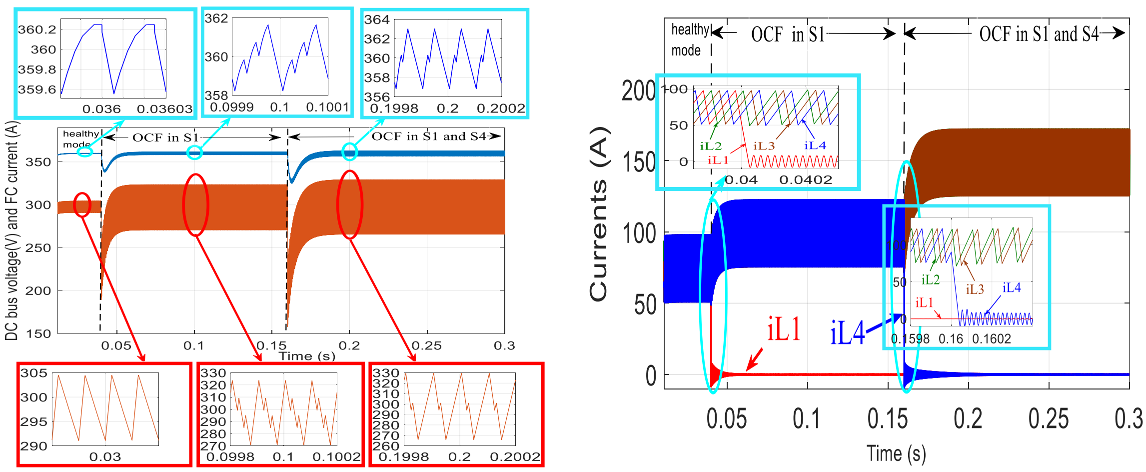
Because the effects of SCFs are well-known in the literature, only the effects of OCFs are investigated in this section. The SCF leads to a substantial and rapid increase in the currents of inductors and FC, which can cause damage to both of these components and the remainder of the circuit. As a result, SCF must be detected precisely and rapidly to isolate the faulty switch and avert system damage.

OCFs have been simulated in power switches S1 and S4 at the following times (t1=40 ms, t2=160 ms, respectively) to identify the effects of one or more OCFs on the 4-Ph IBC and the PEMFC stack. These faults have been simulated by placing each power switch in series with an ideal switch initially closed and opening when the fault is desired. Figure 3 depicts the obtained results.

As shown in Figure 3(a), OCFs in switches significantly increased the ripple of FC current and output voltage. Zoomed images of the FC current show that after an OCF on S1, the peak-to-peak current ripple of the Δifc reaches roughly 54 A (i.e., 42 A more than Δifc of the healthy mode), which is equivalent to 18% of the rated PEMFC current employed here. The ratio of this current ripple attains 22% after the second fault occurs. These increases harm the FC aging and lead to excessive hydrogen consumption [26]–[28]; the FC current ripple should not exceed 10% of the rated FC stack current [17].

Besides, these faults increased the ripple of the DC bus voltage five times more than the healthy mode after the first fault (OCF in S1), while it grew by more than eightfold when the second fault occurred (OCF in S1 and S4). According to Liu *et al*. [29], this rise reduces the capacitor's lifetime, raises its temperature, and generates more power loss, affecting the converter's efficiency and reliability. Also, as can be observed in Figure 3(b), these faults increase the inductor current of healthy phases, creating additional electrical strains on the switches of these phases. The same figure also shows that following OCFs, there was an inappropriate shift between the GCSs of the remaining healthy switches. These GCSs continue to shift between each other with the same time delay of the healthy mode.

The PEMFC current ripple can reduce by growing the size of the inductors; the DC bus voltage ripple can reduce by increasing the size of the capacitors, but this is unsuitable for FCEV applications due to the associated increases in size, cost, and weight. One of the most significant challenges in FCEV design today is detecting more than one power switch fault in these converter topologies and improving their reliability and efficiency without increasing their size or costs. Therefore, in this work, after the proposed FDM detects these faults, a corrective strategy has been applied without adding additional components and size to this converter to reduce these ripples if one or two faults occur.



(a) (b)

Figure 3. Effects of OCFs without applying the corrective strategy (a) DC bus voltage (V) and PEMFC current (A), and (b) phases currents (A)

3.2. Effects of faults with applying the corrective strategy

As previously stated, the proposed corrective strategy highly depends on the defective phase. As a result, faults must be rapidly and precisely detected. To demonstrate the accuracy, quickness, and ability of the developed FDM to detect more than one fault even if they occur simultaneously, as well as to show the effectiveness of the corrective strategy in reducing the ripple of PEMFC current and output voltage. OCFs and SCFs have been simulated for two different cases: in the first case, the OCF on S1 has been affected at (t=40 ms), while the SCF on S4 has been simulated at (t=160 ms), while in the second case, OCF and SCF have been affected on S2 and S3 respectively simultaneously at t=150 ms. The obtained results are shown in Figures 4 and 5.

Compared to degraded operating modes in which the suggested corrective strategy is not applied, as shown in Figures 4(a) and 5(a), the FC current ripple is greatly reduced when using the strategy proposed in this paper. After losing one phase in this converter (i.e., when the 4-Ph IBC became a 3-Ph IBC), this current ripple dropped from 18% in the case of the degraded mode (Figure 3) to 8% (Δifc=24 A) of the rated PEMFC stack current while applying the corrective strategy (i.e., Δi_{fc} has been reduced by 55% in this case). When losing the second phase (i.e., when the 4-Ph IBC turns into a 2-Ph IBC), the PEMFC current ripple decreased from 66 to 33 A (i.e., Δi_{fc} has been reduced by 50% in this state).

Moreover, this strategy also contributed to reducing the DC bus voltage ripple compared to this voltage's ripple without applying the corrective strategy. Figure 4 (a) shows that the ripple of this voltage is nearly identical to the healthy mode after detecting OCF in "S1" and applying the corrective strategy. This strategy also reduced the DC bus voltage ripple by half when this converter loses two phases.

As shown from the zoomed images of the inductor phase currents in Figures 4(b) and 5(b), once the proposed FDM identifies the faulty switches, the corrective strategy executes an appropriate phase shift between the remaining healthy phases. Furthermore, the same figures also demonstrate that when the TRscf identifies an SCF, the inductor current of the affected phase is reduced after isolating this phase until the OCF of that phase is detected, at which point the corrective strategy is applied directly. In addition, as seen in the same figures, the suggested FDM can accurately and quickly detect these faults, where it takes less than one switching cycle to detect the fault, with a detection time of up to 1.7 μs.

Additionally, the results show this method's ability to detect faults of many switches simultaneously (Figure 5) or at different times while the converter runs. These results also confirmed the excellent performance of the corrective strategy in the occurrence's case of one or two faults. Overall, this study's results could contribute to ongoing efforts to strike a middle ground between enhancing reliability and incurring additional costs and size for FCEV applications.

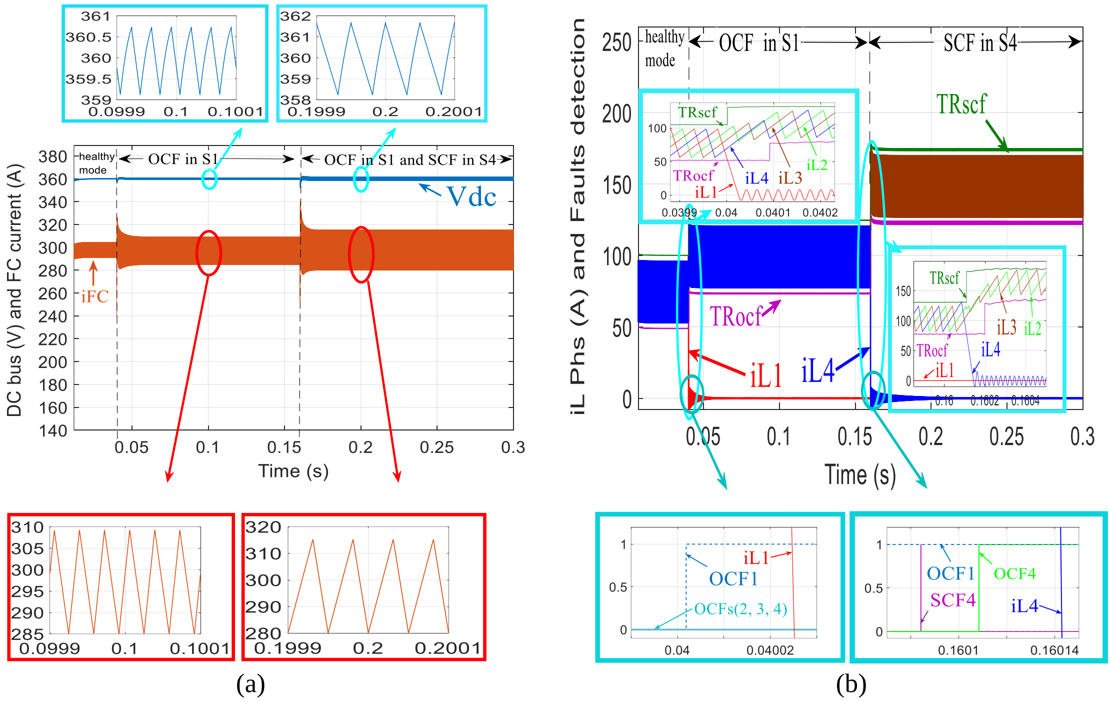
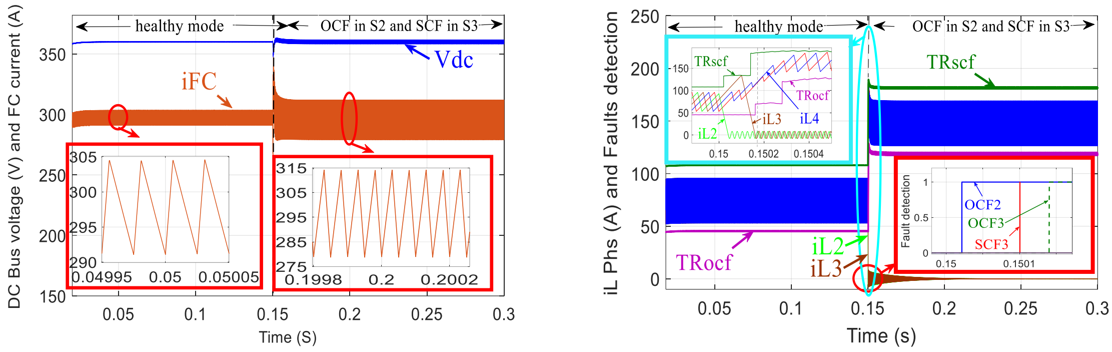


Figure 4. Effects of the corrective strategy and faults detection in phases 1 and 4 (a) DC bus voltage (V) and PEMFC current (A), and (b) phases currents and faults detection



(a) (b)

Figure 5. Effects of the corrective strategy and faults detection in phases 2 and 3 (a) DC bus voltage (V) and PEMFC current (A), and (b) phases currents and faults detection

4. CONCLUSION

This study proposed a quick and inexpensive method for detecting both OCFs and SCFs in MPh-IBC. This method can diagnose these faults in many DC/DC converters and identify multiple switch defects in MPh-IBC. This FDM uses the same sensors already in place for controlling the converter. It is based on comparing the inductor current measured for each phase of the converter with two fault detection thresholds, one for OCFs and the other for SCFs. Without adding additional components to the converter, this paper presents a corrective strategy that lowers the PEMFC current and the DC bus voltage ripple caused by OCFs. The collected findings have demonstrated the corrective strategy's usefulness in lowering these increases to more than 50% if one or two faults occur. These findings also demonstrate the FDM's performance and speed and its ability to identify several switch failures in multi-phase converters, where the speed of this detection method reached up to 1.7 µs.

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