Fault Detection and Management of the Three-Phase 4-Leg Voltage Source Inverter

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Abstract – A novel fault detection and ride-through method for the three-phase 4-Leg Inverter (3 Φ 4L Inverter) used in off-grid applications is addressed in this paper. Open circuit and short circuit faults of the power devices located in the 3 Φ 4L Inverter have been theoretically analyzed. Hence, the fault detection and converter protection strategy has been implemented using a combination of a resonant controller in the $\alpha\beta$ frame and a repetitive observer. The proposed strategy has been at first validated by means of simulation results performed in MATLAB/Simulink environment. The fault detection and ride-through algorithm has been then implemented in FPGA using LabVIEW environment and full experimental verification are performed on the prototype of the three-phase 4-leg inverter.

Index Terms— resonant controllers, disturbance observer, three-phase four-leg inverter, fault detection.

I. INTRODUCTION

In the modern society, three-phase inverters are widely used in all areas, such as power supplies for industrial applications, medical equipment, traction devices, household appliances, distributed generation system, etc. [1]-[3]. In this latter application, for off grid systems, the 3 Φ 4L Inverter is controlled to have high quality voltage waveforms to supply local loads. The main feature of a 3 Φ 4L inverter is to maintain the desired sinusoidal output voltage waveform over all loading conditions (linear and non-linear loads). Furthermore, the continuity of operation is a key feature of the power converter, even in case of faults. Consequently, since the power semiconductors are very sensitive to failures, it is vital to improve the reliability of the power conversion system. In practical operations, the 3 Φ 4L inverter can suffer from various faulty conditions [4], in which the open-circuit and short-circuit faults of the power semiconductors, as well as the short-circuit at load side are the severest cases for inverters [5]. Thus, without proper fault detections and protections, the power semiconductor devices might be irreversibly damaged. According to the nature of the failures, a fault diagnosis is needed and, to minimize the likelihood of any damage, the processing time of the fault diagnosis must be reduced. Especially for the power semiconductor short-circuit fault, the detection and isolation actions must be performed as fast as possible to protect the DC-link and the silicon chips. Many investigations on fault diagnosis of semiconductor devices located in the converter have been performed in literature [6]-[16]. Several fault diagnostic techniques are based on adding a further circuitry to protect the power semiconductors [6]-[11]. In this case, the switches are protected in less than 10 μ s by an additional analog circuit implemented in the gate drivers. In [9] and [10] a redundant fourth-leg and additional devices have been added to

the NPC converter in order to obtain fault-tolerant capability. The fault detection method proposed in [11] identifies the location of the faulty switch and the faulty clamping diode of the NPC inverter without any additional hardware or complex calculations. In [12] and [13] the short-circuit faults of the power semiconductors are managed by adding a parallel converter. In [14] an appropriate control strategy is used to detect and isolate the open- and short-circuit faults. Here too, redundant switches are used to manage the faults. A predictive control algorithm and a fault detection method for current sensors in a three-phase four leg inverter has been proposed in [15]. In this case, the fault detection operates in dq domain, and the implementation of the control algorithm and fault detection method is implemented on a FPGA. In [16] the voltage waveform is examined to identify fault type and location. Here, the faults can be found and managed by changing the current path or using a redundant power semiconductor thanks to the comparison between the fault indicators and the threshold voltage. As it can be noticed, the techniques used in [6]-[11] can detect the fault in a few microseconds at the most (up to 10 μ s) after the initial fault, in the other techniques [13]-[16] the fault is discovered in a time between 10 μ s and 100ms after the initial fault. Thus, the faults can be defined on short-term time scale and long-term time scale [16]. Several fault diagnosis methods for power conversion system are able to detect the fault by analyzing the distortion of the output currents [7], [17]-[19]. In [17]-[19] the output currents are analyzed using different methods, such as ark's transformation, normalized average current method, slope method, etc.

In this paper a novel fault detection and converter protection strategy for the 3 Φ 4L Inverter has been proposed. The detection strategy has been tailored in order to identify the power semiconductor fault and manage it, leading the converter in a safe operating condition. The proposed detection strategy is based on resonant controller in $\alpha\beta$ domain plus a repetitive observer. The proposed technique allows to detect the faults at the latest within half of the switching period, which means that, for a switching frequency f_{sw} equal to 12kHz, the faults are detected in 83.33 μ s. Such reduced times are achieved thanks to the implementation based on a Field Programmable Gate Array (FPGA).

II. SWITCHES FAULT ANALYSIS OF THE 3 Φ 4L INVERTER

This section discusses the 3 Φ 4L Inverter behavior under switches malfunctions in short circuit and open circuit modes. Figure 1 shows the circuit diagram of the 3 Φ 4L Inverter. This topology consists of a three-phase inverter plus an additional leg. The AC side is connected to the output filter and load. The

3 Φ 4L Inverter has 16 different switching states in which two (00000 and 11111) states are redundant. However, the 3 Φ 4L converter can be considered as three-single phase inverters. The driver misfiring or the bonding wire failure can cause the open circuit faults of the MOSFETs or IGBTs, while the short circuit fault of the power devices can be produced by the malfunctions of the gate driver circuit [8].

Figure 1: 3 Φ 4L Inverter topology.

A. Open Circuit faults

Given the symmetry of the structure, only the phase leg A is considered. Assuming the positive current into the single-phase A, the current flows through the switch S_{A1} and S_{A2} (or diode D_{A1}), as shown in Figure 2. When the open circuit fault occurs at the device S_{A1} , immediately the phase current A goes to zero, as illustrated in Figure 3.

Figure 2: Circuit of the single-phase inverter during the positive current.

Figure 3: Three-phase voltage waveforms: open circuit fault of S_{A1} .

In this condition, the fault current flowing in the devices D_{A2} - S_{A2} or C_B - D_{A2} - D_{A1} (path highlighted in red in Figure 3) may damage these switches and eventually lead to destruction of the entire power converter. When the fault occurs to the diode D_{A1} , the device S_{A2} is in the turn-on state also during the dead time (DT), so the voltage waveform is heavily distorted, as illustrated in Figure 4. A similar situation occurs during the negative phase current. Figure 5 shows the current path during normal operation.

Figure 4: Three-phase voltage waveforms: open circuit fault of D_{A1} .

Figure 5: Circuit of the single-phase inverter during the negative current.

As soon as the open circuit fault of the S_{A2} happens, the phase current goes to zero, as illustrated in Figure 6, and starts to flow in the D_{A1} - S_{A1} or C_B - D_{A1} - D_{A2} .

Figure 6: Three-phase voltage waveforms: open circuit fault of S_{A2} .

This situation might cause the destruction of the converter. The device S_{A1} is in the turn-on state during the dead time (DT) when the fault of D_{A2} occurs, thus the voltage waveform is strongly distorted, as shown in Figure 7.

Figure 7: Three-phase voltage waveforms: open circuit fault of D_{A2} .

The open circuit fault of S_{4L1} as well as the open circuit fault of D_{4L1} (or S_{4L2} - D_{4L2}) cause the presence of an offset in the phase voltage waveforms, as shown in Figure 8. It can be seen that the neutral point n is connected to the positive or negative bus according to the fault of S_{4L1} or S_{4L2} , so only the half DC-link is considered.

Figure 8: Three-phase voltage waveforms, open circuit fault of a) S_{4L1} and b) D_{4L1} .

B. Short Circuit faults

Assuming that the load current is positive (flowing out of the converter), the diode D_{A2} is carrying the load current. Then the IGBT S_{A1} is turning-on and the diode D_{A2} is turning-off. If the switch S_{A1} fails in short-circuit, the fault must be detected and cleared by turning-off the switch S_{A2} to avoid the short circuit of the DC-bus, which can cause the explosion of the converter. Figure 9 shows the voltage waveforms during the short circuit fault of S_{A1} .

Figure 9: Three-phase voltage waveforms, short circuit fault of S_{A1} .

Figure 10: Three-phase voltage waveforms, short circuit fault of S_{4L1} .

However, the switch S_{A2} remains short circuited. It creates an asymmetric short circuit via the remaining healthy diodes D_{A2} and 4-Leg. The equivalent circuit diagram is depicted in Figure 9. The fault current can be significantly higher than the nominal current. It may cause the explosion of the switch S_{A2} and eventually the failure of the entire power converter. A dual situation happens when the switch S_{A2} fails in short-circuit. When the short circuit fault of the S_{4L1} (or S_{4L2}), the neutral point n is connected to the positive DC-link (or negative DC-link); thus, the voltage waveforms appear to be asymmetrical as shown in Figure 10. The review of the power device faults, and the behavior of the converter are summarized in Table I.

Table I. Faults summary on the half circuit of the 4L Inverter.

Fault	Converter behavior	Condition
Open-Circuit		
S_{A1}	The positive voltage waveform is missing	Dangerous
D_{A1}	The negative voltage waveform is distorted	Dangerous
S_{A2}	The negative voltage waveform is missing	Dangerous
D_{A2}	The positive voltage waveform is distorted	Dangerous
S_{4L1}, S_{4L2}	Positive offset in the voltage waveform	Quasi-normal
D_{4L1}, D_{4L2}	Negative offset in the voltage waveform	Quasi-normal
Short-Circuit		
S_{A1}, D_{A1}	high distortion of the voltage waveform	Catastrophic
S_{A2}, D_{A2}	high distortion of the voltage waveform	Catastrophic
S_{4L1}, S_{4L2} D_{4L1}, D_{4L2}	Asymmetrical voltage waveform	Catastrophic

As it can be easily seen, the converter can continue to feed the load when the open-circuit fault happens to the power semiconductors located in the fourth leg. In other cases, the faults can seriously damage the converter.

III. FAULT DETECTION AND MANAGEMENT

This section discusses at first the fault detection strategy, followed by, the proposed control structure aimed to manage the fault. The fault detection algorithm is shown in the flow chart of Figure 11. As it can be seen, the acquired voltages and currents are compared in each switching period with the threshold phase voltage, $\pm V_{p,h}$, the threshold phase current, $\pm i_{p,h}$, and the threshold switching voltage, $\pm V_{sw,h}$. When the measured phase-to-neutral voltages, currents and phase-to-neutral switching voltages are different from zero or do not exceed the relative thresholds, the Open-Circuit Fault Indicator (OCFI) and/or the Short-Circuit Fault Indicator (SCFI) is set at low

value. In other words, monitoring the phase voltages before and after the filter, as well as the phase currents, it is possible to understand which device is faulty. For instance, when the open-circuit fault happens at S_{x1} (or S_{x2}), with $x \in \{A, B, C\}$, the phase-to-neutral voltage and current waveforms go to zero and the phase-to-neutral switching voltage is different from zero for half of the fundamental period, as illustrated in Figure 3 and Figure 6. In this case, the open-circuit fault of S_{x1} (or S_{x2}) is detected and the $OCFI_{Sx1}$ is set at high value.

Figure 11: Block scheme of the fault detection algorithm.

The open-circuit fault of the diodes D_{x1} (or D_{x2}) is easy to be recognized since the phase voltage waveform of the faulty leg does not exceed a certain voltage value, as shown in Figure 5 and Figure 7. Thus, when the phase voltage waveform is within the voltage range $\pm\sqrt{2}U_{rms}$, where U_{rms} is RMS phase voltage, the $OCFI_{Dx1}$ (or $OCFI_{Dx2}$) is set at low value. The open-circuit fault of the switch S_{4L1} (or S_{4L2}) and diode D_{4L1} (or D_{4L2}) is detected after one fundamental period how it is explained later. If the phase voltage waveforms never reach the negative peak value (or the positive peak value) an open-circuit fault at S_{4L1} (or S_{4L2}) occurs, as illustrated in Figure 8a and a relative fault indicator $OCFI_{S4L1}$ (or $OCFI_{S4L2}$) is set at high value. The short circuit fault at S_{x1} (or S_{x2}) can be detected as soon as the faulty phase exceeds the peak value and the other phase do not reach the peak value, as shown in Figure 9, so that the fault indicator $SCFI_{Sx1}$ (or $SCFI_{Sx2}$) is set at high value. Finally, the open short circuit fault at S_{4L1} (or S_{4L2}) can be detected by monitoring the three-phase voltage waveforms since the voltages never reach the positive peak value.

Once a fault is detected, the faulty switch will be forced open, and a repetitive observer (RO) based compensation will be activated. Although the three phase voltages during the above faults may not be maintained, it is possible to maintain the post-fault alpha-beta voltage as the same as in pre-fault condition, such that the output voltage vector of the 3 Φ 4L inverter is not affected by the fault. The proposed control scheme is shown in

Figure 12. As it can be seen from Figure 12, two resonant controllers, as proposed in [20], are used to regulate the alpha-beta voltage, respectively. A RO proposed in [21] is used to observe the zero sequence in the feedback voltage and inject the same zero sequence component in the 3 Φ 4L inverter.

Figure 12: The proposed control scheme: a) whole control system, b) repetitive observer, c) equivalent diagram for zero-sequence control.

The zero-sequence voltage is regulated to reconfigure the voltage vector during faults at steady state. The equation for the RO is given in (1).

$$RO(z) = \frac{Lz^{-N+M}}{V_{peak}[1+(L-1)z^{-N}]} \quad (1)$$

Where, $L=0.9$ is the gain of the RO, the delay length N is the ratio between the sampling frequency (e.g. 12 kHz) and the fundamental frequency (i.e. 50 Hz), V_{peak} is the peak value of the grid phase voltage. M equals the length delay caused by the lowpass finite impulse response (FIR) filter in Figure 12. In this work, the FIR filter is chosen to be 15th order one and its cut-off frequency is 250 Hz. Therefore, $M=15$. Space vector pulse width modulation (SVPWM) technique is implemented in the modulation block in Figure 12. Hence, third harmonic will be injected in the zero-sequence voltage, μ and which is within the passband of the FIR filter.

The zero-sequence voltage control is decoupled with the alpha-beta voltage control, its equivalent diagram is drawn in Figure 12, where, in healthy condition, D contains the third harmonics injected by the SVPWM and some high frequency measurement noises. In faulty condition, D contains also the zero-sequence voltage induced by the fault.

When per unit values are used, $V_{peak}=1$. The bode plot of the RO is shown in Figure 13. As it can be seen, the RO tracks components of $50i$ Hz ($i=0,1,...,1200$) in v_0^{err} , i.e. all harmonics

in the zero-sequence voltage, up to the Nyquist frequency. The FIR removes high frequency components in v_0^{err} , thus prevents the RO from tracking the high frequency components.

Figure 13: Bode plot of RO.

IV. SIMULATION RESULTS

The proposed control strategy has been verified by means of a digital-switching model realized in Matlab/Simulink. The 3 Φ 4L Inverter has been simulated using the parameters listed in Table II.

Table II Operating point of the of 3 Φ 4L Inverter.

DC-link voltage V_{DC}	750 V
phase-to-neutral RMS voltage u_{sn}	220 V
switching frequency f_{sw}	12 kHz
fundamental frequency f_0	50 Hz
dead-time	2 μ s

Figure 14 illustrates the three-phase voltages u_{An} , u_{Bn} , u_{Cn} , the three-phase currents i_A , i_B , i_C and the phase-to-neutral switching voltage $u_{An(sw)}$ under open-circuit fault of the switch S_{A1} . As it can be noticed, as soon as the fault happens, the proposed algorithm is able to detect the fault and the OCFI related to the switch S_{A1} changes from low to high value.

Figure 14: Three-phase voltages u_{An} , u_{Bn} , u_{Cn} , three-phase currents i_A , i_B , i_C , phase-to-neutral switching voltage $u_{An(sw)}$ and OCFI under open-circuit fault in S_{A1} .

In this case, the detection algorithm checks both the phase voltage u_{An} and the switching voltage $u_{An(sw)}$. Given that these voltages are in different sector compared to normal operating condition, the fault of the device is detected. In fact, the phase voltage u_{An} goes to zero and the voltage across the switch S_{A1} is equal to the DC-link voltage V_{DC} instead of zero, as it is evident from the switching voltage in Figure 14. Figure 15 shows the voltage and current waveforms under short-circuit fault in S_{A1} .

Figure 15: Three-phase voltages u_{An} , u_{Bn} , u_{Cn} , three-phase currents i_A , i_B , i_C , switching voltage $u_{An(sw)}$ and SCFI under short-circuit fault in S_{A1} .

Here, the fault detection algorithm can identify the fault as soon as it occurs too and the fault indicator SCFI, related to the switch S_{A1} , is set at high value. In both cases, the open-circuit and the short circuit of the switch S_{A1} is detected within the switching period. The open-circuit fault of S_{4L1} (or S_{4L2}) is detected in one fundamental period as illustrated in Figure 16. This fault is very difficult to detect due to the converter behavior that is very similar to the normal operation.

Figure 16: Three-phase voltages u_{An} , u_{Bn} , u_{Cn} , three-phase currents i_A , i_B , i_C , phase-to-neutral switching voltage $u_{An(sw)}$ and OCFI under open-circuit fault in S_{4L1} .

In this condition, the algorithm checks whether the phase voltage and current waveforms reach their maximum peak in

the fundamental period. Since the voltage and current waveforms never reach the negative peak and exceed the positive peak in case of S_{4L1} fault (or the voltage and current waveforms never reach the positive peak and exceed the negative peak in case of D_{4L1} fault), in the following fundamental period the fault is detected by enabling the $OCFI$ related to the switch S_{4L1} (or D_{4L1}), as illustrated in Figure 16. The short-circuit of the device S_{4L1} is immediately detect since the phase voltage u_{xn} and the phase-to-neutral switching voltage $u_{xn(sw)}$ are in different sector from the normal operation condition and the fault indicator is set at high value.

Figure 17: Three-phase voltages u_{An} , u_{Bn} , u_{Cn} , three-phase currents i_A , i_B , i_C , phase-to-neutral switching voltage $u_{An(sw)}$ and $SCFI$ under short-circuit fault in S_{4L1} .

Figure 18: Open circuit fault management of S_{A1} : with/without RO for zero sequence injection.

When the open circuit fault of S_{A1} occurs, the v_a , v_b , and the zero-sequence voltage v_0 with and without RO are compared in Figure 18. The results indicate that, with RO to regulate the zero-sequence voltage, the alpha-beta voltage can track the reference as if there is no fault. Figure 19 shows the voltage waveforms when open circuit faults happen at both S_{A1} and S_{B1} . As it is shown, v_a , v_b are maintained with RO. The voltage waveforms when both S_{A1} and S_{A2} are open and when S_{4L1} is open are shown in Figure 20 and Figure 21, respectively. According to Figure 21, the alpha and beta voltages are maintained both with and without RO, so it is optional to

activate RO or not in this case. The short-circuit faults of any power semiconductors have strong impact on the converter, leading to high short-circuit current flowing in both the power switches and DC-bus capacitors. In this case, the control algorithm is able to identify and to isolate the faulty leg, as well as to change the current path into the healthy leg.

Figure 19: Open circuit fault management of S_{A1} and S_{B1} : with/without RO for zero sequence injection.

Figure 20: Open circuit fault management of S_{A1} and S_{A2} : with/without RO for zero sequence injection.

Figure 21: Open circuit fault management of S_{4L1} : with/without RO for zero sequence injection.

V. EXPERIMENTAL RESULTS

Experimental tests have been performed to verify the validity and effectiveness of the proposed fault detection and control

algorithm. The proposed fault detection and control algorithm have been implemented in LabVIEW environment and it has been tested on the prototype of 3 Φ 4L Inverter with a suitably designed output filter [22], as shown in Figure 22.

Figure 22: 3 Φ 4L Inverter prototype with the three-phase output filter.

Looking at the figure, it is possible to recognize the 3 Φ 4L Inverter, the filter board and the control board which are based on the National Instruments sbRIO-9651 System on Module (SoM) [23]. The converter has been built using four SEMIX module (SEMIX303GB12Vs) 300A-1200V. The prototype of the converter has been tested considering the DC-link voltage $V_{DC}=400$ V, the phase-to-neutral RMS voltage $u_{sn}=220$ V, the switching frequency $f_{sw}=12$ kHz and the fundamental frequency $f_0=50$ Hz. The DC-link voltage has been kept at 400 V by the multi-port DAB converter available in the laboratory [24]. Voltage and current waveforms are investigated using the Yokogawa DL9140 oscilloscope. Figure 23 shows the phase-to-neutral switching voltage $u_{An(sw)}$, the phase-to-neutral voltages u_{An} , u_{Bn} , the phase current i_A , under open-circuit fault at S_{A1} .

Figure 23: Waveforms under open-circuit fault in S_{A1} : a) phase-to-neutral switching voltage $u_{An(sw)}$ (violet trace, 200V/div), b) phase-to-neutral voltages u_{An} , u_{Bn} (yellow trace and green trace, 200V/div), c) phase current i_A , (cyan trace, 20A/div), d) OCFI (red trace 5V/div).

As it can be seen, the positive phase current and the positive phase-to-neutral voltage u_{An} go to zero and the voltage across the switch S_{A1} is equal to DC-link voltage V_{DC} instead of zero. The fault is correctly identified as soon as it happens, so that the $OCFI_{SA1}$ changes from 0V to 5V. Figure 24 shows the experimental test when the open-circuit fault has occurred in S_{A1} .

Figure 24: Waveforms under open-circuit fault in S_{A1} : a) phase-to-neutral switching voltage $u_{An(sw)}$ (violet trace, 200V/div), b) phase-to-neutral voltages u_{An} , u_{Bn} (yellow trace and green trace, 200V/div), c) phase current i_A , (cyan trace, 20A/div), d) OCFI (red trace 5V/div).

Figure 25: $\alpha\beta 0$ output voltages v_a^{fbk} , v_β^{fbk} , v_0^{fbk} under the open-circuit fault in S_{A1} : a) with RO and b) without RO. v_a^{fbk} green trace, 100V/div, v_β^{fbk} yellow trace, 100V/div and v_0^{fbk} violet trace, 400V/div.

In this case, there is only an offset in the phase-to-neutral voltages u_{An} , u_{Bn} and phase current i_A . Unlike other cases, the fault detection algorithm is able to identify the fault in the subsequent fundamental period, as illustrated in Figure 24. Figure 25 shows the waveform in $\alpha\beta\theta$ domain under the open-circuit fault in S_{A1} with and without RO. As it can be seen, the RO is able to compensate the fault by keeping the $\alpha\beta\theta$ output voltages, v_d^{fbk} , v_β^{fbk} , v_θ^{fbk} , in pre-failure condition. When the RO is disabled the $\alpha\beta\theta$ output voltages are distorted due to the fault. Thus, after the detection of the fault, the fault-tolerant control is applied and, in some cases, the converter can operate feeding the load.

VI. CONCLUSIONS

This paper presents a novel fault detection and ride/through method for a 3 Φ 4L Inverter in stand-alone applications. The open circuit and short circuit faults of the power semiconductors have been illustrated and the control strategy to detect and manage these faults has been proposed. The performance of the proposed control strategy has been at first verified through a numerical model in Matlab/Simulink. Experimental results to validate the effectiveness of the proposed control strategy are also presented. The results demonstrate that the proposed fault detection and management control method allows to effectively manage open and short-circuit faults. In summary, the proposed method can maintain the $\alpha\beta\theta$ output voltages, v_d^{fbk} , v_β^{fbk} , v_θ^{fbk} , under the following conditions:

- when there is one switch open;
- with any two switches open;
- when the 4th leg of the converter has one switch shorted;

when there is a short-circuit fault in the three-phase legs, the faulted half leg should be open, such that it becomes an open circuit fault. Specially, the RO itself can work without knowing exactly the location of the open circuit faults. Existing methods tend to leave-open the whole leg when any of the half leg is open or shorted. However, the proposed method only requires to leave-open the broken half leg, while the healthy half leg can still be used.

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