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Fault detection and localization for T-Type Converter

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Abstract—In this paper, an Open-circuit switch fault diagnosis method for a five-level H-Bridge T-type converter is presented. The proposed fault detection method and the fault localization algorithm are based on the switching patterns and the converter output voltage level observation. The proposed fault diagnosis approach is capable to detect and localize an open circuit fault for all switches. The proposed approach is validated by simulations in Matlab Simulink and SimPowerSystem toolbox environments.

Index Terms—Open-switch fault; fault diagnosis; fault detection; fault localization; Multilevel converter; Neutral Point Piloted converter; T-type converter; H-bridge

I. INTRODUCTION

In recent years, multilevel converters (MLC) have been widely used in many different applications, such as transport (railway, electric vehicle, ...), motor drive and renewable energy [1]. These converters have many advantages: high power capacity, better power quality (reduced total harmonic distortion THD for AC voltage and current), reduced blocking voltage requirement for the power switches and fault-tolerant capability [2], [3]. Among the different MLC typologies, some converters such as the cascaded H-bridge inverter, the Neutral Point Clamped (NPC), the T-Type (Neutral-Point Piloted (NPP)) and the flying capacitor converters have been used in industrial applications [4], [5]. The T-type converter is more attractive than other MLC structures for industrial applications thanks to its low conduction switching losses, compared to other converters. The T-type converter topology is presented in Fig. ??(a).

Based on the research results, around 34% of the failures in power electronic converters are caused by the semiconductor components [6]. Therefore, fault diagnosis and fault-tolerant operation are one of the major design criteria for safety critical applications.

Power switch failures are mainly classified into Open Circuit Fault (OCF) and Short Circuit Fault (SCF) [6]. The SCF

normally leads to a breakdown of the converter; therefore, the system is protected by fast fuses integrated into the converter circuit. In the case of an SCF, the fast fuses isolate the faulty switch from the converter, and then the SCF is turned into an OCF switch fault. The OCF leads to current distortion and increased voltage stress, which can lead to a breakdown if the fault persists for a long time; thus, the switch failure must be detected and isolated rapidly. Therefore, having a fast and reliable fault detection and localization method for the power electronic converters is necessary.

Several fault detection methods have been proposed in the scientific literature [3], [4], [7]–[11]. Most of these works have been focused on the classical two-level and multilevel inverters [7], [8]. However, due to the actual importance of renewable energy resources, in the latest years, the study of fault diagnostic and fault tolerant operation of MLC became very attractive. Some fault detection methods and fault-tolerant approaches for the PV grid-connected systems using MLC are proposed in [3], [9], [10]. In [12] a fault diagnosis method based on the mass center of the voltage pattern is proposed for the T-type converter topology. In [11], Lee et al. have proposed a fault tolerant control based on the neutral-point voltage balance for the switch OCF, in a 3L-NPC converter and a T-type converter used in wind energy systems. In [1] a carrier-based fault-tolerant control strategy for a T-Type Active Neutral-Point-Clamped Converter (T-ANPC) in the case of typical OCF switch fault is proposed.

This paper proposes a fault diagnosis method for a five-level H-Bridge T-Type (5L HB T-Type) converter. Because of the numerous switches that are used in this 5L- HB-T-Type converter, this topology is very vulnerable to switch faults. The proposed fault diagnosis is composed of two parts: Fault Detection Method (FDM) and Fault Localization Algorithm (FLA). The proposed FDM is based on the output voltage observation. This FDM method compares the measured output voltage with the desired (estimated) value of the output volt-

age. The estimated voltage is computed from the switching pattern and the converter states for each possible combination of switches and diodes (see Fig.??(b)). If any mismatch appears, it means that a switch fault has probably occurred. When an OCF is declared, the proposed FLA activates the localization process as well as the identification of the faulty switch. To do that, the output voltage values in all the possible cases of OCF have been previously calculated and saved in a table. The FAL compares the measured output value with the values registered in the table and thus determines the faulty switch. In some cases, an additional step is needed, that will be detailed later, because several switch OCF cases can lead to the same output voltage value (for the same state).

In the next section, the 5L HB T-type and the different states are presented. Then, in section III, the principle of the proposed fault diagnosis method for the 5L HB T-type is detailed. In section IV, the proposed approach is validated by simulation. Finally, some conclusions are provided.

II. FIVE LEVEL H-BRIDGE T-TYPE TOPOLOGY

Fig. ??(a) shows the 5L HB-T-Type converter. This converter has 8 switches (that can be IGBT or MOSFET) with antiparallel diodes. The HB-T-Type converter is supplied by a DC voltage source (V_{dc}) with a central neutral point, called N. Depending on the switching pattern (control orders), the converter can generate 5 different voltage levels: $V_{dc}/2$, V_{dc} , 0, $-V_{dc}/2$, and $-V_{dc}$. In this paper, for each voltage level that depends on a specific switching pattern, a state (S1 to S9) is introduced. The states, voltage levels, and the switches that are in conduction mode for each state are depicted in Fig. ??(b). In the next section, the fault diagnosis approach is detailed.

III. FAULT DIAGNOSIS METHOD

The proposed fault detection method is based on the switching pattern and the output voltage value observation. For the studied 5L HB-T-Type converter, 9 states must be considered (switching order and the associated output voltage). In each state, some switches are on and some diodes are in conduction mode. The states and output voltage value are illustrated in Fig. ??(b). As it can be seen, the output voltage has five levels: $V_{dc}/2$, V_{dc} , 0, $-V_{dc}/2$, and $-V_{dc}$.

A. Fault detection method

The fault detection algorithm compares the measured output voltage (v_o) with the estimated (desired) output voltage (v_{oe}). The v_{oe} is estimated by entering the switching commands (δ_1 to δ_8) in a lookup table bloc as depicted in Fig. ?? . If the measured and estimated value of the output voltage have the same value ($v_{oe} = v_o$), it means that the converter works in healthy condition. Otherwise, the error signal "err" is not null.

To avoid all the false detections, two criterions are considered. The first one compares the error value with an accepted tolerance (ϵ), if the error is bigger than ϵ , the "enb" signal switches to '1' level. The second criterion is the time criterion. When "enb" becomes equal to '1', the increment counter is activated and the "cnt" value increases. If "cnt" passes the

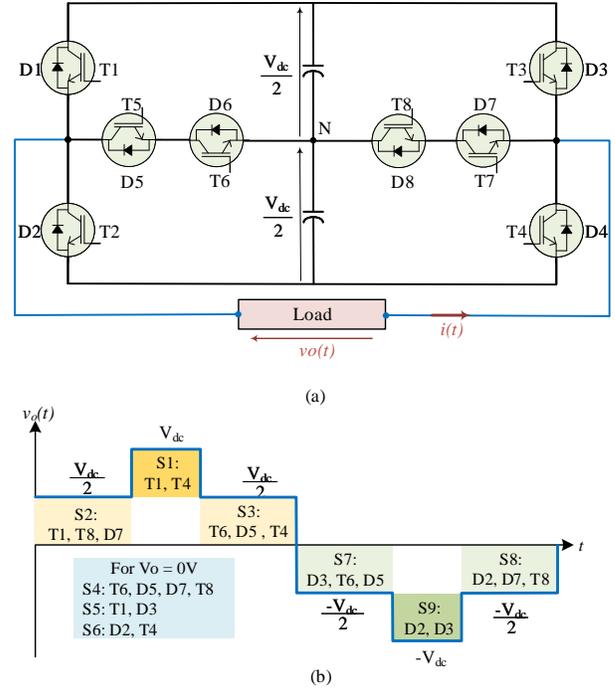


Fig. 1. (a) T-Type converter (b) Output voltage levels and corresponding states.

threshold value "N" and the "enb" is always equal to '1', the fault detection method declare a fault occurrence and "FD" step up to '1' .

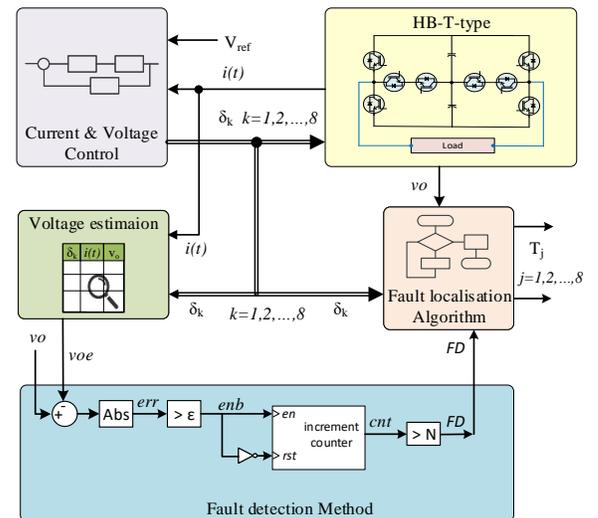


Fig. 2. Fault diagnosis approach.

B. Fault localisation method

Fault diagnosis methods have two steps:

- 1) fault detection,
- 2) fault localization.

In the previous fault detection step, the switch fault is declared by the FDM, but it is not localized yet. The T-type converter has 8 semiconductor switches (IGBT, MOSFET, ...) therefore identifying the faulty switch is not simple and needs an efficient and fast algorithm.

As depicted in Fig. ??, the localization algorithm (FLA) is activated by the "FD" signal of the FDM bloc. The FLA is shown in Fig. ?. The output voltage values for each possible OCF case are calculated and registered in a table. This FLA recognizes the states by encoding the switching commands (δ_1 to δ_8) and then compares the measured output voltage with the value of the voltage table to find the faulty switch. For some states there two switches that can be faulty. To understand the localization algorithm, the states can be arranged into three groups:

- S9, just 2 diodes are active (group1).
- S5, S6, S7, and S8: a single switch and diodes are active (group2).
- S1, S2, S3, and S4: 2 switches and diodes are active (group3).

For the group1 (S9), there are just 2 diodes in the circuit, therefore a switch (IGBT or transistor) failure cannot occur. Thus, fault localization is not necessary for this group. For group 2, the algorithm can localize the faulty switch in a single step by comparing the measured output voltage and the predefined value for output voltage, in case of a switch fault for each state, as illustrated in Fig.??.

But, for group3, there are two passing switches in each state, and thus, the fault cannot be localized in a single first comparison step. As Fig. 3 shows, the proposed algorithm needs to do an additional operation to detect the faulty switch. For example, in S1, the fault can occur for T1 or T4. To find the faulty one, the algorithm turns off the switch T7 and observes the output voltage. If $V_o = 0$, T1 is the faulty switch. If $V_o = V_{dc}/2$, the fault has occurred on T4. For the other three states, the same additional operation must be done to localize the faulty switch. Fig. ?? shows the fault localization approach for other states of this group.

It is noticeable that the fault detection and localization are detailed for a case when $i(t)$ is positive. We have to do the same operations for $i(t) < 0$. It means that there are 18 states in total which have been considered in the simulations.

IV. SIMULATION RESULTS

To validate the performance of the proposed switch fault detection method applied to the HB-T-Type, some simulations are performed in the Matlab/Simulink environment using the SymPowerSystem library. This converter supplies a load (R, L) with $R = 30\Omega$ and $L = 10\text{mH}$. The value of V_{dc} is equal to 1200V. The five possible output voltage levels of the converter have already been recorded in Fig. ?? (b), according to the associated switching states.

An OCF in state S3 is considered as an example of simulation results and shown in Fig. ?. First, an OCF is artificially

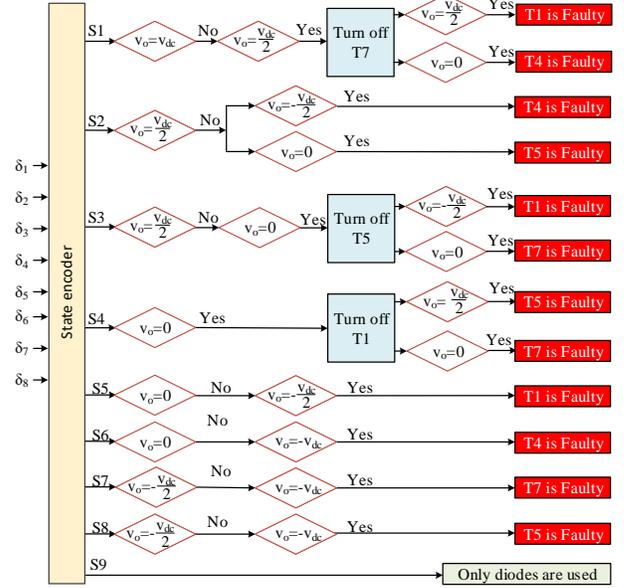


Fig. 3. Fault localization algorithm.

imposed at T1 (δ_1 set to "0"), "Fault Generation" signal in Fig. ?? is the signal that turns off the switch T1. Thus, at $t = 8.7 \text{ ms}$, T1 is turned off and acts as a faulty switch (OCF occurred). The fault is detected immediately and "FT" switches to "1". The switch S3 is in group3, then there are 2 switches in the circuit. Therefore, the localization algorithm needs to run the additional operation and turn off T5 to recognize the faulty switch (T1 or T5). As the simulation result shows, the localization algorithm has correctly located the faulty switch (T1).

Fig. ?? is a zoomed view of Fig. ?? around the fault occurrence time. Before the time t_2 , that the OCF is artificially generated, the switching command of T1 is off ($\delta_1 = 0$) during the time interval $[t_1, t_2]$. Therefore, the HB-T-Type converter works correctly and, any fault should not be declared. At t_2 , the switching command of T1 goes to '1' ($\delta_1 = 1$), and the output voltage $v_o(t)$ remains zero instead of steps up to $V_{dc}/2 = 600\text{V}$. The fault detection algorithm detects the OCF and then the "FT" signal steps up to "1" at t_3 . As Fig. ?? shows, $v_o(t)$ and $v_{oe}(t)$ are not equal, therefore the fault is correctly declared. After turning off the switch T5 at t_4 , the fault is located on T1 by the fault localization algorithm at t_5 .

V. CONCLUSION

This paper proposes a switch open circuit fault diagnosis for a five-level H-bridge T-Type multilevel converter. The fault diagnosis approach is decomposed into two parts. The first part is the fault detection method which is based on the output voltage value observation. The second part is the fault localization algorithm. When the fault detection method declares an OCF, for 4 states of operation that involves two switches, the fault localization is necessary. The FLA can localize the

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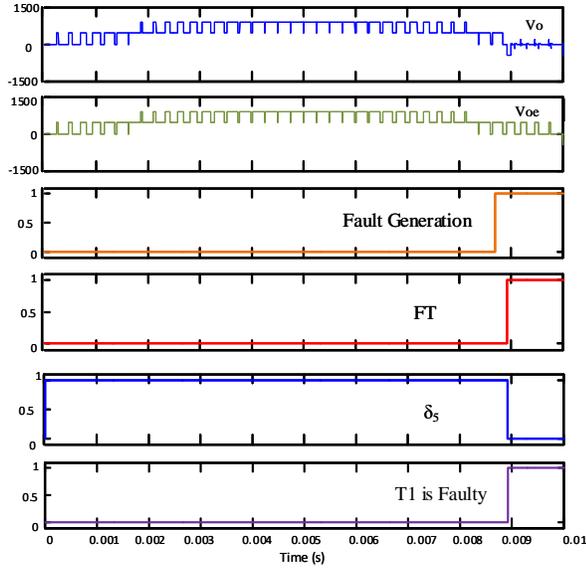


Fig. 4. Simulation results during an OCF on T1.

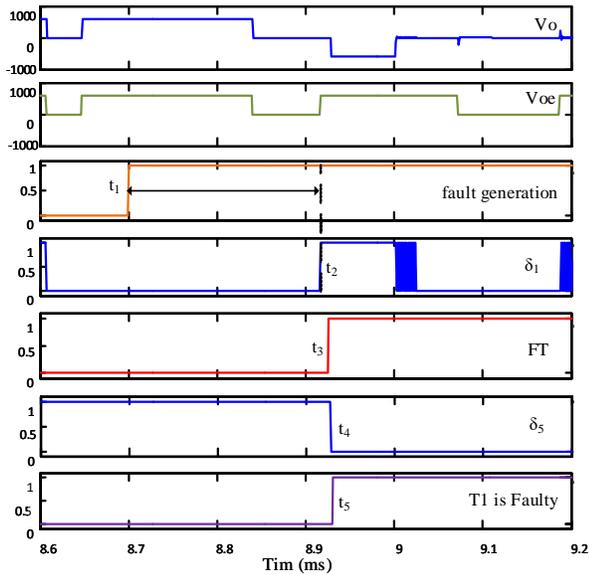


Fig. 5. Simulation results zoomed during an OCF on T1.

faulty switch by a comparison between the measured output voltage and predefined value of the output voltage that can be generated in case of an OCF on each switch. The validity and the performance of the proposed method are confirmed by the simulations in Matlab Simulink.