ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

Vol. 7, Issue 1, January 2018

Cross-Correlation Based Open-Switch Fault Detection Method in Parallel Inverters System

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Abstract: This paper proposes a new detection method of the open-switch fault, this method is based on the crosscorrelation of the zero-sequence current in N-parallel inverters system. Under the open-switch fault conditions, the appearance of the circulating currents between the faulty and healthy inverters, is inevitable. The zero-sequence current is used to identify the faulty open-circuited switch by the cross correlation. The line current of the faulty phase, is so small or nearly zero, while the resulting zero-sequence current will be synchronized with a reference current which is corresponding to the faulty phase current. So there is a significant correlation of the faulty phase by its reference and the resulting zero-sequence current. While the waveform between the healthy phases and the resulting zero-sequence current show a significant irrelevance. By taking the advantage of this feature between the healthy, faulty and zero-sequence current, the detection method can correctly select out the faulty open-circuited switch. The effectiveness of the proposed open-switch fault detection algorithm is theoretically analyzed and validated by the simulations and the experiments.

Keywords: Parallel inverters; Cross-correlation; Zero sequence current; Open-switch fault; Fault detection

I. INTRODUCTION

The reliability, continuity, and fault issues have attracted more interests in the development of the parallel inverters system. In the high capacity solar power generation systems, the parallel connection of the converters, is an efficient and inevitable method, to meet the high-power requirements. The parallel connection of the converters is important for the critical customers due to the financial constraints [1,2]. Then the number of the parallel inverters in terms of reliability and cost optimization, can be achieved [3-6]. The major concern for the parallel operation is the problem of the circulating currents at the common connection of each inverter. The definition of the phenomenon of the circulating currents [7,8]. The fault diagnosis and localization problem have an important issue to improve the safety and to reduce the high repairing cost. The inverters under fault conditions, are often exposed to high stresses that can lead to failure of the inverter power semiconductor devices [9]. In the case of the open-switch fault, without a sufficient and early fault detection system, the failure may expand to the entire system, may cause a serious damage, and may lead to excessive thermal stresses, in consequence, leads to a secondary open-switch fault within the same inverter or in the other units [10,11]. The schema of the device studied is given in Figure 1.

The fault diagnosis techniques have been reviewed for the open-switch fault in the ac systems [12]. The fault detection has gradually attracted the research interest in many practical applications such as the wind energy systems [13], electric or hybrid distribution systems [14], and multilevel inverter [15]. To detect and identify the open-switch fault location, the Park's vector current and the phase angle in the complex plan have been used [16,17]. However, these methods have a major drawback of being load-dependent and relatively complex, this method is not appropriate to be integrated into the ac drive controller. The open-switch fault in the asymmetric bridge converter for the switched reluctance motor drives, has been detected by using the real time current state [18,19]. The open-switch fault diagnosis in the power converters of PMSG-based wind turbine has been developed [20,21]. The voltage-based open-switch fault detection methods which are based on the inverter output voltage model, are investigated in order to reduce the detection time [22-25]. The voltage based detection methods need many voltage sensors. These methods add more cost and complexity to the detection system. The detection process may be influenced by the variations of the input supply voltage and the output power. A fault detection method is presented, this method is based on the spectrum analysis of the measured voltage and the current in the converter [22,23]. This method may need more measurements, calculations and time. The detection method for the open-switch fault in the grid connected T-Type rectifier, is based on the measured voltages, however this method requires additional voltage sensors [23]. Under the nonlinear loads conditions, the detection will be difficult due to existence of deviation between the reference, and the measured variables, this deviation is resulting from the non-ideal switching behavior of the inverter. So an estimator is needed instead of the direct use of the reference variables [24-26]. An openswitch fault detection method which is based on averaging of the absolute value of the current, as principal quantities for the diagnostic method [27-30]. However, these methods necessitates additional measurements for the line currents.

The fault detection algorithm for the three-phase NPC inverter is achieved by measuring the pole voltage [31]. However, this method necessitates complicated calculations. An algorithm is achieved by using the relative magnitude of the second-order harmonic component in the phase currents [32,33]. It may not be effective for the nonlinear or unbalanced loads, since the harmonic content is high under the nonlinear or the unbalanced loads. The failure detection technique is based on the gate-signal monitoring for the IGBTs under the open- or short-circuited switch failures [34]. This method implies addition of an analog and auxiliary circuit which adds more cost to the system. A failure detection method of the open-phase fault for the PMSM drive system is presented [35,36]. This method is based on the zero-sequence voltage component. It uses the FFT analysis and it needs at least one complete cycle to complete the calculation. The current path of the capacitance is used to detect the open-switch fault; this method needs more calculations for the detection process [37]. The current deviation in the stationary reference frame *αβ*, is employed as a fault indicator [37-39]. This method may not be accurate for the unbalanced or nonlinear load.

In this paper, a new open-switch fault detection algorithm is proposed to detect the internal fault occurrence in the three phase parallel inverters system. This algorithm is based on the cross-correlation analysis of the waveforms. The proposed fault diagnosis and localization algorithms are described to detect the open-switch fault for *N*-parallel inverters. The algorithm can be easily inserted into the control scheme as a subroutine without major modifications and with low-complexity. It depends on the change in the current waveform that occurs during the internal fault. Compared with the existing current-based methods, the proposed method is based on the symmetry analysis between the correlation coefficients, this symmetry cannot be found anywhere else.

II. STRUCTURE DESCRIPTION AND MODELING

The power supply system which is presented in this paper consists of *N*-non-isolated inverters as shown in Figure 1.

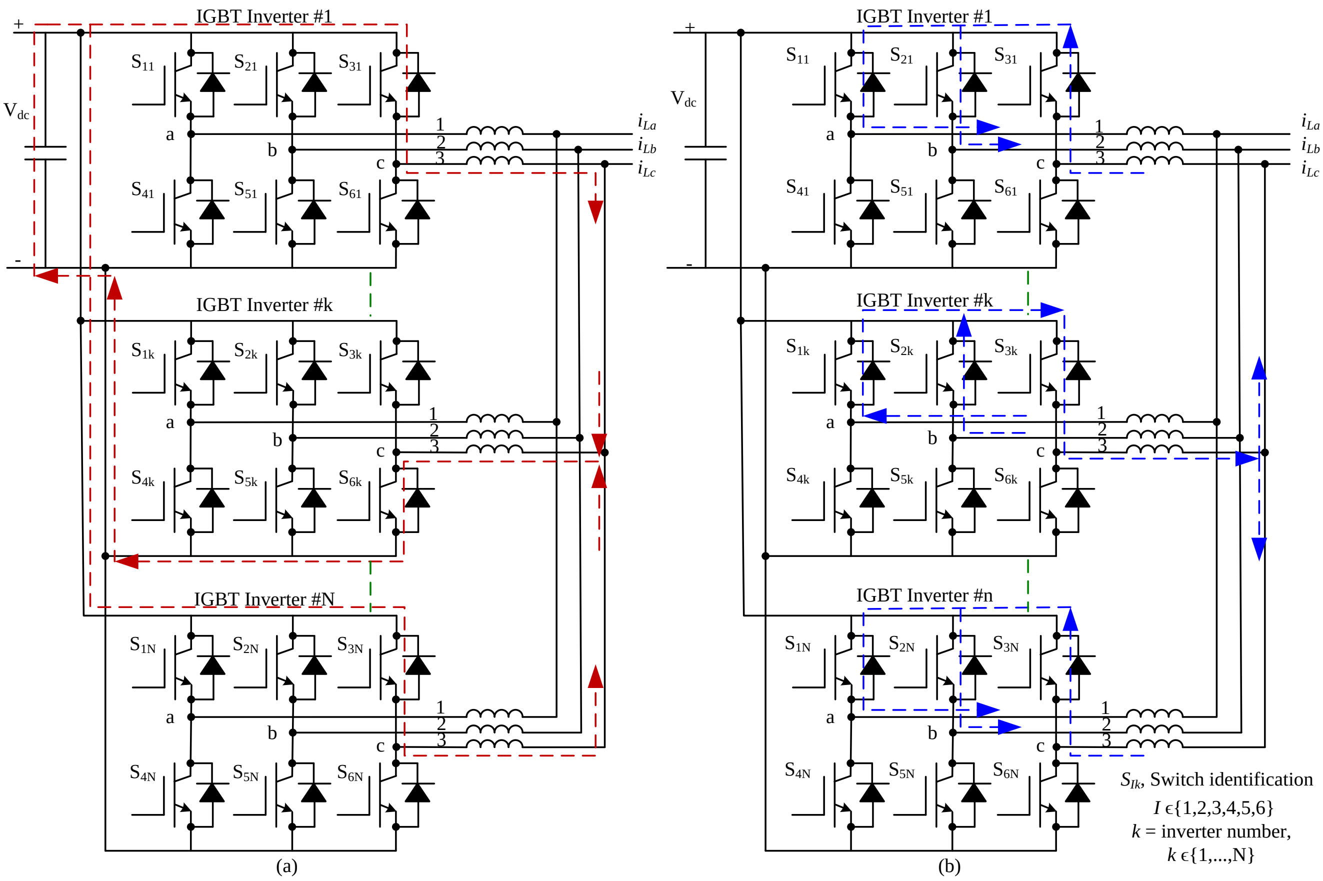


Figure 1: Architecture of complete DC/AC system of N- parallel inverters with the circulating current paths under faulty condition (S_{11}, inverter *k*).

By taking a random subsystem under the open-switch fault conditions, the resulting circulating currents can flow between the parallel inverters through the dc-link and the anti-parallel diodes. The circulating currents can be divided into two kinds: one is the zero-sequence circulating current as shown in Figure 1a, this current can be transferred only to the zero-axis. The others are the cross currents as shown in Figure 1b, these currents involve three-phase currents that can be transformed to the *d*-axis and *q*-axis.

III. PRINCIPLE OF THE PROPOSED CORRELATION TECHNIQUE

The Correlation is a very important tool in the signal processing, it's often used to search for the similarity of two signals or the self-similarity after a delay of signal [40-44]. There are two types of the Correlation; auto and crosscorrelation; the auto-correlation is the correlation of a signal with itself at different points with the time. The crosscorrelation is a measure of the similarity of two series as a function of the lag of one relative to the other. The crosscorrelation is similar to the convolution of two signals [41-45]. The cross-correlation can eventually make the detection of the faulty open-circuited switch under the faulty conditions. The proposed open-switch fault technique is based on the cross-correlation between the resulting normalized value of the zero-sequence current and the corresponding reference currents waveforms.

According to MathWorks [46], for given two signals *i* and *j*, the cross-correlation measures the similarity between *i* and the shifted (lagged) copies of *j*. If *i* and *j* have different lengths, the function gives zeros at the end of the shorter vector, so it has the same length *N* as the other [46]. The coefficient $f_{ij} = xcorr(i, j)$ returns the cross-correlation of the two discrete-time sequences; *i* and *j* [46]. According to the previous definition, the cross-correlation function involves the multiplication of two signals. For the continuous functions *i* and *j*, the cross-correlation coefficient of $i(t)$and *j(t)* is defined as follows:

$$f_{ij} = \sum_{n=0}^{N-1} i(n)\, j(n) \left[\sum_{n=0}^{N-1} i^2(n) \sum_{n=0}^{N-1} j^2(n) \right]^{-1/2} \qquad (1)$$

Where; $f_{xy} \epsilon \{-1,0,1\}$ The value "+1" means that, the two signals are in a perfect positive correlation, while the value "-1" indicates they are in a perfect negative correlation, the value "0" indicates a lack of correlation and the two signals are totally different and has no relationship with each other. Expressing the currents by using Park's transformation as an efficient formulation, allows location of the faulty open circuited switch by using the conventional *dq0* model. The relationship between the *k*th inverter line currents in the three phase stationary coordinates and those in the synchronous rotating coordinates (Parks') are expressed by (2) and (3).

$$\begin{pmatrix} i_{ak} \\ i_{bk} \\ i_{ck} \end{pmatrix} = I_{mk} \begin{pmatrix} sin(\theta - \varphi_a) \\ sin\left(\theta - \varphi_b - \frac{2\pi}{3}\right) \\ sin\left(\theta - \varphi_c + \frac{2\pi}{3}\right) \end{pmatrix} \qquad (2)$$

$$\begin{pmatrix} i_{0k} \\ i_{dk} \\ i_{qk} \end{pmatrix} = P(\theta) \begin{pmatrix} i_{ak} \\ i_{bk} \\ i_{ck} \end{pmatrix}, P(\theta) = \sqrt{\frac{2}{3}} \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ cos(\theta) & cos\left(\theta - \frac{2\pi}{3}\right) & cos\left(\theta + \frac{2\pi}{3}\right) \\ -sin(\theta) & -sin\left(\theta - \frac{2\pi}{3}\right) & -sin\left(\theta + \frac{2\pi}{3}\right) \end{pmatrix} \qquad (3)$$

Where; θ is an arbitrary time-dependent angle, *Imk* is the peak value of i_{ak}, i_{bk} and i_{ck}, φ_a, φ_b, and φ_c are the phase difference between the phases voltages and currents. Under the unbalanced or fault conditions, there will be circulating currents between the parallel units. These circulating currents can be compensated by a nonlinear current controller to keep the output currents stable and the load power non-changed. Therefore the circulating currents controller for this system should contain controllers on all the three axes; namely *d*controller, *q*-controller, and *z*-controller. These controllers minimize the circulating currents and ensure that the load power is equally shared between the parallel inverters. The considered model of the circulating current minimization is a direct application of Shahin et al. [8] as given in Equation (4).

$$y_{zik} = \begin{pmatrix} y_{z0ik} \\ y_{zdik} \\ y_{zqik} \end{pmatrix} = \begin{pmatrix} i_{0i} - i_{0k} \\ i_{di} - i_{dk} \\ i_{qi} - i_{qk} \end{pmatrix}, \forall k \in \{1,...,N\}, k \neq i \quad (4)$$

where y_{zik} represents the current difference between the faulty inverter k^{th}, and a reference inverter (i.e., the first inverter in this case; i=1). The detection algorithm will be activated when there will be a zero-sequence current under the open-switch fault conditions. In this case, the value of y_{zik} will not be null and the detection algorithm will start.

IV. PROPOSED FAULT DIAGNOSTIC ALGORITHM UNDER OPEN-SWITCH FAULT

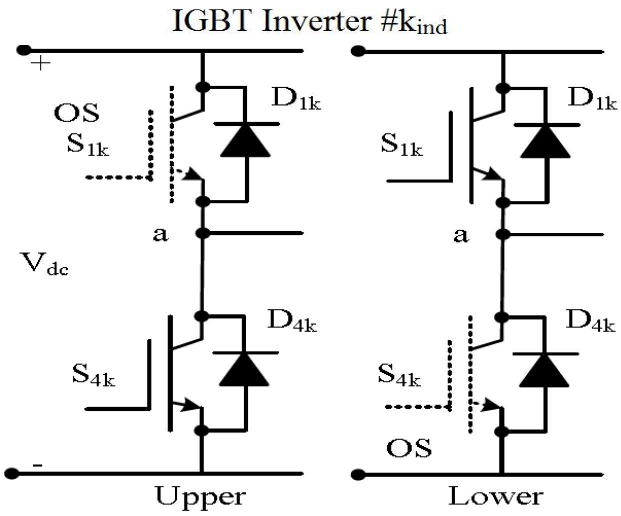
A. Currents Behavior Under Open-Switch Fault Condition

The point of common connection PCC at the output ac bus, represents the conduction path of the circulating currents as shown in Figure 1. Since the load has no neutral point, so the neutral points of the parallel inverters system will be established by the anti-parallel diodes for one inverter by the other units in the parallel system. So the sums of the currents which are drawn by the load and the ac bus equal zero under both healthy and faulty conditions. Therefore the sum of the load and line currents is null under both normal and abnormal conditions at PCC as given by (5) and (6).

$$\sum_{i=a,b,c} i_{Li} = 0 \quad (5)$$

$$\sum_{k=1}^{N} \left(i_{ak} + i_{bk} + i_{ck} = 0 \right) \quad (6)$$

Under the faulty conditions like the open-switch fault in any inverter in the parallel system, there will be a large circulating current between the parallel units. The zero-sequence current is no more zero, since it is not full disconnection as given by (6). The sign of the zero-sequence current, indicates the location of the open-circuited switch, the sign will be negative for the upper open-switch fault case and positive for the lower fault case. By applying (3), the *dq0* currents components will be influenced by the transient values of the inverter currents *iak*, *ibk*, and *ick* under the corresponding open-switch fault as shown in Figure 2.



OS: open-circuited switch.
S_{1k}: open-circuited switch (upper).
S_{4k}: open-circuited switch (lower).
$k=k_{ind}$: index inverter number.

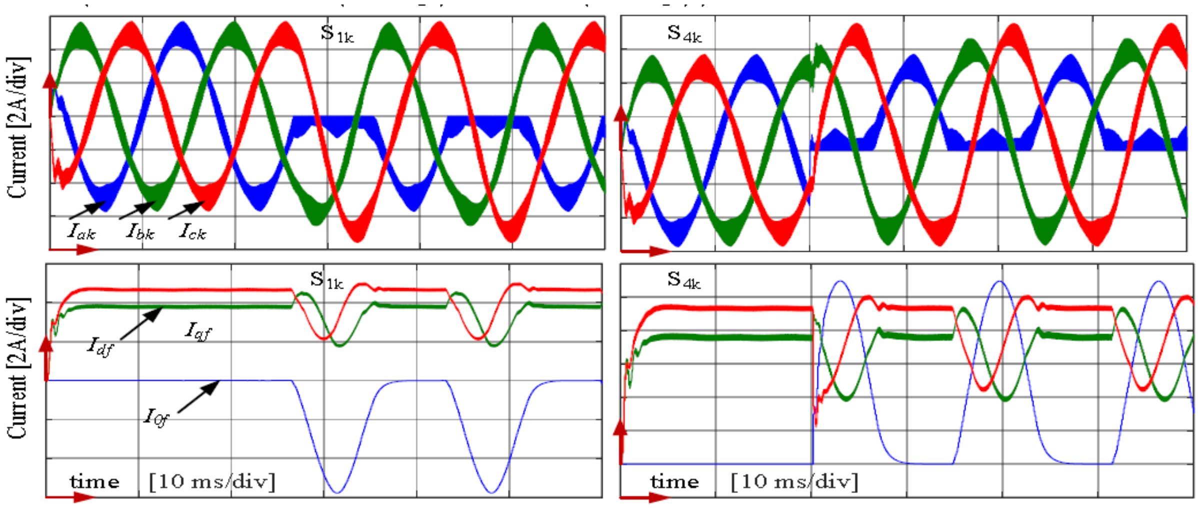


Figure 2: Current waveforms for faulty open-circuited switch conditions (S_{1k}; upper and S_{4k}; lower, inverter: k=k_{ind}).

According to Figure 1, the fault localization problem relies on only one probable open-switch fault case in any k^{th} inverter in the parallel inverters system. The zero-sequence current of the faulty inverter flows at the point PCC to all the parallel inverters system, while those zero-sequence currents that are running in the healthy inverters are totally opposite to the zero-sequence current that flow in the faulty inverter. In case of the open-circuit fault conditions, there are only $N-1$ zero-sequence current paths in the given N subsystems. So the sum of the zero-sequence current will be null, i.e. $\sum_{j=1}^{N} i_{0j} = 0$. The zero-sequence current i_{0k} of the faulty k^{th} inverter can be found by the sum of $N-1$ zero-sequence currents of the healthy inverters and it can be given as:

$$i_{0k} = -\sum_{l=1}^{N} i_{0l}, l \neq k \quad (7)$$

The sign and the wave form of the zero-sequence current will depend on the corresponding phase and the moment of the fault occurrence, where the zero-sequence current of the k^{th} path, namely i_{0k} as a direct application of (3) of each respective inverter, is

$$i_{0k} = \frac{1}{\sqrt{3}}\left(i_{ak} + i_{bk} + i_{ck}\right), \forall k \in \{1, \ldots, N\} \quad (8)$$

So the zero-sequence current i_{0k} can be expressed by three parts; positive current i_{0k+} for the lower open-switch fault case, negative current i_{0k-} for the upper open-switch fault case and zero for the normal operation or the full disconnection.

B. Currents Model under Open-Switch Fault Conditions

The components of the zero-sequence current can be investigated by the location of the faulty open-circuited switch by inserting the identification variables in eq. (8). Then the zero-sequence current components appearance is related to the faulty inverter line currents during the fault conditions as following:

$$i_{0k} = \begin{pmatrix} i_{0k-} \\ i_{0k+} \\ 0 \end{pmatrix} = \frac{1}{\sqrt{3}} \begin{pmatrix} FS_{1k} & FS_{2k} & FS_{3k} \\ FS_{4k} & FS_{5k} & FS_{6k} \\ 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} i_{ak} \\ i_{bk} \\ i_{ck} \end{pmatrix} \quad (9)$$

Where; FS_{jk} $\forall j \in \{1, \ldots, 6\}$, represents the corresponding open-switch detection identifiers. Under the full disconnection of any inverter, the zero-sequence current equals zero, so (9) can be reduced to (10), where *Imk* is the maximum value of the line current of each inverter.

$$\begin{pmatrix} i_{0k-} \\ i_{0k+} \end{pmatrix} = \frac{1}{\sqrt{3}} \begin{pmatrix} FS_{1k} & FS_{2k} & FS_{3k} \\ FS_{4k} & FS_{5k} & FS_{6k} \end{pmatrix} \begin{pmatrix} i_{ak} \\ i_{bk} \\ i_{ck} \end{pmatrix} = \frac{I_{mk}}{\sqrt{3}} \begin{pmatrix} FS_{1k} & FS_{2k} & FS_{3k} \\ FS_{4k} & FS_{5k} & FS_{6k} \end{pmatrix} \begin{pmatrix} sin(\theta) \\ sin\left(\theta - \frac{2\pi}{3}\right) \\ sin\left(\theta + \frac{2\pi}{3}\right) \end{pmatrix} \quad (10)$$

$$I_{ref} = norm\left(\mathcal{F}\left(I_L\right)\right) = \begin{pmatrix} i_{aref} \\ i_{bref} \\ i_{cref} \end{pmatrix} = norm\left(I_{mL} \begin{pmatrix} sin(\theta) \\ sin\left(\theta - \frac{2\pi}{3}\right) \\ sin\left(\theta + \frac{2\pi}{3}\right) \end{pmatrix} \right) = \begin{pmatrix} sin(\theta) \\ sin\left(\theta - \frac{2\pi}{3}\right) \\ sin\left(\theta + \frac{2\pi}{3}\right) \end{pmatrix} \quad (11)$$

For the parallel inverters system, the continuity of the load is guaranteed by the parallel operation. So a reference current can be extracted by normalizing the load current. The reference currents can by expressed by (11), where $\mathcal{F}$ is the filtration of the load currents, I_{mL} is the maximum value of the load currents. The output line currents of each inverter under the normal condition can be related to I_{ref} as following:

$$\begin{pmatrix} i_{ak} \\ i_{bk} \\ i_{ck} \end{pmatrix} = I_{mk} I_{ref} = I_{mk} \begin{pmatrix} sin(\theta) \\ sin\left(\theta - \frac{2\pi}{3}\right) \\ sin\left(\theta + \frac{2\pi}{3}\right) \end{pmatrix} \quad (12)$$

The procedures of the open-switch fault detection can be activated by the detection of the maximum value of the resulting zero-sequence current according to (4), to identify the faulty inverter index k_{ind}, where

$$\left[i_{0k}, k_{ind}\right] = \max\left(i_{01}, \ldots i_{0f}, \ldots i_{0N}\right), \forall f = k_{ind} \quad (13)$$

The sign of the corresponding zero-sequence current will indicate either upper or lower open-switch fault case.

$$\begin{pmatrix} i_{0k-} \\ i_{0k+} \end{pmatrix} = \begin{cases} if\ i_{0k} < 0 \\ if\ i_{0k} > 0 \end{cases}, \forall k = k_{ind} \quad (14)$$

By applying the normalization to (12) and (14), where the sign "^" refers to the normalization. All the currents, and are normalized and become:

$$\begin{pmatrix} \hat{i}_{ak} \\ \hat{i}_{bk} \\ \hat{i}_{ck} \end{pmatrix} = Norm\left(I_{mk} \begin{pmatrix} sin(\theta) \\ sin\left(\theta - \frac{2\pi}{3}\right) \\ sin\left(\theta + \frac{2\pi}{3}\right) \end{pmatrix} \right) = \begin{pmatrix} sin(\theta) \\ sin\left(\theta - \frac{2\pi}{3}\right) \\ sin\left(\theta + \frac{2\pi}{3}\right) \end{pmatrix} \quad (15)$$

$$\begin{pmatrix} \hat{i}_{0k-} \\ \hat{i}_{0k+} \end{pmatrix} = Norm \begin{pmatrix} i_{0k-} \\ i_{0k+} \end{pmatrix} \quad (16)$$

The normalization of the signal $FS_{jk}\ \forall j \in \{1, \dots, 6\}$ is equal to “1”. From (10), the normalized zero-sequence current can be expressed by (17). To limit the intervention of the zero-sequence current and the corresponding reference currents, a discretization of the normalized measured variables around its peak value, is used as given in eq. (18). The discrete values of the normalized reference currents are given as a pulse around the peak value of the waveforms.

$$\begin{pmatrix} \hat{i}_{0k-} \\ \hat{i}_{0k+} \end{pmatrix} = Norm\left(\frac{I_{mk}}{\sqrt{3}} \begin{pmatrix} FS_{1k} & FS_{2k} & FS_{3k} \\ FS_{4k} & FS_{5k} & FS_{6k} \end{pmatrix} \begin{pmatrix} \sin(\theta) \\ \sin\left(\theta - \frac{2\pi}{3}\right) \\ \sin\left(\theta + \frac{2\pi}{3}\right) \end{pmatrix} \right) = \begin{pmatrix} FS_{1k} & FS_{2k} & FS_{3k} \\ FS_{4k} & FS_{5k} & FS_{6k} \end{pmatrix} Norm\left(\frac{I_{mk}}{\sqrt{3}} \begin{pmatrix} \sin(\theta) \\ \sin\left(\theta - \frac{2\pi}{3}\right) \\ \sin\left(\theta + \frac{2\pi}{3}\right) \end{pmatrix} \right) \quad (17)$$

$$discr\begin{pmatrix} \hat{i}_{0k-} \\ \hat{i}_{0k+} \end{pmatrix} = \begin{pmatrix} FS_{1k} & FS_{2k} & FS_{3k} \\ FS_{4k} & FS_{5k} & FS_{6k} \end{pmatrix} discr\begin{pmatrix} \hat{i}_{ak} \\ \hat{i}_{bk} \\ \hat{i}_{ck} \end{pmatrix} = \begin{pmatrix} FS_{1k} & FS_{2k} & FS_{3k} \\ FS_{4k} & FS_{5k} & FS_{6k} \end{pmatrix} discr\begin{pmatrix} \sin(\theta) \\ \sin\left(\theta - \frac{2\pi}{3}\right) \\ \sin\left(\theta + \frac{2\pi}{3}\right) \end{pmatrix} \quad (18)$$

The detection identifiers can be expressed in eq. (19). The expected discrete value of the zero-sequence current under the fault conditions and the corresponding discrete value of the reference currents for each phase are given in eq. (20) and (21), according to their relative position to the three-phase line currents of each inverter with respective to the load currents at the ac bus. Where “0” refers to no zero-sequence current and “1” means that there is a zero-sequence current for both positive and negative part, also the values of the reference currents are corresponding to their peak value.

$$\begin{pmatrix} FS_{1k} & FS_{2k} & FS_{3k} \\ FS_{4k} & FS_{5k} & FS_{6k} \end{pmatrix} = \left(discr\begin{pmatrix} \hat{i}_{0k-} \\ \hat{i}_{0k+} \end{pmatrix} disc\begin{pmatrix} sin(\theta) \\ sin\left(\theta - \frac{2\pi}{3}\right) \\ sin\left(\theta + \frac{2\pi}{3}\right) \end{pmatrix}^{t} \right) \quad (19)$$

$$discr\begin{pmatrix} \hat{i}_{0k-} \\ \hat{i}_{0k+} \end{pmatrix} \in \begin{Bmatrix} 100000 & 010000 & 001000 \\ 000100 & 000010 & 000001 \end{Bmatrix} \quad (20)$$

$$discr\begin{pmatrix} sin(\theta) \\ sin\left(\theta - \frac{2\pi}{3}\right) \\ sin\left(\theta + \frac{2\pi}{3}\right) \end{pmatrix} \in \begin{Bmatrix} 100100 \\ 010010 \\ 001001 \end{Bmatrix} \quad (21)$$

By employing the model given by (19), (20) and (21), the faulty open-circuited switch identifiers FS_{jk} can be calculated by the cross-correlation between expected discrete values of the zero-sequence current and the corresponding discrete values of the reference current which is corresponding to the faulty phase as given by (22). Under the fault conditions, the values of the detection identifiers are assigned to “1”, and they can be given by one-to-one scalar product of the expected value of the zero-sequence current with the corresponding value of the reference current as given by (23).

C. Algorithm of Cross-Correlation based Fault Detection

The schematic diagram of the proposed open-switch fault detection algorithm which is based on the cross-correlation, is shown in Figure 3. To effectively detect and identify the faulty open-circuited switches according to their distinctive fault signature in a systematic way, six by N open-switch fault cases are dealt in Figure 3. The three phase line currents i_{ak}, i_{bk}, and i_{ck} for any unit, are measured for the control purpose and these currents are used by the current error vector y_{zk} to detect if there is a circulating current between the parallel units. Under the normal conditions, there is no circulating current between the parallel units. Under the abnormal conditions of any inverter, the procedure for the proposed fault diagnosis algorithm which is given through (13) to (23), is activated by employing (4). For the open-switch fault case, it is evidence that, i_{0k} is the maximum resulting value for N>2. In the case of only two inverters in parallel, there will be only one zero-sequence current path between the two inverters. In this case the vector y_{zk} will be employed to choose the faulty inverter instead of the maximum zero-sequence current criterion.

$$\begin{pmatrix} FS_{1k} & FS_{2k} & FS_{3k} \\ FS_{4k} & FS_{5k} & FS_{6k} \end{pmatrix} = XCorr\left(discr\begin{pmatrix} \hat{i}_{0k-} \\ \hat{i}_{0k+} \end{pmatrix} disc\begin{pmatrix} sin(\theta) \\ sin\left(\theta - \frac{2\pi}{3}\right) \\ sin\left(\theta + \frac{2\pi}{3}\right) \end{pmatrix}^t \right) \quad (22)$$

$$\begin{pmatrix} FS_{1k} & FS_{2k} & FS_{3k} \\ FS_{4k} & FS_{5k} & FS_{6k} \end{pmatrix} = XCorr\left(\begin{Bmatrix} 100000 & 010000 & 001000 \\ 000100 & 000010 & 000001 \end{Bmatrix} \left(\begin{Bmatrix} 100100 \\ 010010 \\ 001001 \end{Bmatrix} \right)^t \right) \quad (23)$$

V. SIMULATION RESULTS

To validate the proposed open-switch fault diagnosis method, a model based on MATLAB-Simulink has been performed. Three three-phase parallel inverters are considered (i.e. N=3). In this simulation, the parameters of the proposed system are listed in Table 1. Figure 4 shows the simulation behavior results for the proposed fault detection method. Figures 4(a1) and 4(b1) show FS_{jk}, I_{abc}, I_{dq0}, and I_{ref}, when the switch S_{11} (consequently S_{21} and S_{31}), as upper switches of the first inverter (i.e. k_{ind}=1), is under the open-switch fault conditions. A detection signal was occurred at t=32 ms. The faulty phase has negative unidirectional current as shown in Figure 4(a1). At the moment of the open-switch occurrence, the zero-sequence current for the faulty inverter is no longer zero and represents the maximum resulting value between the parallel inverters as shown in Figure 4(b1). The currents I_{dq} of are perturbed by the lost part of the line current.

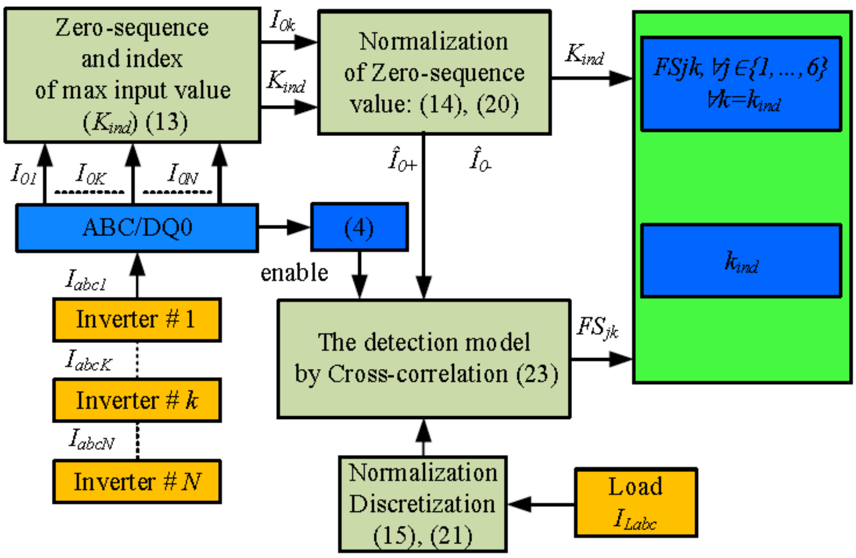


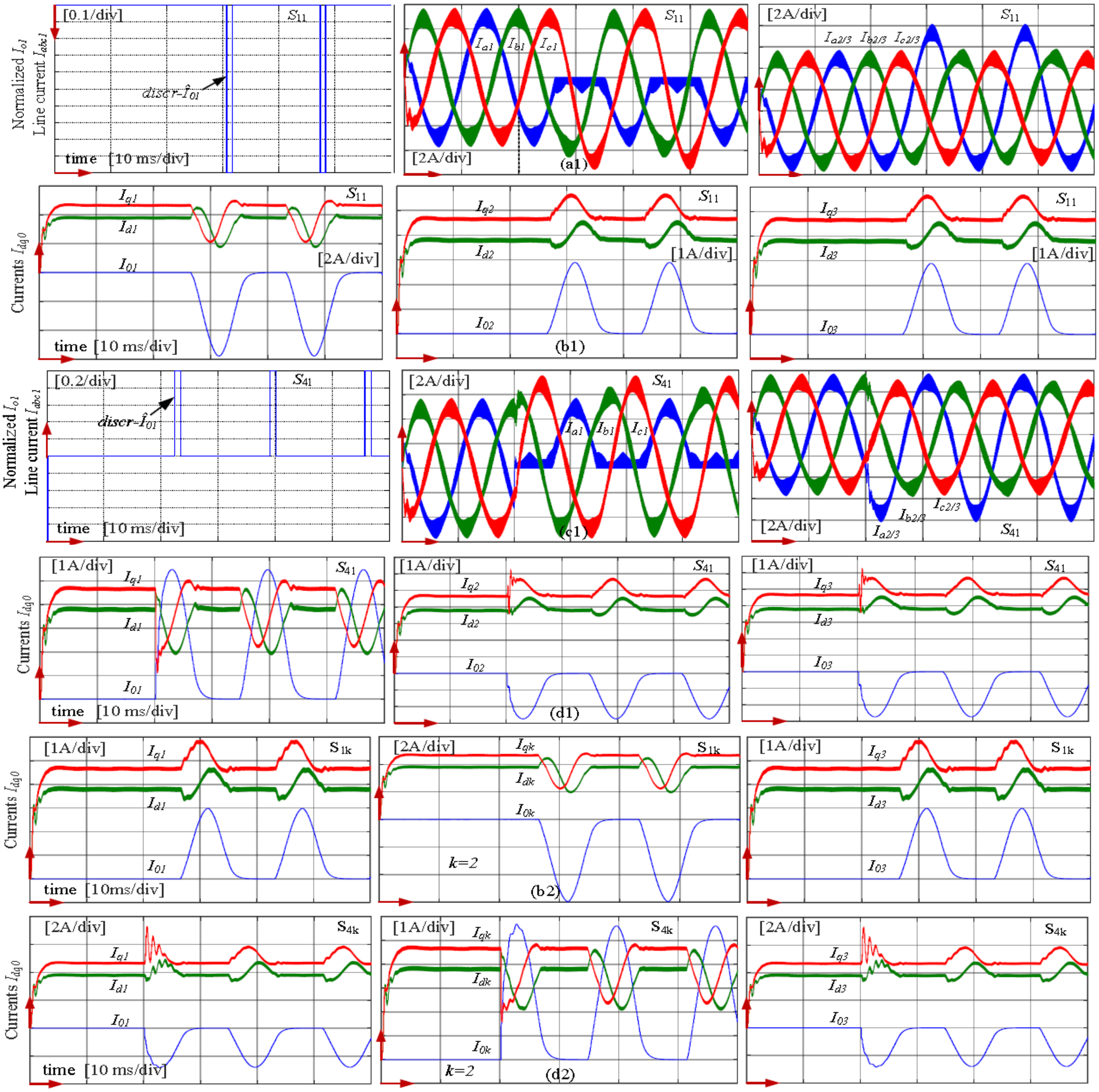
Figure 3: Schematic diagram of the proposed cross-correlation-based openswitch fault detection method for *N*-

parallel inverters.

Output AC filter inductances	$L_1 = L_2 = L_3 = 1$ mH, $r_1 = r_2 = r_3 = 0.7\ \Omega$
DC bus capacitance	$C_{dc} = 1100\ \mu$F
AC output voltages	110 V-60 Hz
DC input voltages	500 V
Switching frequency	$f_{sw} = 15$ kHz

Table 1: System parameters.

The same criterion can be applied for the switch *S*41 (consequently *S*51 and *S*61) as lower switches of the first inverter as shown in Figures 4(c1) and 4(d1), where a detection signal was occurred at *t*=22 ms. Figure 4(e1) shows the waveform of the normalized three-phase reference currents with their discrete values (*discr-Îabcref*), around their peak value as they are extracted from the load currents. The current behavior for the *kth* inverter, is shown in Figure 4(b2) and 4(d2).



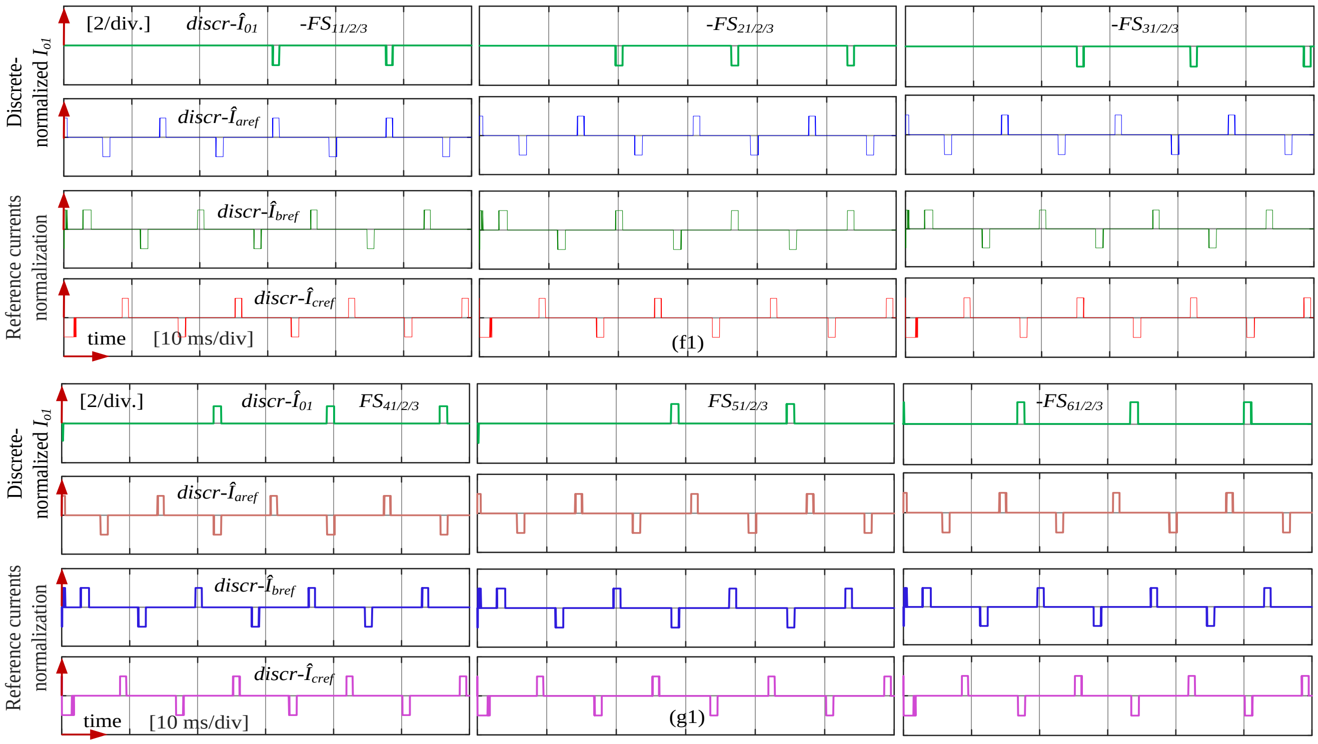


Figure 4: Proposed open-switch fault detection behavior for upper and lower faulty open-circuited switch for each inverter; line currents, corresponding currents *Idq0*, detection identifiers *FSjk* and reference currents (*Vdc*=500 V, *Vrms* =110 V, *Pload*=3.2 kW). (a1) Discrete-normalized zero-sequence current and line currents under open-switch fault; *S*11. (b1) Current *Idq0* for upper open-switch fault case. (c1) Discretenormalized zero-sequence current and line currents under open-switch fault; *S*41. (d1) Current *Idq0* for lower open-switch fault case. (b2) Current *Idq0* for upper open-switch fault case; *S1k*. (d2) Current *Idq0* for lower open-switch fault case; *S4k*. (f1– g1) Detection identifiers *FSjk* and reference currents for upper and lower open-switch fault cases of the three inverters.

Figures 4(f1) and 4(g1) shows the waveforms of the discrete values of the normalized zero-sequence current, the resulting detection identifiers and the discrete values of the normalized reference currents for all probable open-switch fault cases; upper and lower of the first inverter (the same behavior for the second and third inverter). The detection identifier is the same as the discrete value of the zero-sequence, but always positive and is synchronized with the discrete value of the reference current which is corresponding to the faulty phase. The detection identifier is calculated by the cross-correlation between the discrete-normalized zero-sequence current and the discrete-normalized reference currents, for each probable upper or lower open-switch fault cases.

VI. EXPERIMENTAL RESULTS

To verify the validity of the proposed open-switch fault detection method, the experiments are performed on 5 kW workbench model which consists of two parallel inverters (i.e. N = 2). These experiments are done with the photo in Figure 5, (the same photo is used in [8] and the same experimental bench). The parameters which are used for the experiments, are listed in Table 1. The proposed open-switch fault detection method is realized by MATLAB-Simulink-RTW software. The control method is implemented owing to the dSPACE-1105 real-time control card. Figure 6 shows the experimental results for the proposed open-switch fault detection method. Figure 6a shows the discrete value with an amplitude equals “1”of the corresponding normalized reference currents. This value is obtained by saturating the maximum value of the reference current to 90% of its maximum value, and normalizing the resulting waveforms; phase “a” and phase “b”, consequently for the phase “c”.

Figure 6b shows the normalized values of the zero-sequence current around its maximum value for both upper and lower open-switch fault case. The discrete value of the normalized zero-sequence current has an opposite sign to the zero-sequence current to have the same sign of the corresponding discrete value of the reference currents to obtain positive detection identifier.

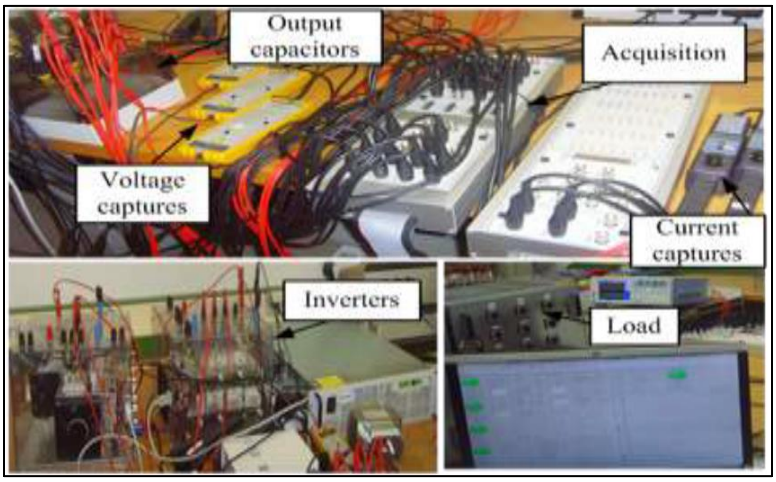
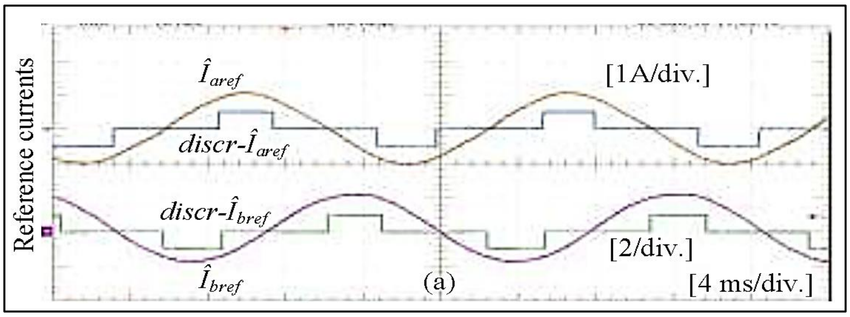


Figure 5: The experimental workbench of the two parallel inverters system. (The same photo is used in [8]).

Figures 6c and 6d shows the reference currents and zero-sequence current for both linear and nonlinear load without normalization under the open-switch fault conditions of the switches $S_{11/2}$ as upper case and $S_{41/2}$ as lower one. Figure 7a shows the waveforms of the output line currents and the corresponding zero-sequence current component when one switch of S_{11}, S_{21} and S_{31} as upper switches of the first inverter, is under the open-switch fault conditions. By applying the proposed detection algorithm, a detection signal which corresponds to the peak value of the zero-sequence current, is alerted, this signal is resulting from the cross-correlation between the discrete-normalized corresponding zero-sequence current and the discrete-normalized reference currents. The fault detection identifier equals "1" as shown in Figure 7b. The same behavior for the lower open-switch fault case is shown in Figure 7c, when one switch of S_{41}, S_{51} and S_{61} as lower switches of the first inverter, is in open-switch fault case. The corresponding zero-sequence current for the lower open-switch fault case, is positive. The detection signal was alerted and the fault detection identifier equals to "1" for the lower open-switch fault as shown in Figure 7d. The proposed detection method still validate under the nonlinear – unbalanced load condition as shown in Figures 7e and 7f. Figure 8a shows the waveforms of the discrete values of the normalized zero-sequence current (with opposite sign), the detection identifier and the reference currents for all probable open-switch fault cases. The detection signal is the same as the discrete value of the zero-sequence, but always positive as shown in Figures 8a and 8b, for all probable open-switch fault cases. The experimental results show the validity of the proposed cross-correlation method as open-switch fault detection method. The circulating zero-sequence current between the parallel units, is used as the turnkey for the proposed open-switch fault detection. The proposed detection can be used for any inverter in the parallel system in a straightforward way with the fault signature for each case.



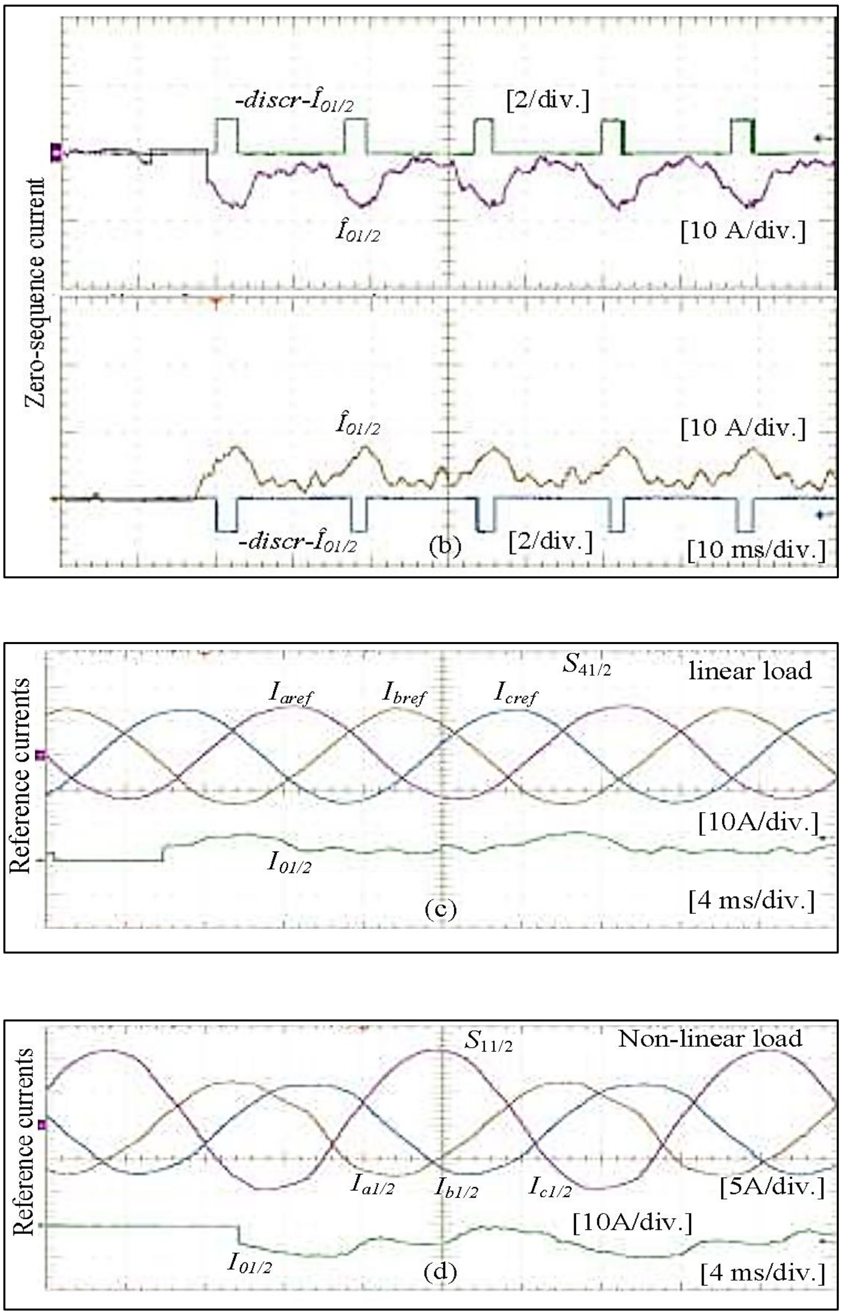
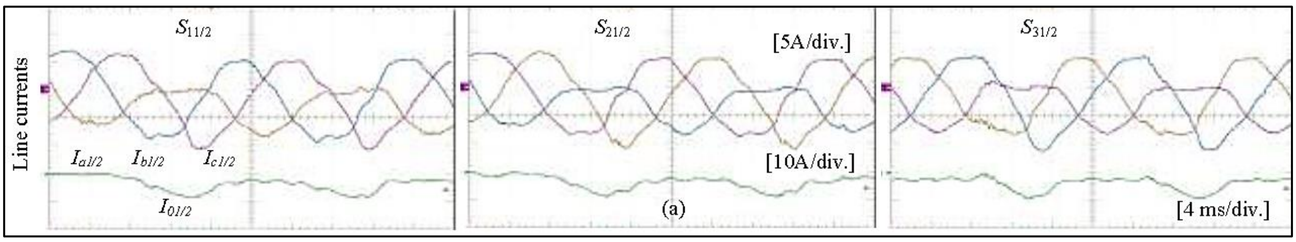


Figure 6: Behavior of the reference currents and zero-sequence current under linear and non-linear load. (a) The reference currents and their discrete-normalized values. (b) Zero-sequence current and their discrete-normalized values for both upper and lower open-switch fault case. (c), (d) Reference currents and zero-sequence current for both linear and nonlinear load without normalization.



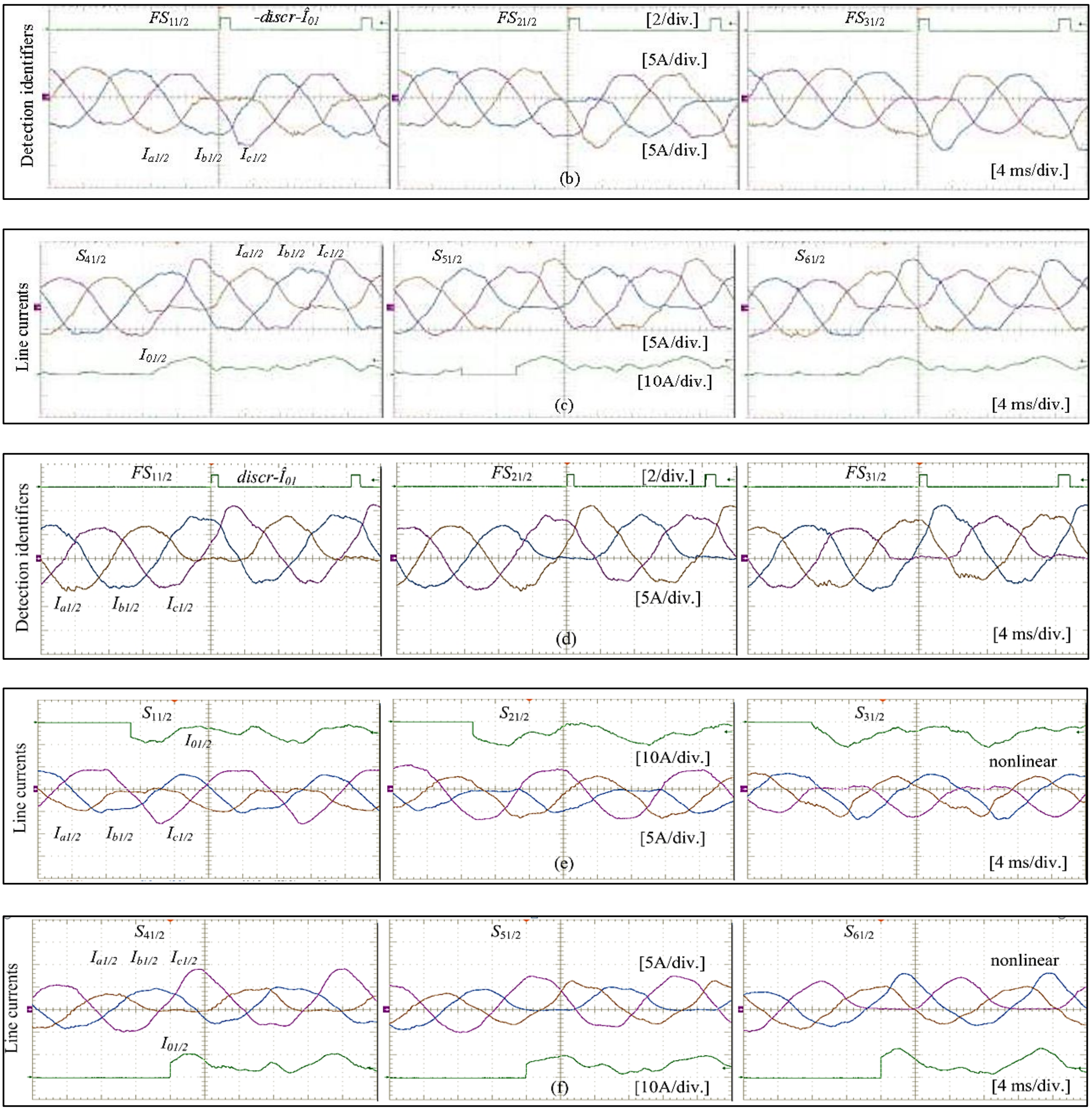
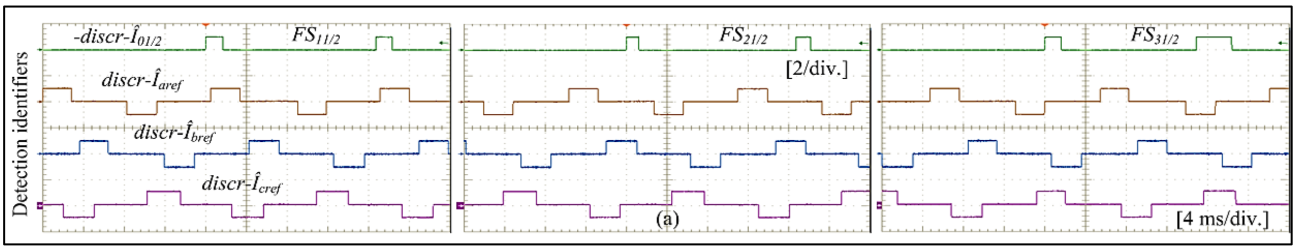


Figure 7: Detection identifiers and line currents under open-switch faults; upper and lower for first or second inverter and their behavior under linear or nonlinear load conditions (V_{dc}=500 V, V_{rms} =110 V, P_{load}=3.2 kW). (a) Line currents of the faulty inverter and corresponding zero-sequence current for upper open-switch fault case. (b) Line currents of the faulty inverter and detection identifiers for upper open-switch fault case. (c) Behavior for the lower open-switch fault cases. (d) Detection identifiers for the lower open-switch fault cases. (e), (f) Line currents of the faulty inverter under linear and nonlinear load conditions.



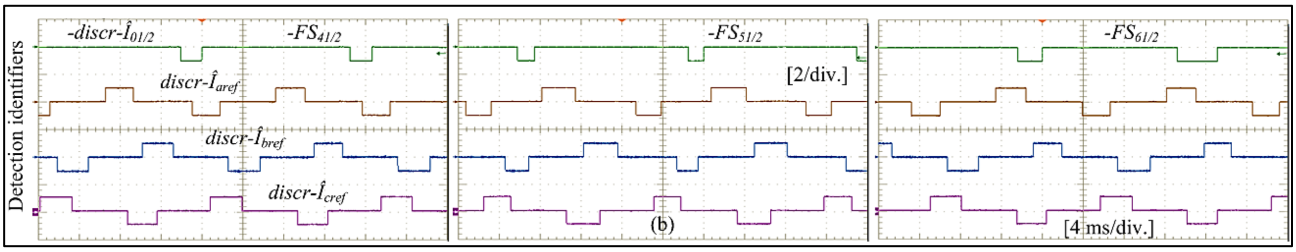


Figure 8: Detection identifiers for all probable open-switch fault cases for two inverters (*Vdc*=500 V, *Vrms* =110 V, *Pload*=3.2 kW).

VII. CONCLUSION

This paper has presented practical online cross-correlation fault detection method. This method has employed the zero-sequence current by using only the measured line currents. The proposed method has been done without any additional hardware for the detection, identification and localization of the faulty open-circuited switch. The experimental results show the validity of the proposed detection method for the open-switch fault detection. The proposed method detects the open-switch faults according to their distinctive fault signatures in a much more straightforward way.

VIII. ACKNOWLEDGEMENT

This work is cooperation between the Laboratory LEMTA, University of Lorraine- France and the Department of Electrical Engineering, Faculty of Engineering –Mansoura University-Egypt.

VII. AUTHOR BIOGRAPHY

Ahmed Shahin (M’08 - SM’15) received the B.Sc. and M.Sc. degrees in electrical engineering from Mansoura University, Egypt respectively in 2000 and 2004, and the Ph.D. degree in electrical engineering from Ecole Nationale Supérieure d’electricité et de Mécanique, Université de Lorraine, Nancy, France, in 2011. Since 2012, he has been engaged as a Doctor at Mansoura University, Egypt. His current research interests concern renewable energy systems, modeling, optimization methods oriented to power flows management, control and diagnosis of photovoltaic power systems and fault tolerant power electronic systems.

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