Open-switch Fault Tolerant Operation of a Two-Stage Buck/Buck-Boost Converter with redundant synchronous switch for PV systems

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***Abstract*—In PV systems, DC-DC converters have been identified as one of the most critical and challenging subsystem in terms of failure rate. Thus, this paper proposes fault tolerant operation of a two-stage Buck/Buck-Boost converter under open-circuit switch failure. Remedial actions are efficient in any failure of one of the two switches of the converter. Here, a new unified approach is considered, for the overall fault tolerant operation of the two stages of the converter. The fault tolerant circuit we propose lies on performing redundancy by implementing the equivalent synchronous switch for the two main switches of the two stages, in offline mode. The fault tolerant circuit results from the basic two-stage Buck/Buck-Boost converter and its equivalent circuit with a synchronous switch, merged together to form the new DC-DC fault tolerant circuit. Therefore, post-fault operation at full power can also be performed. By using a switch fault management unit with reduced complexity, inserted between the control block and the switches, we have designed an unified, efficient and optimized fault tolerant control, suitable in both healthy and post-fault operations. Some selected experimental tests, which all confirm the good performances of the proposed fault tolerant approach, are presented and discussed.**

***Index Terms*—Switch failure, fault tolerant operation, open-circuit failure, two-stage converter, Buck, Buck-Boost, synchronous redundant switch.**

I. Introduction

In the past decades, many research works have targeted the use of renewable energy sources such as Photovoltaic (PV). A failure may occur in any part of the system such as PV panel or DC-DC conversion. To ensure service continuity, an approach based on fault tolerant operation is mandatory. Research works in PV reliability studies are focused on storage devices and power electronic converters that are identified as the most critical and challenging utility interface in terms of failure rate, lifetime, and maintenance cost [1]. The converter failures, caused by semi-conductors, account for 21% of the total failures in power converters, thus challenging the reliability of the system [2]. According to a survey [2], semiconductor and soldering joints failures in power devices take up 34% of power electronic system failures. Therefore, fault tolerant operation for converters used in PV systems should be proposed.

Service continuity under switch failure in PV systems is the general goal of this paper. It can be performed with the integration of fault tolerance and requires two main steps: first, fault detection and identification, also known as "fault diagnosis"; and second, "remedial actions" [1], also called "Fault tolerant operation" [2], [3]. The first step identifies the location and nature of the failure: open or short circuit failures can be considered. The "remedial actions" are the process to first electrically isolate the faulty component, if needed, and then, reconfigure the converter by using a suitable fault tolerant control. Physical fault isolation is always required in the case of a short-circuit switch failure to cut the current path, before reconfiguring the converter. In this case, the damaged switch can be electrically isolated by a fuse or by controllable components (relay, triac or switch). These additional components can be inserted in series with the faulty switch or in a shoot-through loop across the DC bus. Whatever solution is implemented, the short-circuit switch failure becomes an open-circuit switch failure, after isolation. For this reason, only open-circuit switch failure will be addressed in our contribution. More, one can also notice that system performances could be degraded in post-fault operation [2].

In this paper, the "fault diagnosis" step is not considered. Switch fault diagnosis in DC-DC converters has been the subject of intensive research for more than several decades and fruitful results have been reported [3]–[13]. One of these algorithms and methods can be indifferently used for open circuit switch fault diagnosis for the studied two-stage converter. Our contribution focuses on "remedial actions" for service continuity in two-stage converters under open-circuit failure of one of the two switches. It proposes the design of a redundant circuit associated with an optimized control strategy, which employs an added switch S to replace functionally both of the two original switches S_1 and S_2 of the two-stage converter in faulty mode. In doing so, the proposed method is better than the conventional redundancy approaches in terms of switch number.

In the following section, a general overview of fault tolerant approaches for DC-DC converters is presented. Then, the "remedial actions" proposed in this paper in the case of a Buck/Buck-Boost converter are introduced and their originality is highlighted, compared with the state of the art.

In Section III, the proposed Buck/Buck-Boost fault tolerant circuit is introduced and studied in detail. It is efficient in any open-circuit failure of one of the two switches in the circuit; more, it guarantees service continuity at full power. Then, in Section IV, a suitable and optimized fault tolerant control is also proposed. An unified control is applied in both healthy and faulty conditions; only a fault management interface is placed between the unified control outputs and the drivers of the switches. It applies the suited switching pattern by adapting the switching control orders in open circuit switch failure. For verification, experimental tests are realized. The fault-tolerant Buck/Buck-Boost converter was built in our laboratory; the control is implemented on a dSPACE target and tested experimentally. Some selected experimental results are provided in Section V. It is shown that the fault-tolerant converter continues to supply the load at full power, even with an open circuit failure in one of the semiconductor switches.

II. Remedial actions for fault tolerant DC-DC converters

A. Introduction

When considering fault tolerant operation, the word "redundancy" comes to mind. Let's first define what is covered by this common concept of redundancy; "redundancy" means that some components are duplicated or added in the basic converter structure, as a precaution against switch failure and to perform service continuity. This means that the principle of parallel operation of similar subsystems, converters or components, widely used in industrial applications and commonly called "N+k redundant configuration", is not the only one concerned and only some components can be added (switch, relay, semi-conductor-controlled rectifier, thyristor, ...) for fault tolerant purpose. In general, k is equal to 1, for cost considerations. In any case, it is commonly accepted that fault tolerant operation is always based on hardware redundancy design with a corresponding fault tolerant control [2].

Numerous remedial actions and approaches for fault tolerant DC-DC converters are separately reported in the recent literature. In the case of semiconductor failures, a general classification about fault tolerant techniques for power electronics converters was recently proposed by W. Zhang et *al.* [2]. In this survey, three-phase and multilevel converters are the most concerned; therefore, the particular case of DC-DC converters is not considered. In the spirit of this survey and based on the various cases presented in the literature, this section aims to present a comprehensive synthesis of the remedial actions in non-isolated DC-DC converters case, illustrated by some selected publications. The innovative approach we propose will be finally discussed, comparatively.

Based on the scientific literature, remedial actions for non-isolated DC-DC converters are based on redundant switches. Various scenarios are proposed in the literature; they can be categorized in two cases, depending if the redundant switch is connected in parallel with the main switch, or separated from it. Let's first consider the case of DC-DC circuits where the redundant switch is connected in parallel with the main switch. In this case, the redundant switch is not separated from the main switch. It is not used during normal operation and is activated during the reconfiguration process of the circuit, to replace the corresponding faulty switch. This approach has been proposed in [4] where fault diagnosis and remedial actions for single switch DC-DC converters are studied. Nevertheless, in such an offline scheme, extra switches do not operate in healthy conditions; consequently, for cost considerations, they can be shared in a system to replace multiple main switches of similar DC-DC converters, potentially faulty. In this case, additional linking components, such as selecting relays or thyristors, are often associated with the shared redundant switch. In [5], this approach has been validated in multiple parallel step-up DC-DC converters connected to a common DC bus, where a single redundant switch is shared with all the converters. Notice that when the redundant switch is shared, it becomes separated from the main switches by the linking components.

Dylan Lu et *al.* proposed a step-down dual-switch DC-DC converter with open-switch fault-tolerant capability, where the redundant switch is not connected in parallel to the main switch [14] but is separated from it. This new converter is derived from the two classical Buck and Buck-Boost step-down topologies, merged together to form the new DC-DC circuit. Consequently, when one of the two switches fails, the other one can be activated to continue step-down operation. Nevertheless, the duty cycles being different in Buck and Buck-Boost operation modes, the post-fault control must be modified accordingly, to guarantee the same regulation.

B. Proposed reconfiguration based on synchronous redundant switch

Open-circuit switch fault tolerance of two-stage DC-DC converters, by implementing a global reconfiguration (for the two stages) and based on synchronous redundant switch, is a novel approach, first proposed in this paper. It is first introduced in this sub-section and will be detailed and applied in Section III, in the case of a two-stage Buck/Buck-Boost converter. As mentioned before, fault tolerant approach is always based on hardware redundancy, associated to a suitable control strategy; this is also the case of the approach we propose. Furthermore, all the hardware fault tolerant approaches published in the literature concern single-stage DC-DC converters or modular converters based on identical DC-DC conversion modules; so, an unified approach for the overall fault tolerant operation of two-stage converters has never been considered.

Nevertheless, two-stage converters are commonly used in PV systems; conventionally, the front stage tracks the Maximum Power Point while the second one regulates the output voltage. Here, we consider a Buck/Buck-Boost two-stage structure, thus including two active switches. Commonly, these two switches are separately and asynchronously controlled. Based on the state of the art, the first idea that comes to mind to perform fault tolerant operation is to apply in offline mode the "redundant switches" approach, by connecting one redundant switch in parallel with each of the two main switches. Furthermore, for the considered converter, it is not possible to share a common redundant switch with linking components because

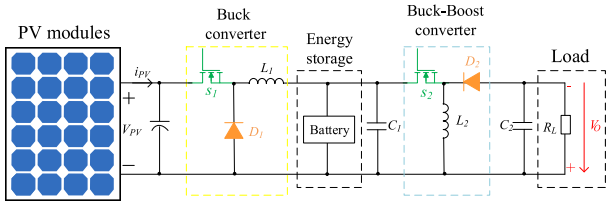


Fig. 1. PV system with two-stage DC-DC conversion and energy storage.

the main switches have not the same current directions, as it will be demonstrated in the following section. Finally, considering the classical approaches, using two redundant parallel switches is mandatory. The new approach we propose lies on performing redundancy by implementing in the fault tolerant converter the equivalent synchronous switch for the two main switches, in offline scheme. The proposed fault tolerant two-stage converter circuit results from the basic two-stage circuit and its equivalent circuit with synchronous switch, merged together to form the new DC-DC fault tolerant converter. Excepted the two switches from the basic circuit and the synchronous switch, all other parts of the fault tolerant circuit are shared in healthy conditions and post-fault operation. In this case, the redundant switch is the synchronous switch, used in offline mode. As a synchronous switch includes a single switch and two diodes [15], the redundant switch (and driver) number is reduced to one. More, post-fault operation at full power can also be performed without degrading the overall system performances. Nevertheless, a suitable synchronous control must be applied in post-fault operation, instead of the asynchronous control applied in healthy conditions; the way of reducing the complexity of the associated fault tolerant control in a unified approach will be detailed later, based on a fault management unit. Here, in the case of an open-circuit failure of one of the two main switches, both switches are opened by the fault management unit and functionally replaced by the redundant equivalent synchronous switch.

III. Buck/Buck-Boost Fault Tolerant Circuit

The studied PV system with two DC-DC conversion stages separated with a battery for energy storage is shown in Fig. 1. Given that the PV output voltage is often higher than the battery's one, the first stage is a step-down Buck converter, whereas the second stage allowing to supply a load with different voltage levels (higher or lower than the battery voltage) is a Buck-Boost converter. This PV system is controlled with two control signals applied to the switches S_1 and S_2. To ensure continuity of service of the proposed PV system and minimize the number of redundant components (i.e. switches), one solution may be to share a single redundant switch between S_1 and S_2, as discussed in Section II.B and published in [5]. In order to find a common node between S_1 and S_2 and mutualize a single redundant switch, these two switches (see Fig. 1) are moved towards each other while maintaining the same electrical behavior of the converter, as shown in Fig. 2a. The opposite current directions in the switches S_1 and S_2 (see Fig. 2a), however, do not allow

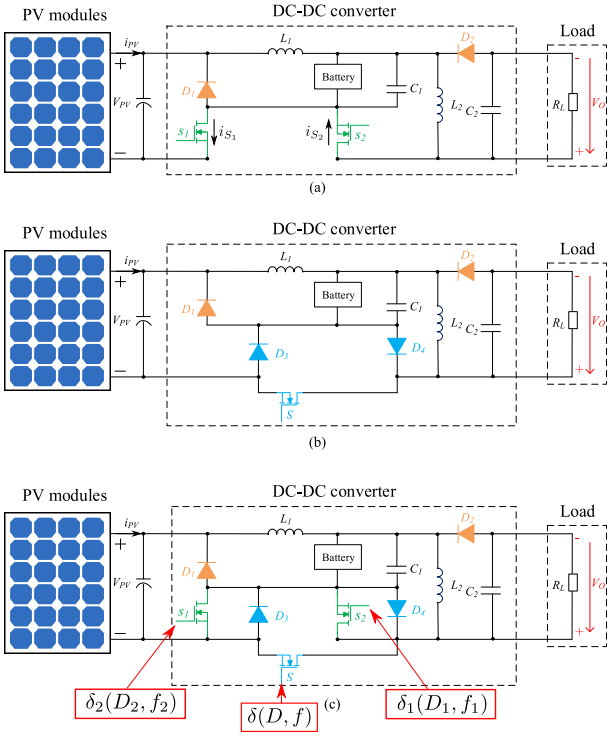


Fig. 2. PV system: (a) initial two-stage DC-DC conversion system, (b) electrically equivalent circuit to (a) when synchronous control is applied to S_1 and S_2, (c) proposed fault tolerant DC-DC conversion circuit based on circuits (a) and (b).

the sharing of a single additional switch between these two switches. On the other hand, the drain of the switch S_1 shares a common node with the source of the switch S_2. Thus, if a synchronous control is applied to these two switches S_1 and S_2 having a common drain-source node, they can be replaced with a synchronous switch based on a single switch S associated to two diodes D_3 and D_4 [15], as shown in Fig. 3. Consequently, the DC-DC conversion circuits presented in Fig. 2a and b are electrically equivalent. Note that these two circuits have the same electrical behavior only if a synchronous control is applied to the switches S_1 and S_2.

To ensure the continuity of service of the proposed PV system, we propose a new and original fault tolerant conversion circuit presented in Fig. 2c. It results from a combination of the initial two-stage two-switches DC-DC conversion circuit presented in Fig. 2a with the single switch DC-DC conversion topology from Fig. 2b. The fault tolerant circuit in Fig. 2c has been first introduced and validated by simulation in a conference paper [16]. In [16], the same synchronous control is applied to the fault tolerant circuit under both modes (healthy conditions and post fault operation), to perform fault

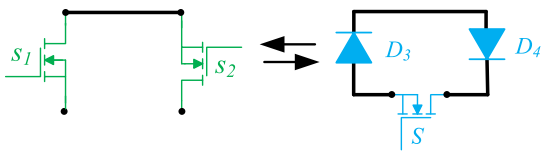


Fig. 3. Synchronous switch equivalent circuits.

tolerant operation whereas, in this paper, a new optimized fault tolerant control is proposed in Section IV. It is based on an asynchronous control applied in healthy conditions and a synchronous control, applied in post fault operation. The fault-tolerant topology proposed in Fig. 2c guarantees the continuity of service of the PV system at full power in the case of an open-circuit fault (OCF) either on S_1 of the Buck converter or on S_2 of the Buck-Boost converter. The conventional redundancy approach where each switch has its own redundant counterpart has been avoided in this topology. On the contrary, it employs a reduced number of redundant switch allowing to replace functionally both switches (S_1 and/or S_2) in faulty mode (whenever an OCF is detected on S_1 and/or S_2) and ensures normal operation of the PV system. The overall fault-tolerant PV system is driven either by the switches S_1 and S_2 (S is OFF) or by the switch S (S_1 and S_2 are OFF). In healthy conditions, the asynchronous control signals applied to S_1 and S_2 ensure the normal operation of the system whereas in faulty mode, after the diagnosis of an OCF on either S_1 or S_2, the control signal applied to S ensures the continuation of the normal operation of the system. In both modes, the same system operation at full power is carried out without degrading the performances of the overall system. In healthy conditions, the available control variables are the duty ratios (D_1 and D_2) and frequencies (f_1 and f_2) of both control signals (δ_1 and δ_2) applied to the switches S_1 and S_2 (see Fig. 2c). On the other hand, in faulty conditions, the number of available control variables is smaller than in the healthy ones and is equal to two: the duty ratio D and the frequency f of the control signal δ applied to the switch S are used to drive the overall fault tolerant PV system (see Fig. 2c).

IV. Fault-tolerant control

In the previous section, where the fault-tolerant two-stage circuit for PV systems has been presented, driving the switches S_1, S_2 and S depends on the operational conditions: in the healthy conditions the asynchronous control is used to drive the switches S_1 and S_2 (S is OFF), whereas in the faulty conditions the synchronous control is applied to the switch S (S_1 and S_2 are OFF). In this section, the main goal is to propose and design a fault-tolerant controller which is as simple as possible for both operational modes (healthy and faulty) and which allows to switch rapidly from one operational mode to another without degrading the overall performances of the PV system.

A. Efficient control strategy with fast post-fault management

If we observe the control variables identified in the previous section, we can note that four control variables are available to drive the proposed fault-tolerant circuit from Fig. 2c in the healthy conditions (equivalent to Fig. 2a) : the duty ratios D_1 and D_2, and the frequencies f_1 and f_2 of the signals δ_1 and δ_2 respectively (see Fig. 2c). On the contrary, only two control variables, the duty ratio D and the frequency f of the signal δ, are available for the synchronous control used to drive the post-fault circuit from Fig. 2c (equivalent to Fig. 2b). These

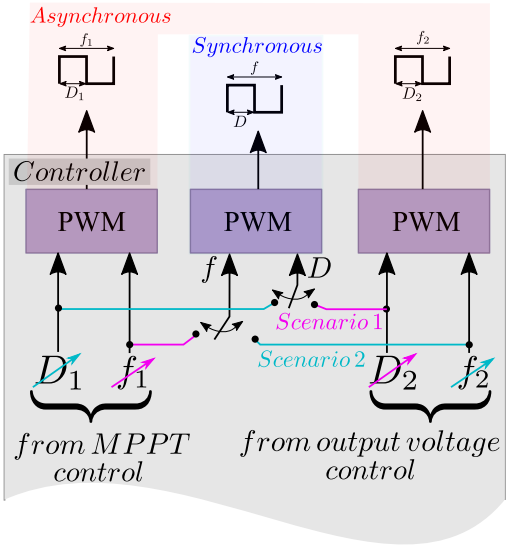


Fig. 4. Principle of the PV control strategy proposed in this paper: the first scenario (cyan) where the synchronous control signal δ driving the post-fault circuit has the same frequency as the signal δ_1 ($f = f_1$) and the same duty ratio as the signal δ_2 ($D = D_2$); the second scenario (light blue) where the control variables D and f of the synchronous signal δ are $D = D_1$ and $f = f_2$ respectively.

control variables, no matter the operational mode (healthy or faulty conditions), allow simultaneously the tracking of the Maximum Power Point at the output of the PV panel and the regulation of the output voltage v_O supplied to the load (see Fig. 2c). To design a fault tolerant controller allowing to switch smoothly and rapidly from the asynchronous to synchronous mode (healthy to faulty mode), the equivalent circuits shown in Fig. 2a and b must have the same operating point before and after the occurrence of an OCF on S_1 and/or S_2. Having the same operating point in both modes implies that the control variables from two sets, $\{f_1, f_2, D_1, D_2\}$ and $\{f, D\}$ for the asynchronous and synchronous control respectively, have the same values before and after an OCF: $f = f_1$ or f_2 and $D = D_1$ or D_2. Therefore, there are two possible scenarios allowing to perform independently and simultaneously the functionalities, the MPPT and output voltage regulation: the first one where $f = f_1$ and $D = D_2$; or, the second scenario where $f = f_2$ and $D = D_1$. These two scenarios are summarized in Fig. 4. The other scenarios ($f = f_1$ and $D = D_1$; $f = f_2$ and $D = D_2$) would not allow to keep the same operating point after the occurrence of an OCF and would perform at a time only one of the two mentioned functionalities. Consequently, by choosing one of the two presented scenarios, the PV controller will be able to generate the control signals driving all three switches (S_1, S_2 and S) of the proposed circuit for both asynchronous and synchronous modes in advance, and therefore only the speed of multiplexing of the right control signals will define the overall speed of reconfiguration from healthy to post-fault operation.

The proposed control strategy based on the same operating point before and after an OCF (one of the two presented scenarios, see Fig. 4) implies that MPPT and voltage output regulation in both modes are performed simultaneously with

two control variables of different nature: $D = D_1$ or D_2 and $f = f_1$ or f_2. Consequently, the conduction modes of the energy transfer inductors L_1 and L_2 of the proposed fault-tolerant circuit (see Fig. 2c) must be different: if both operate either in continuous conduction mode (CCM) or in discontinuous conduction mode (DCM), it is not possible (see Eqs. 1 and 2) to control their conduction modes and thus the previously mentioned functionalities (MPPT and V_O regulation) independently. The only solution would therefore be to have the inductors L_1 and L_2 operating in different conduction modes.

In the following, we chose the inductors L_1 and L_2 to be operating in DCM and CCM, respectively. This choice is justified by the fact that the output load must be permanently supplied with power and thus the inductor L_2 should operate in CCM while L_1 in DCM. Moreover, the first scenario of sharing control signals presented in Fig. 4 is also adopted in this work, where $f = f_1$ and $D = D_2$.

B. Asynchronous control in healthy conditions

In healthy conditions, each DC-DC conversion stage is controlled independently in the asynchronous mode, where the switches S_1 and S_2 are driven by two different control signals δ_1 and δ_2 respectively (Fig. 5). The Buck converter driven with the control signal δ_1 tracks the Maximum Power Point (MPP) using a Maximum Power Point Tracking (MPPT) algorithm [17]. On the other hand, the Buck-Boost converter which is driven with the control signal δ_2 is used to regulate the output voltage across the load. As previously explained, in order to control independently these two conversion stages in the faulty mode, they must operate in different conduction modes. Therefore, DCM has been chosen for the Buck converter, whereas CCM is the conduction mode of the Buck-Boost converter.

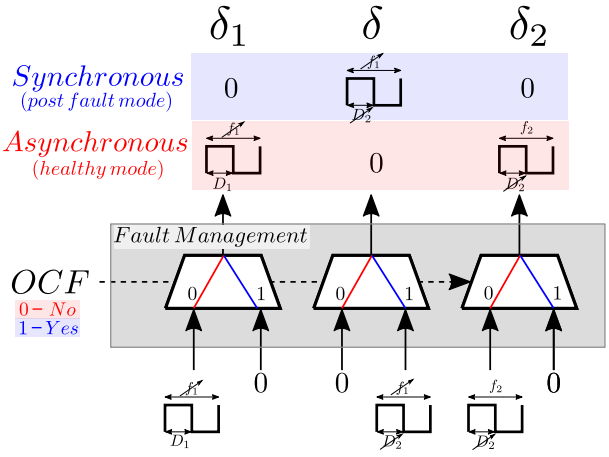


Fig. 5. Asynchronous and synchronous control: in the absence of OCF on S_1 and/or S_2 (OCF=0, in red), the asynchronous signals δ_1 and δ_2 drive the fault tolerant circuit; otherwise (OCF=1, in blue), only the synchronous signal δ drives the fault-tolerant circuit and ensures the continuity of service.

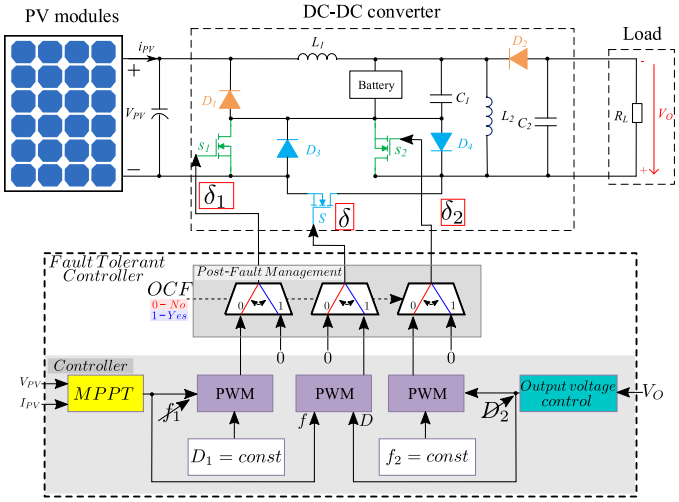


Fig. 6. The proposed fault-tolerant circuit with associated control in both healthy and faulty conditions.

The Buck converter transfer function in DCM is given by:

$$M_{Buck,DCM} = \frac{2}{1 + \sqrt{1 + \frac{8 \cdot L_1 \cdot f_1}{D_1^2 \cdot R_L}}}. \quad (1)$$

where either the duty ratio D_1, the frequency f_1 or both can be used to track the MPP at the output of the PV panel. In this work, we chose to keep the duty ratio D_1 constant and track the MPP only by regulating the frequency f_1 of the signal δ_1 as presented in Fig. 6.

The Buck-Boost converter transfer function in CCM is given by:

$$M_{Buck-Boost,CCM} = \frac{V_O}{V_B} = \frac{D_2}{1 - D_2}. \quad (2)$$

where D_2 is the duty cycle of the control signal δ_2 (see Fig. 6) driving the Buck-Boost converter. By analyzing this transfer function, the choice of control variable (D_2 or f_2) of the Buck-Boost converter is easily made: the regulation of the output voltage V_O is performed by acting on the duty ratio D_2 of the signal δ_2, while its frequency f_2 is kept constant (see Fig. 6).

C. Synchronous control: an OCF on S_1 and/or S_2

When an OCF occurs and is detected on S_1 and/or S_2, both control signals δ_1 and δ_2 used to asynchronously control the switches S_1 and S_2 in the healthy mode are disabled (see Fig. 5). Therefore, S_1 and S_2 are always open and no longer used in this synchronous mode. This is why the precise location of the OCF occurrence (S_1 or S_2) is not necessary. Moreover, by disabling the control signals δ_1 and δ_2 and opening the switches S_1 and S_2, the switch S and the diodes D_3 and D_4 can conduct and thus take over the control of the fault tolerant circuit. The control signal δ of the switch S ensures that the proposed fault tolerant circuit has the same functionalities in the faulty operational mode (synchronous control) as in the healthy conditions (asynchronous control), without degrading the performances of the PV system. Indeed, the frequency f of the synchronous control signal δ is equal to the frequency f_1 of the asynchronous control signal δ_1 used to control the

Buck converter in the healthy mode and allows to track the MPP in the same way as in the healthy mode according to Eq. 1. On the other hand, the duty cycle of the synchronous control signal δ is equal to D_2 of the asynchronous control signal δ_2 and allows to regulate the output voltage V_O according to Eq. 2, in the same way as in the healthy conditions.

Fig. 6 summarizes the control of the proposed fault tolerant circuit: the asynchronous control in healthy and synchronous control in faulty conditions. The advantage of using the asynchronous control in the healthy mode to control the proposed fault tolerant circuit is the possibility to choose different frequencies f_1 and f_2 of the control signals δ_1 and δ_2 respectively. The frequency f_1 is used to track the MPP of the first conversion stage, while the frequency f_2 is not used as a control variable of the second conversion stage to regulate the output voltage V_O, due to the CCM operational mode. By choosing different values for f_1 and f_2, the switching losses of the second conversion stage (Buck-Boost converter) driven with the asynchronous control signal δ_2 whose frequency is f_2 can be reduced.

V. Experimental results

TABLE I
Parameters of the PV system.

Elements	Value	Elements	Value
L_1	$15\mu H$	C_2	$22\mu F$
L_2	$470\mu H$	V_B	$12V$
C_1	$100\mu F$	R_L	25Ω

The proposed two-stage fault tolerant circuit for PV systems with optimized fault tolerant control is validated experimentally. The experimental parameters are presented in Table I. The choice of inductance values L_1 and L_2 is based on the chosen conduction modes (DCM and CCM) for both conversion stages. Given the focus of this paper on remedial actions in open-circuit switch failure, the PV source is replaced with a voltage source for a fixed operating point. Thus, for the PV panel at the input of the proposed fault tolerant circuit, one fixed operating point corresponding to the full power of 20W of two 10W PV panels connected in parallel has been chosen ($V_{PV} = 17.5V$ and $I_{PV} = 1.14A$). The experimental setup used for this validation is presented in Fig. 7. It comprises the fault tolerant two-stage Buck/Buck-Boost converter presented in the previous sections, a DC voltage source and a resistive load R_L. A dSPACE DS1104 control card and CPL1104 dSPACE interface device are used to generate the control signals δ_1, δ_2 and δ, which represent respectively the control signals of the switches S_1, S_2 and S for both asynchronous healthy and synchronous faulty modes, and interface them to the fault tolerant circuit. The switches S_1, S_2 and S are all MOSFET components IRFP4110 from Infineon/International Rectifier. Schottky barrier diodes MBR10100 from ON Semiconductor are used for all diodes. The current measurements are carried out with $5MHz$ bandwidth current probes, I-prober 520 by Aim & Thurlby Thandar Instruments. The sampling period used in the dSPACE control system is $50\mu s$.

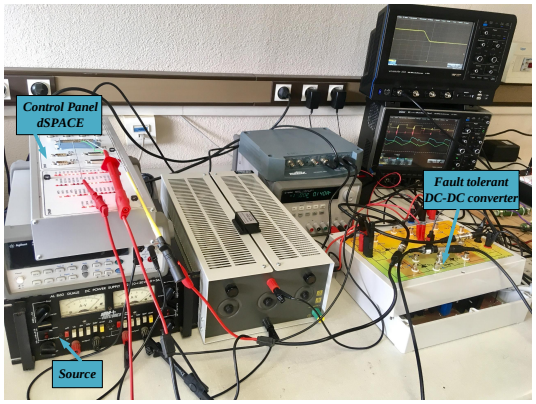


Fig. 7. Fully experimental setup.

All signals were recorded with a Lecroy oscilloscope WaveSurfer 4000 with the following parameters for all presented waveforms: the vertical sensitivity of $2V/div$ for the control signals of all switches, $10V/div$ for the fault detection signal and output voltage V_O, $2A/div$ for the currents i_{L1}, i_{D1} and i_{D3}, and $1A/div$ for the currents i_{L2}, i_{D2} and i_{D4}.

The experimental results showing the asynchronous control applied in healthy conditions in steady state are shown in Figs. 8, 9 and 10, and also on the left-hand side of the presented waves in Figs. 13, 14 and 15 in transient state in the case of an OCF on S_1 (Figs. 13 and 14) or S_2 (Fig. 15). On the other hand, the experimental results showing the synchronous control of operation in post-fault conditions in steady state are shown in Figs. 11 and 12, and also on the right-hand side of the presented waves in Figs. 13, 14 and 15. For the asynchronous control in healthy conditions, the frequency f_1 of the control signal δ_1 driving the Buck converter is set to $25kHz$, while the frequency f_2 of the control signal δ_2 of the Buck-Boost converter is set to $10kHz$ (see Fig. 8). In addition, the shapes of currents i_{L1} and i_{L2} show that the inductor L_1 operates in discontinuous conduction mode, while the inductor L_2 is in continuous conduction mode. Moreover, the currents of free wheeling diodes D_1 and D_2 of the first Buck and the second Buck-Boost converter are shown in Figs. 9 and 10 respectively. On the other hand, in post-fault mode, the fault tolerant circuit is driven synchronously only with the signal δ at the switching frequency of $25KHz$ (see Fig. 11). In steady state, the currents of all diodes, the free wheeling ones (D_1 and D_2) and those used in conjunction with the synchronous switch (D_3 and D_4), are also given for post-fault mode in Fig. 12. By comparing the currents of free wheeling diodes D_1 and D_2 in healthy and post-fault mode (see Figs. 9, 10 and 12), it can be noticed that these currents have the same shapes. As explained in Section IV, the proposed fault tolerant circuit guarantees the same functionality before and after an OCF occurrence, which can justify these same shapes of currents i_{D1} and i_{D_2} in both modes.

It should also be noted that the current i_{L1} during the asynchronous control used to drive the fault tolerant circuit in healthy conditions (see Fig. 8) does not have exactly the same shape as in steady state after the fault occurrence and

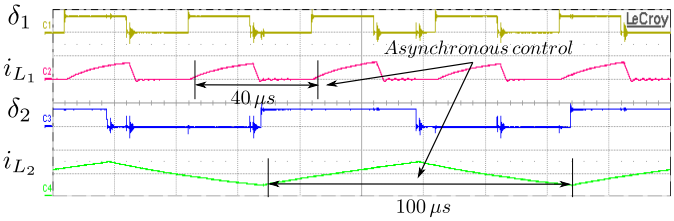


Fig. 8. Steady state of the proposed fault tolerant topology in healthy conditions.

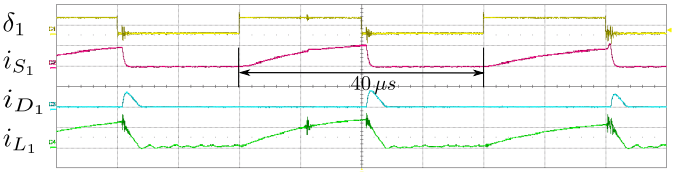


Fig. 9. Steady state of the fault tolerant topology in healthy conditions: the relevant currents of the first Buck stage (i_{S_1}, i_{D_1} and i_{L_1}).

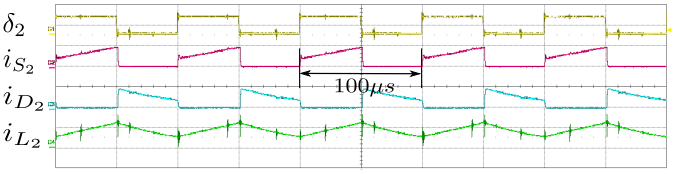


Fig. 10. Steady state of the fault tolerant topology in healthy conditions: the relevant currents of the second Buck-Boost stage (i_{S_2}, i_{D_2} and i_{L_2}).

transition to the synchronous mode of operation (see Fig. 11). This is explained by the fact that the current paths in the proposed fault tolerant PV system are not the same in healthy (before OCF occurrence) and in faulty conditions (after OCF occurrence). In the healthy conditions, where the asynchronous control is used to drive the switches S_1 and S_2, the positive growth of the current i_{L1} is only ensured by the ON state of the switch S_1 and the current path goes only through this active component. On the other hand, after the detection of an OCF and the transition to the synchronous control mode, the control signal δ is only applied to the switch S and consequently the current paths (and energy exchanges) in the fault tolerant circuit during the ON state change. The positive growth of the current i_{L1} during the ON phase of the switch S goes through two modes: in the first phase it is simultaneously ensured by the switch S and the diode D_3 (see Fig. 12, red part), while in the second phase it passes through the switch S and the diode D_4 (see Fig. 12, blue part). The transition from the first (red) state to the second (blue) one is dictated by the condition $i_{L1} < i_{L2}$. These different current paths cause some additional voltage drops on these current paths thus modifying the slope (and the shape) of the current i_{L1} in the synchronous mode of operation.

To realize experimental results of the transition from healthy to faulty conditions, the following scenario is carried out: an OCF on the switch S_x ($x \in \{1, 2\}$) is generated at a random time by forcing the reset of the control signal supplied to the switch. This can be seen on the top waveform (yellow) of Fig. 13 in the case of an OCF on S_1. The occurred OCF is

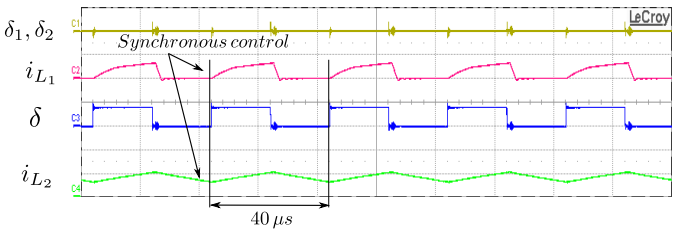


Fig. 11. Steady state of the fault tolerant topology in post-fault operation.

detected by the fault tolerant detection signal active on the falling edge. In the phase 1 (denoted by ① in Fig. 13), the two switches S_1 and S_2 are controlled with the asynchronous control signals δ_1 and δ_2, while the control signal applied to the switch S is equal to zero. After the OCF occurrence denoted with the falling edge of the signal "Fault detection" (F_D), the system response is not immediate (see Fig. 13, the phase 2). The main reason for this delay is the dSPACE system sampling time which limits the update of all measured and computed values to the timing interval of $50\mu s$. That is why after the falling edge of the signal F_D, an additional period of the control signal δ_1 is still generated. The second phase (denoted by ② in Fig. 13) starts with a first step consisting in the reconfiguration of the proposed fault tolerant circuit: the control signals δ_1 and δ_2 are not generated anymore while the control signal δ starts to be generated. Consequently, the continuity of service of the proposed fault tolerant PV system is ensured. After the reconfiguration and the transition from the healthy (asynchronous) to faulty (synchronous) mode (denoted by ③ in Fig. 13), the currents i_{L1} and i_{L2} still respect their conduction modes of operation. In addition, the current i_{L2} in the reconfigured faulty mode has a slightly different shape (smaller period) because the switch S is now driven at a frequency of $25kHz$ (period of $40\mu s$) instead of $10kHz$ (period of $100\mu s$) in the healthy mode (see Fig. 11).

Figs. 14 and 15 show the influence of the transition from healthy to faulty mode of operation on the output voltage v_O, depending on the fault location: S_1 (Fig. 14) and S_2 (Fig. 15). After the occurrence and detection of an OCF (top yellow signal on both figures), there are still some parasite asynchronous signals δ_1 and δ_2 for the same reasons explained above. Nevertheless, in the experimental results shown in Fig. 14, it can be seen that the OCF occurrence on S_1 does not influence the average value of the output voltage v_O, which keeps its same value from healthy conditions, mainly due to the efficiency of the optimized fault-tolerant control. The only difference is the frequency of ripples which is higher in faulty mode due to the use of higher frequency to control the circuit with the synchronous signal δ. On the other hand, in the case of an OCF occurred on S_2, the experimental results are shown in Fig. 15. Consequently, the output voltage v_O starts to drop and needs some time before achieving the same average value as in the healthy conditions.

VI. Discussion

In the previous sections, we have presented a general approach allowing to guarantee the service continuity at full

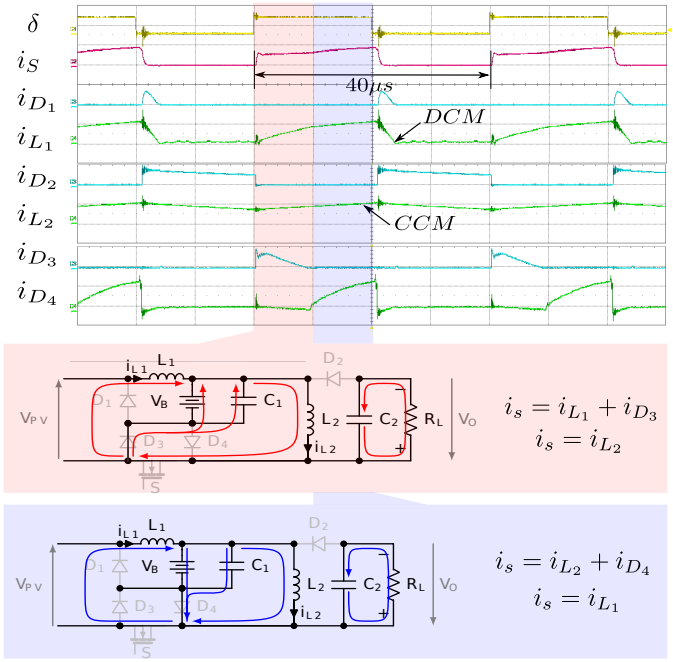


Fig. 12. Steady state of the fault tolerant topology in post-fault operation: the currents in all diodes (i_{D_1}, i_{D_2}, i_{D_3} and i_{D_4}), inductors (i_{L_1} and i_{L_2}) and single switch i_S.

power of a two-stage DC-DC circuit, under both OCF and/or SCF as well, bearing in mind that in all cases, an SCF after the cut of the short circuit path will be considered as an OCF. Indeed, a short-circuit must be first isolated and the current path cut before applying remedial actions. In healthy conditions, the two-stage converter behaves as a usual structure where both stages are single switch non-isolated DC-DC converters with an asynchronous control. In the considered application case, the first stage is a Buck converter whereas a second one is a Buck-Boost converter.

The effectiveness of the service continuity of the studied Buck/Buck-Boost circuit has been validated through experiments. Because of the applied synchronous control in the post fault mode, only two control parameters are available: duty cycle D and frequency f, requiring different conduction modes for the two DC-DC converters. It does mean that one converter must operate in DCM whereas the other one in CCM. In our application case, we have chosen to control the first stage Buck converter in DCM and the second stage Buck-Boost converter in CCM, mainly for output voltage regulation and continuous load feeding purposes. It is clear that the use of a first stage Buck converter introduces some additional PV current ripples, worsened with the DCM mode. Nevertheless, in the same spirit of the presented approach, another first stage non-isolated DC-DC converter (Boost or Buck-Boost) can be chosen to reduce these drawbacks, if allowed by the application requirements. Similarly, as for the first stage, the choice of the second stage non-isolated DC-DC converter can be reconsidered. However, the main goal of our contribution was to present a new fault tolerant design approach applied on two cascaded DC-DC converters and based on single switch redundancy, illustrated in the case of a Buck/Buck-Boost converter, but not exclusively limited to this combination.

VII. Conclusion

This paper proposes the open-circuit switch fault tolerant operation of a two-stage Buck/Buck-Boost circuit for PV systems. Remedial actions are based on an original unified approach where the overall fault tolerant operation of both stages at full power is considered. The fault tolerant circuit and the optimized fault-tolerant control we proposed lies on performing redundancy by implementing the equivalent synchronous switch for the two main switches of both stages, in offline mode. The equivalent synchronous switch includes a single switch and two diodes, thus reducing as low as possible the number of redundant switches. Excepted the switches, all other parts of the fault tolerant circuit are shared in healthy and post-fault operations. Therefore, post-fault operation at full power can also be performed if a suitable synchronous control is applied, instead of the asynchronous one used in healthy conditions. The proposed efficient control allows switching very quickly from healthy to faulty conditions, without the necessity to be reconfigured. Some selected experimental results are given to verify the validity of the theoretical approach. Thus, the service continuity is validated in any open-circuit switch fault of one of the two switches of the Buck/Buck-Boost circuit.

The new remedial actions we have proposed, based on redundant synchronous switch approach, is an efficient, fast and original solution to guarantee the service continuity of two-stage converters, if a suitable and unified fault tolerant control is also designed.

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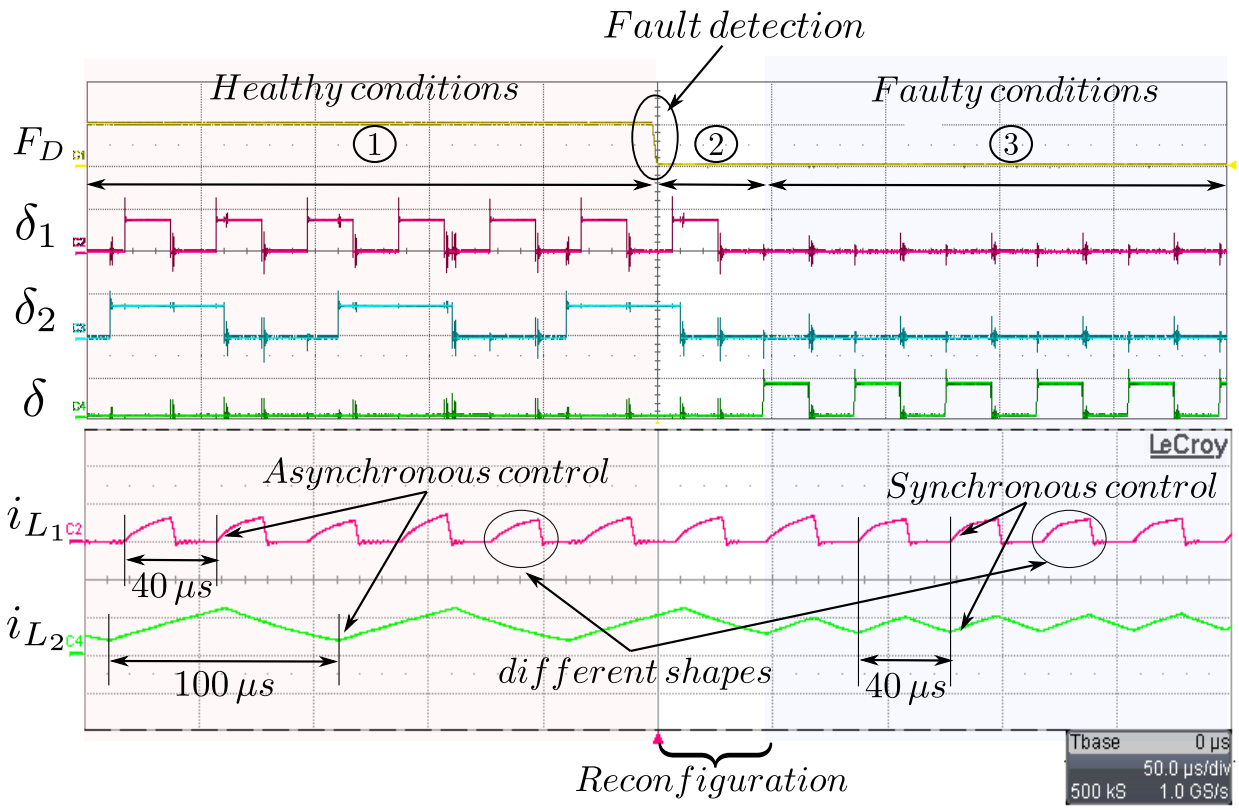


Fig. 13. Control of the proposed fault tolerant topology in both healthy and faulty conditions: transition from asynchronous to synchronous control in the case of an OCF on S_1.

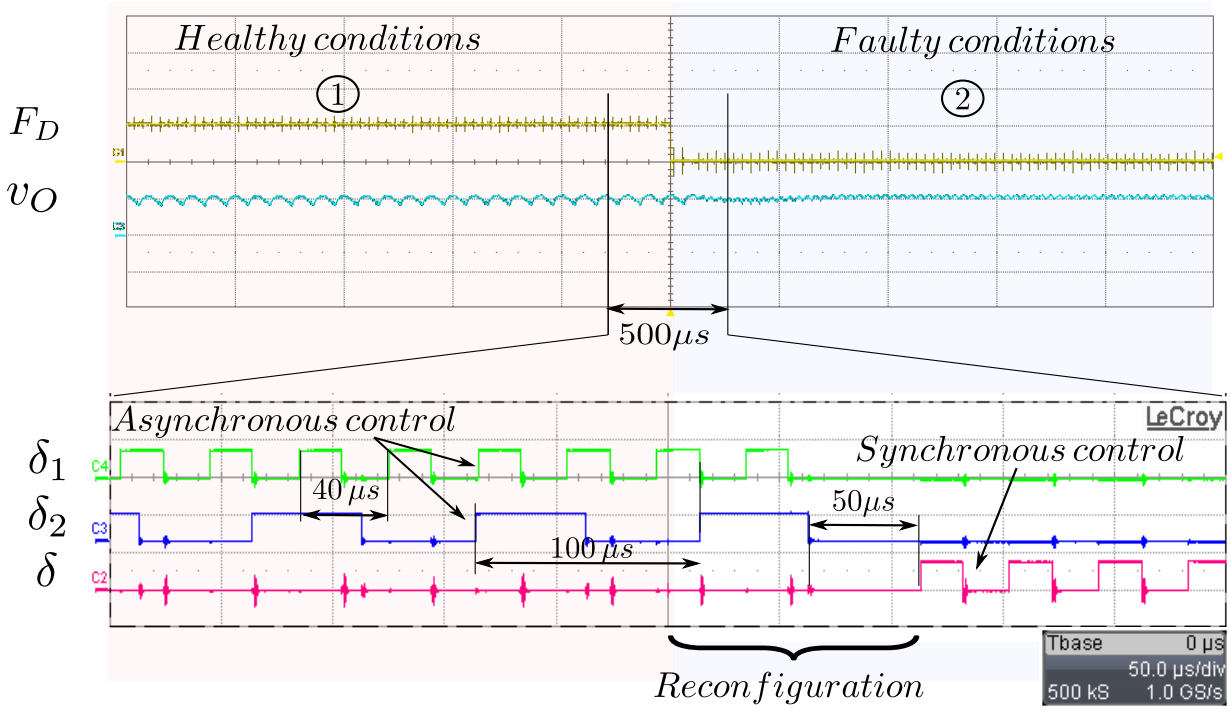


Fig. 14. Influence of the transition from healthy to post-fault mode of operation on the output voltage v_O: case of an OCF on S_1.

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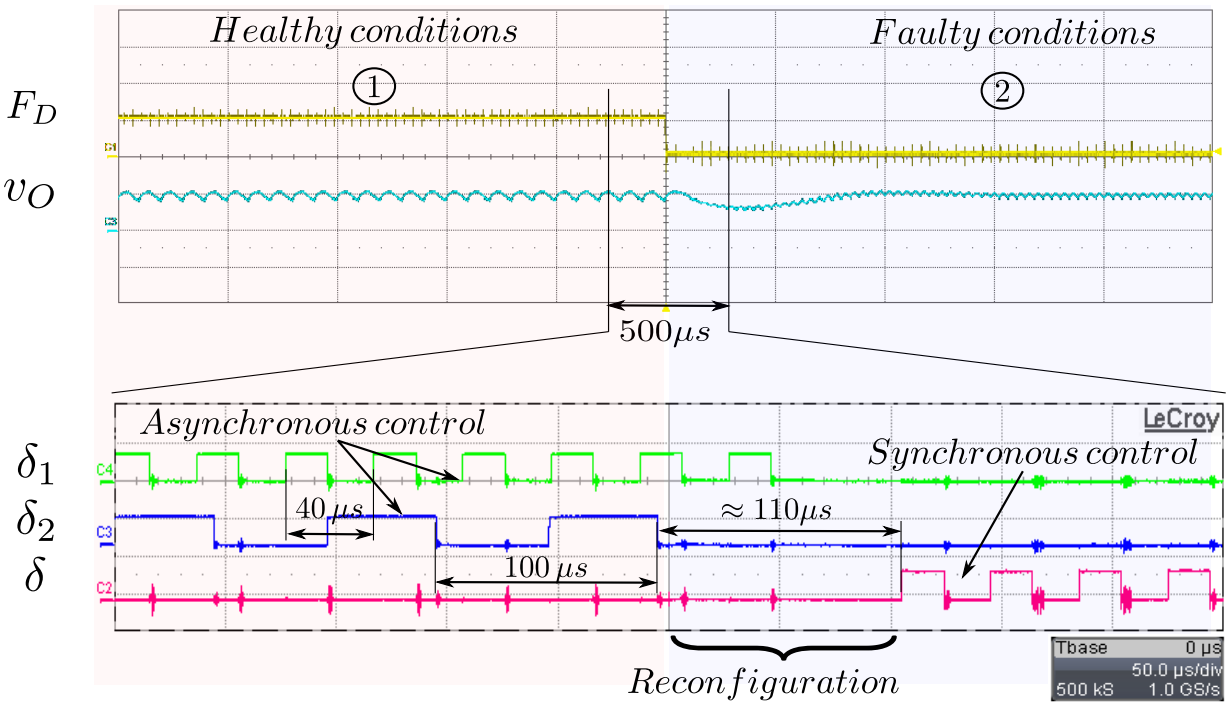


Fig. 15. Influence of the transition from healthy to post-fault mode of operation on the output voltage v_O: case of an OCF on S_2.

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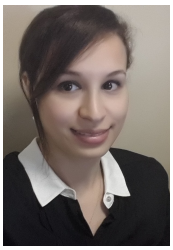
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