A Fault Diagnosis Scheme Based on the Normalized Indexes of the Images eccentricity for a Multilevel Converter of a Switched Reluctance Motor Drive

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***Abstract*—This paper addresses the fault detection and diagnosis of a fault in the switches of the Switched Reluctance Machine (SRM) power electronic converter. Due to the advantages of using multilevel converters with these machines, a fault detection and diagnosis algorithm is proposed for this converter. The topology under consideration is the asymmetric Neutral Point Clamped (ANPC), and the algorithm was developed to detect open and short circuit faults. The proposed algorithm is based on an approach that discriminates eccentricity of the images formed by the converter voltages. This discrimination is realized through the development of normalized indexes based on the entropy theory. Besides the different fault type the algorithm is also able to detect the transistor under fault. The possibility to implement the proposed approach will be verified through simulation tests.**

***Index Terms*—Fault Detection, Entropy, SRM, Fault tolerant, multilevel converters.**

I. INTRODUCTION

Electrical machines play a very important role in nowadays' life. There is a huge number of applications in which they are needed and used. However, usually there are several types of electrical machines that allows an optimal choice taking into consideration the application. One of the machines that has been more and more selected is the switched reluctance machine (SRM). In fact, it has been used in an important number of applications. Some examples of these applications can be seen in the areas of the aeronautics, electric vehicles, mining industry, pumping and wind generators [1-9]. This option is related with several interesting characteristics like high efficiency, low cost, nonexistence of magnets and high reliability [10]. However, this machine is characterized by the need of a power electronic converter. In order to maintain the robustness of the full system, the power electronic converter needs to have fault tolerant capability.

Due to the importance of ensuring high reliability to the SRM system several power electronic converters with fault tolerant capability have been presented. In order to design these converters, some extra components like power electronic semiconductors and switches were introduced [11-13]. Another adopted approach was through the change of the structure of the SRM [14]. A review of the several approaches regarding fault tolerant schemes for the SRM can be seen in [15,16]. Initially, the adopted converters were characterized by topologies with two voltage levels. However, in the last years, the number of multilevel topologies for the SRM has been increased [16-20]. These topologies are very interesting since they allow high torque range and at least some fault tolerant capability without changing the classical topology. An example of this is the Neutral Point Clamped Asymmetric Half-Bridge (NPC-AHB) that provides fault tolerance to some open and short-circuits faults.

One important aspect, fundamental to be associated to converters with fault tolerant capability, is the incorporation of a fault detection algorithm. The fault tolerant operation will only start after the detection of the fault. Moreover, the identification of the switch under fault, as well as the fault type is fundamental. In this way, several fault detection algorithm have been proposed. The development of these algorithms was based on the measured signal. Thus, several algorithms in which current signals were used, were proposed. Other approaches used voltage signals, although in a reduced number since these methods usually requires extra sensors [21-25]. However, practically all the methods were developed for power electronic topologies with two voltage levels. In this way, there is an important lack of fault detection algorithms for multilevel topologies applied to the SRM.

This paper will be focus on a new algorithm for the detection of a fault in a drive for the SRM. This algorithm will be developed for a topology with multilevel voltage characteristics. It has the capability to detect the switch under fault, as well as, the fault type. This approach is based on the current signals avoiding extra signals and is independent of the operation mode. Fault detection and diagnosis based on simulation results will be presented.

II. Multilevel Topology for the SRM Drive

Due to the advantages of the multilevel converters as part of the SRM drive, several topologies have been proposed. One of the topologies that was considered very interesting was the Neutral Point Clamped Asymmetric Half-Bridge (NPC-AHB). The scheme of this converter is presented in Fig. 1.

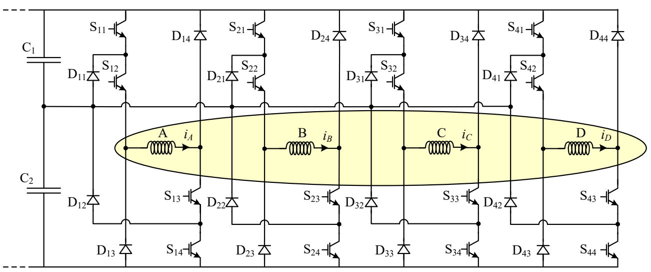


Fig. 1. Scheme of the of the multilevel converter Neutral Point Clamped Asymmetric Half-Bridge.

The topology presented in Fig. 1 has the possibility to apply several voltage levels. From this last figure it is possible to confirm that the voltages that can be applied to the motor winding are $+V_{C1}+V_{C2}$, $+V_{C1}$ (or $+V_{C2}$), 0, $-V_{C1}$ (or $-V_{C2}$) and $-V_{C1}-V_{C2}$. There are some redundant combinations of the switches for the same voltage level. This is the case of mode 2, mode 3 and mode 4. For example, for mode 2, instead of turn ON switches S_{12}, S_{13} and S_{14}, it can be used switches S_{11}, S_{12} and S_{13}. This confirms that these multilevel topologies also provide some fault tolerant capability to switch faults.

In typical two-level topologies, when there is a fault in one of the switches, the operation of the SRM drive will be affected. In this topology there are several faults in which the drive can still operate practically in normal situation. For example, in the case of a short-circuit fault of the outer switches (S_{11} or S_{14}), it allows to apply the maximum voltage but not the intermediate (V_{C1}). Since it is possible to cut the positive voltage and apply the negative, overcurrents will not appear. The most critical problem, under a short-circuit fault, is a short-circuit in the lower switch (S_{12} or S_{13}). In this case, it is only possible to apply half of the total voltage for the demagnetization process. Regarding the open switch fault, the most critical situation is for the inner switch (S_{12} or S_{13}).

III. Proposed Fault Detection Algorithm for the Multilevel Topology

A new method to detect the several fault types in the multilevel converter applied to the SRM is proposed. This approach is designed with the purpose to be reliable and fast. The proposed fault diagnosis method is based on the definition of indexes related to the pattern of the SRM winding currents. Those indexes are based on the Shannon entropy feature obtained using a sliding window of the four current signals. This definition of entropy was introduced in the mathematical theory of communication [26]. The Shannon's entropy uses a large number of data to measure the uncertainty of the system variables for evaluating structures and patterns.

To implement the entropy feature approach for the identification of the faulty patterns, it is necessary to perform the signal acquisition of the motor winding currents through current sensors. In order to obtain the time behavior of the current patterns, it is used a sliding window with n samples for each current. A generalized I matrix of N currents will be created (1) where T_s represents the sampling period.

$$I = \begin{bmatrix} i_A(t) & i_B(t) & \ldots & i_N(t) \\ i_A(t+T_s) & i_B(t+T_s) & \ldots & i_N(t+T_s) \\ & & \ldots & \\ i_A(t+(n-1)T_s) & i_B(t+(n-1)T_s) & \ldots & i_N(t+(n-1)T_s) \end{bmatrix} \quad (1)$$

From the data of each current signal presented in I matrix it will be computed the corresponding entropy at i^{th} instant using (2). The patterns arise with the calculation of the entropy of each column of the matrix I allowing its identification.

$$H_k(i) = -\sum_{j=1}^{n} \frac{1}{n}\left|i_k(j)\right| \log_2\left(\frac{1}{n}\left|i_k(j)\right|\right), k = A, B, C, D \quad (2)$$

where $i = \{i_A, i_B, i_C, i_D\}$ is a set of current phase variables with a data sample matrix with n samples for each current phase and $k = A, B, C, D$ is the index of each current phase. When the current amplitude is 0, and in order to avoid a computation problem, it is considered that the current has a very small value equal to 2^{-52}.

In order to allow the diagnosis and identification of the faulty switch, without being affected by the speed and load of the motor, after the entropy computation for each current at instant i , a normalized index (3) is determined.

$$IAV_T = \sum_{k=A}^{D} H_k(i) \quad (3)$$

Through Equations (2) and (3) it is possible to obtain the symmetry/asymmetry index (*SI*). Four *SI* indexes (*A*, *B*, *C*, and *D*) are defined for the SRM drive, in accordance with (4):

$$SI_k = \frac{4\,H_k(i)}{IAV_T}\ ,k = A,B,C,D \qquad (4)$$

The different values of the diagnostic variables (*SI* index) will identify the power device under failure. If the current patterns are symmetric then the correspondent four indexes will be, approximately, equal to one. If there is an asymmetry in the patterns due to a short or open-circuit failure, then the *SI* indexes will be no longer near one. So, for an open-circuit failure, the diagnostic variable associated with the faulty power device will change from one to half of this value or to zero depending on the faulty switch. The other diagnostic variables will also change, but for a positive value higher than one. In case of a short-circuit failure, the diagnostic variable associated with the faulty power device will change from one to a positive value higher than one. The other three diagnostic variables will change from one to a positive value lower than one.

From the diagnostic indexes function of the switches condition (Table II) it is possible to verify that one of the fault is not possible to identify. That fault is the one associated to the short-circuit switch S_{11} (upper). In this way, a new index will be introduced to identify and discriminate this fault. However, to introduce this new index, it is needed to acquire the current that flows from the middle point of the capacitors to the clamping diodes. So, the new index that is designated by short-circuit index (SSI) is given by:

$$SSI_k = \frac{4\sum_{j=1}^{n} I_{Nk}(j)}{\sum_{k=1}^{D}\sum_{j=1}^{n} I_{Nk}(j)}\ ,\quad k = A,B,C,D \qquad (5)$$

where I_N is the current that flows from the middle point of the capacitors to the clamping diodes.

Using the severity index given by (5) it is possible to discriminate a short-circuit in the upper switches. In a normal situation all the SSI indexes will give a value that is approximately one. However, in case of a fault in one of these switches, the SSI associated to the leg in which the switch is located has a value of zero. In this way, this fault is detected.

IV. Algorithm Testing

The developed fault detection and diagnosis algorithm for the multilevel NPC-AHB for the SRM drive was tested through computer simulation tests. The machine model, controllers and fault detection and diagnosis algorithm were defined by the program Matlab/Simulink. It was used an 8/6 SRM model that is available in this program.

All the tests that were performed were implemented in a way that first the drive is in normal mode and suddenly a fault appears. The first test was for the open switch fault in semiconductor S_{12} (inner transistor). The results of this test can be seen in Fig. 3 in which the voltage in the winding associated with the leg under fault, motor currents and fault indexes are presented. It is possible to confirm that before the fault all the indexes present the same value (equal to one). However, after the fault, they changed, with a reduction on the value of the index associated to the leg of the switch fault and an increase on the values of the other ones.

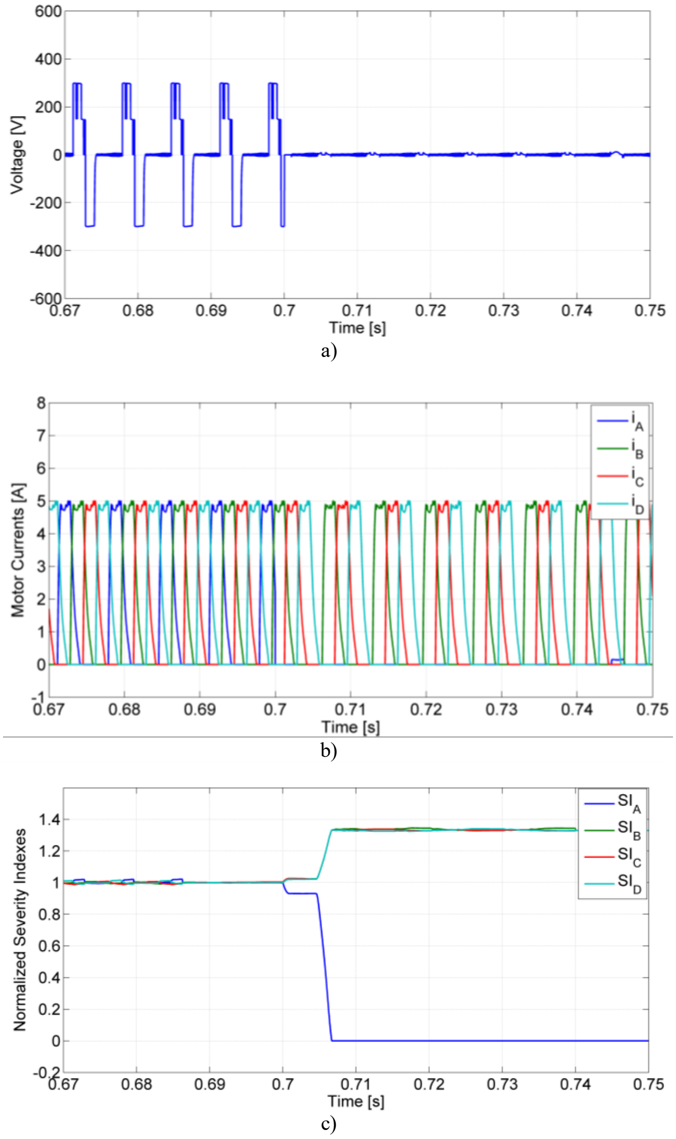
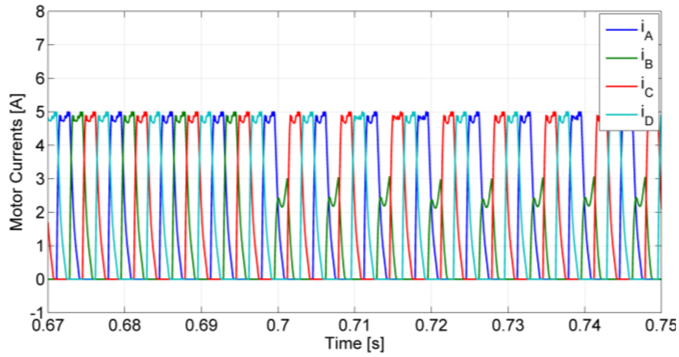
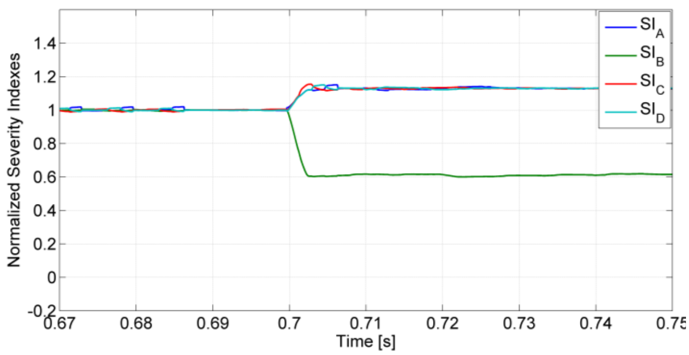


Fig. 3. Results of a test for an open switch fault in S_{12} (a) voltage in the winding associated with the leg under fault (b) motor currents (c) fault indexes.

The second test was again performed for the open switch fault but now of the semiconductor S_{21} (inner transistor). The obtained new results can be seen in Fig. 4 where is possible to verify the voltage in the winding associated with the leg under fault, motor currents and fault indexes. In this case the voltage applied to the winding associated to the leg under fault is severely affected during the magnetization process. On the other hand, after the fault, they changed but the index associated to the leg of the switch fault reduced to zero and the other ones present a higher increase.

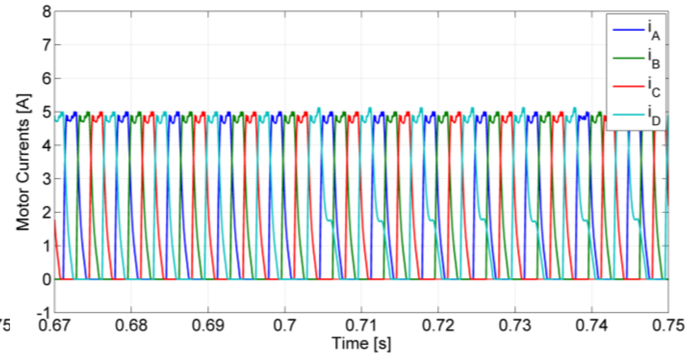


a)

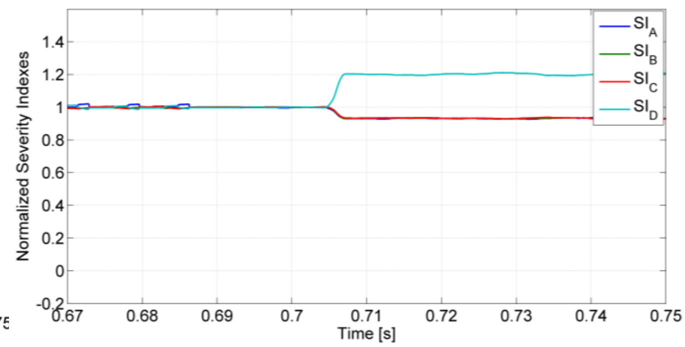


b)

Fig. 4. Results of a test for an open switch fault in S_{21} (a) motor currents (b) fault indexes.



a)

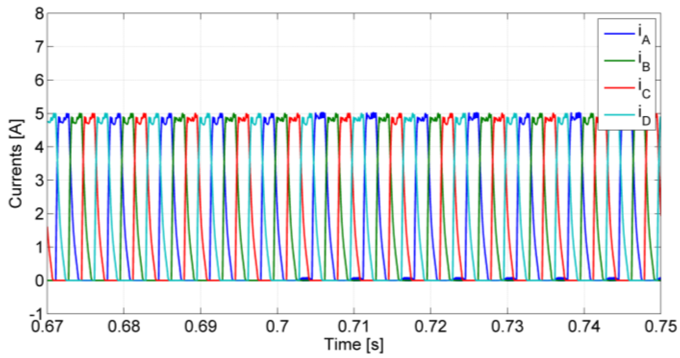


b)

Fig. 5. Results of a test for a short-circuit fault in S_{42} (a) motor currents (b) fault indexes.

Another test, in which a different fault type was considered, was also implemented. In this case, a short-circuit fault for the switch associated to the leg of the fourth motor winding was considered. Initially the converter operates in normal mode but at t=0.7 s a short-circuit fault appeared in the switch S_{24}. The corresponding waveforms associated to the converter are presented in Fig. 5. It is possible to confirm that the level voltage that is affect is associated to the demagnetization process (it is not possible to apply the maximum voltage). In this way, the demagnetization occurs in a more slowly way. Regarding the indexes, it is possible to verify that the one associated to the leg under fault increases its value when the short-circuit fault appears while the other ones decrease. So, the behaviour of these variables are the inverse of the over verified for the open switch fault.

A short-circuit fault, but now for the upper switch S_{11}, was also tested. As expected and shown in Fig. 6 a), now the identification of this fault is extremely difficult to obtain. However, as described previously, through the short-circuit index (SSI) it is possible to clearly identify this fault. This is confirmed by the result presented in Fig. 6 b).



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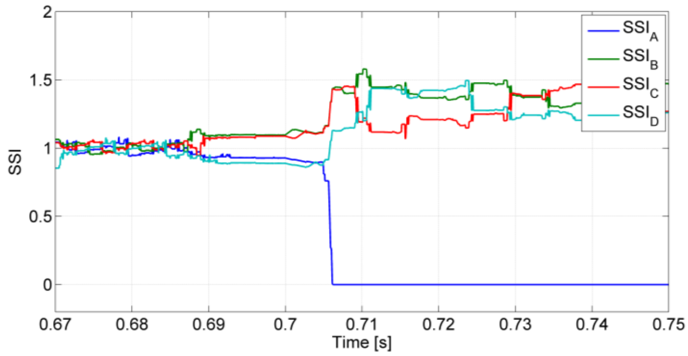

b)

Fig. 6. Results of a test for a short-circuit fault in S_{11} (a) motor currents (b) short-circuit fault indexes.

V. Conclusions

This paper focuses on the problem of the fault detection and diagnosis in a multilevel converter used in a SRM drive. The converter under consideration is one of the most interesting ones, namely the Neutral Point Clamped

Asymmetric Half-Bridge. To address the problem of the detection of a switch fault in this converter, a new algorithm was proposed. This algorithm allows to discriminate the fault type and the switch under fault. The approach was based on the current signals, avoiding extra signals, and is independent of the operation mode. Fault detection and diagnosis based on simulation results were presented. The results showed fault indexes associated to each of the windings that in normal mode all of them present an equal value. However, under fault, all the indexes changed their values. Moreover, the values depend on the fault type and switch under fault being possible to detect and discriminate the fault type and the switch.

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