Fault diagnosis of open and short-circuit faults in a parallel multi-cell converter based on sliding mode observer

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Abstract

This paper presents an observer-based diagnosis approach of open and short-circuit switch faults in a parallel multi-cell converter composed of three buck type converters. Motivated by its convergence qualities in a finite time and its robustness to external uncertainties and disturbances, a first-order sliding mode switched observer is used in residual generation. The residuals are then compared to a fixed threshold to obtain the different faults signatures. The selected residual evaluation function provided more information about residual signals which allowed the isolation and identification of the faults. Taking into account the hybrid behavior of the studied system, this method ensures both the detection and the identification of the fault, and eventually, the isolation of the faulty switch in the case of single and multiple faults. Moreover, it provides a fast diagnosis and thus allows a timely intervention to reconfigure the system and ensure safety and continuity of operation. The performance of the proposed approach is established by numerical simulations.

Keywords Fault detection · Fault identification · Parallel multi-cell converters · Switched systems · Switched observers

1 Introduction

Most real systems are subject to dynamic changes due to several factors such as nonlinearities, parameter changes, faults, discrete events, and control. All these elements can lead to the presence of continuous and discrete dynamics in interaction, thus revealing a hybrid behavior. These systems called hybrid dynamical systems (SDH) has drawn the interest of several researchers since they can represent a wide range of complex systems.

Power converters have inherently a hybrid behavior where the power switches are the source of discrete event dynamics. Furthermore, power converters are used extensively in embedded and cyber-physical systems omnipresent in critical areas where safety and dependability are a major concern such as robotics, electrical energy production, automotive and avionics.

In this respect, motivated by the ever-increasing need for reliability, performance, and availability, the fault diagnosis of such systems is receiving considerable attention.

Switching devices can be affected by short-circuit and open-circuit switch faults.

Short-circuit faults can cause great damages and immediate system shutdown. Consequently, they require a diagnosis at an early stage. In this context, the problem of short-circuit faults diagnosis has been extensively studied in the literature. Most of them are based on the analysis of the gate switching signals [1] [2] [3], the dc-link current [2], and the phase current signals [4].

A method for short-circuit fault diagnosis of a Three-Phase Inverters is proposed in [1]. This approach is based on the analysis of PWM switching signals in a time-free domain called voltage space. Moreover, authors in [2] presented a method based on the monitoring of both the dc-link current and the switching signals for the diagnosis

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of switch short-circuit faults of a phase-shifted full-bridge converter and also proposed a remedial strategy by modifying the topology of the converter.

Nowadays converters are generally equipped with hardware-based solutions such as protection circuits like fast-acting fuses [5], protection switches [6] and disconnect switching [7] to be protected against short-circuits.

Considering this, this type of fault can result in open-circuit faults, and hence, several research results investigating open-circuit faults can be reported in [5, 9–18].

While open-circuit faults are not as destructive as short-circuit faults, they can affect the system performances and lead to different faults in the remaining drive components [8]. Based on the analysis of the switching function model of the inverter, [9] proposes a diagnostic method of open-switch faults by calculating the error between switch voltages under normal and faulty conditions. In [10] a method based on the analysis of stator currents is developed for open-circuit faults detection in permanent magnet synchronous motors drives. In [11] a sliding mode observer-based fault detection for a multi-cell converter four quadrants is developed. In [12] a sliding mode observer-based approach for open-circuit fault detection of switch faults in a multilevel converter is addressed.

A few works have investigated both open and short circuit faults as in [13] and [14] where diagnosis approaches based on field-programmable gate array (FPGA) were proposed. Unlike the first method, the second can detect and identify both types of fault.

The hybrid behavior of power converters was taken into account in a few research studies that focused on fault diagnosis. For instance, in [5] a diagnosis algorithm of open switch faults is developed based on mixed logical dynamics models. Moreover, in [15] an approach based on a hybrid super twisting sliding mode observer and a hybrid automaton is designed for the diagnosis of inter-turn short circuit faults and open-circuit switch faults. In [16] and [17] the authors developed hybrid diagnosers for the fault diagnosis of a three-cell series power converter. In [18] switch faults diagnosis in a three-cell series power converter was tackled by developing a method based on a super twisting sliding mode observer and a decomposition of the hybrid model of the system.

In this paper, we present a fault diagnosis method based on a first sliding mode switched observer for the detection and isolation of open and short-circuit switch faults in a parallel multi-cellular converter. We studied the cases of single and multiple switch faults.

The paper is structured as follows; in Sect. 2 a parallel multi-cell converter model is presented. Sect. 3 is devoted to the proposed fault diagnosis method for open and short-circuit switch fault. Finally, simulation results

demonstrating the efficiency of the approach is given in Sect. 4 and discussed in Sect. 5.

2 Parallel multi-cell converter model

Parallel multi-cell converters are converters with p switching cells that are interconnected through independent link inductances [19]. They are used often in embedded systems since they can provide a high output current from a low input voltage.

In this work we consider a parallel multi-cell converter consisting of three buck type converters. Its structure is given in Fig. 1.

A parallel multi-cell converter with p phases is given by the set of the following differential equations:

$$\begin{cases} L \frac{di_1}{dt} = -r_L i_1 - V_{C_1} + s_1 E \\ \vdots \\ L \frac{di_p}{dt} = -r_L i_p - V_{C_p} + s_p E \\ C \frac{dV_o}{dt} = \sum_{k=1}^p i_k - \frac{V_o}{R} \end{cases} \quad (1)$$

where L and r_L are respectively the inductance and the resistance of each converter, C is the equivalent capacitance, R is the load resistance, E is the input voltage, V_o is the output voltage.

Fig. 1 Three-cell parallel converter

Let $x = [i_1 \dots i_p V_o] \in \mathbb{R}^n$ be the state variable, the system (1) can be represented as a switched system in the following state form [20]:

$$\begin{cases} \dot{x} = g_q(x, u, t) = A_q x + B_q E \\ y = h_q(x, u, t) = H_q x \end{cases} \quad (2)$$

where

$$A_q = \begin{bmatrix} \frac{-r_L}{L} & 0 & \dots & 0 & \frac{-1}{L} \\ 0 & \ddots & \ddots & \vdots & \vdots \\ \vdots & \ddots & \ddots & 0 & \vdots \\ 0 & \dots & 0 & \frac{-r_L}{L} & \frac{-1}{L} \\ \frac{1}{C} & \dots & \dots & \frac{1}{C} & \frac{1}{RC} \end{bmatrix},$$

$B_q = [s_1 \dots s_p 0]^T$ is the discrete input control,

$$H_q = \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \dots & 0 & 1 \end{bmatrix}.$$

The nominal discrete mode is defined as follows: $q = 1 + 2^0 s_1 + 2^1 s_2 + \dots + 2^{p-1} s_p$ where s_k is the state of the k th switch such that $s_k = \begin{cases} 0 & \text{open} \\ 1 & \text{closed} \end{cases}$ for $k = 1, \dots, p$ known based on the switch control.

A direct control method based on PWM is used with a phase shift of $\frac{2\pi}{p}$ between two adjacent converters.

3 The proposed approach for open-circuit switch fault diagnosis

Motivated by its convergence qualities in a finite time and its robustness to external uncertainties and disturbances, the use of sliding mode observers have gained an increased interest in fault diagnostic applications. This type of observer can be applied for a large class of systems more particularly to hybrid dynamical systems thanks to their variable structure.

A first-order sliding mode observer is used to estimate the phase currents and voltage output. The residuals consisting of the estimation errors are then evaluated in order to detect and isolate the fault.

3.1 First-order sliding mode based residual generation

We propose the first sliding mode observer for the system (1) given by

$$\begin{cases} \dot{\hat{i}}_k = \frac{-r_L}{L} \hat{i}_k - \frac{1}{L} \hat{V}_o + s_k \frac{E}{L} + \lambda_k \text{sign}(e_k) \\ \dot{\hat{V}}_o = \frac{1}{C} \sum_{k=1}^p \hat{i}_k - \frac{\hat{V}_o}{RC} + \alpha \text{sign}(e_v) \end{cases} \quad (3)$$

where λ_k and α are chosen such that the observation error defined as $e = [e_k \ e_v]^T = [i_k - \hat{i}_k \ V_o - \hat{V}_o]^T$ converges to zero in the absence of faults. Using (1) and (3) yields the following observation error dynamics

$$\begin{cases} \dot{e}_k = \frac{-r_L}{L} e_k - \frac{1}{L} e_v - \lambda_k \text{sign}(e_k) \\ \dot{e}_v = \frac{1}{C} \sum_{k=1}^p e_k - \frac{e_v}{RC} - \alpha \text{sign}(e_v) \end{cases} \quad (4)$$

Considering the positive definite Lyapunov candidate function defined by

$$V = V_1 + V_2 \quad (5)$$

where

$$V_1 = \frac{1}{2} e_k^2 \quad (6)$$

and

$$V_2 = \frac{1}{2} e_v^2 \quad (7.)$$

The first time derivative of V_1 is given by:

$$\dot{V}_1 = e_k \dot{e}_k = e_k \left(\frac{-R_L}{L} e_k - \frac{1}{L} e_v - \lambda_k \text{sign}(e_k) \right) \quad (8)$$

Similarly, the first time derivative of V_2 is given by:

$$\dot{V}_2 = e_v \dot{e}_v = e_v \left(\frac{1}{C} \sum_{k=1}^p e_k - \frac{e_v}{RC} - \alpha \text{sign}(e_v) \right) \quad (9)$$

Taking into account (8) and (9) the derivative of V is expressed as

$$\dot{V} = \dot{V}_1 + \dot{V}_2 \quad (10)$$

Based on Lyapunov theory the error dynamics is asymptotically stable at $e = 0$ if the following conditions are verified:

1. $V(e) = 0$ for $e = 0$ and $V(e) > 0$ for $e \neq 0$
2. $\dot{V}(e) = 0$ for $e = 0$
3. $\dot{V}(e) < 0$ for $e \neq 0$

The first and the second condition of Lyapunov stability theory are satisfied. The third condition is satisfied if the derivative of the Lyapunov candidate function is negative definite. And this requires that λ_k and α satisfy

$$\lambda_k > \frac{r_L}{L} |i_k|_{\max} + \frac{1}{L} |V_c|_{\max} \quad (11)$$

$$\alpha > \frac{p}{C} |i_k|_{\max} + \frac{1}{RC} |V_c|_{\max} \quad (12)$$

This yields the convergence of the error to zero.

3.2 Residual evaluation for fault detection and isolation

We chose to compare the residuals with a fixed threshold without going through the norm function to exploit the information on the sign of the residues to be able to detect and locate the faults that affect the switches of the converter.

Theoretically, the residual value is supposed to be zero in normal conditions, however, in practice, it's different from zero due to disturbances and modeling uncertainties. Therefore, instead of comparing the residuals to zero to determine fault signatures, it is more accurate to compare them with the threshold calculated as a little larger than the maximum value of residuals in the absence of faults as follows:

$$\varepsilon \geq \text{Max} |e_i|_{i=1,2,3} \quad (13)$$

A fault signature is defined based on a comparison of the observation error of the phase currents with the positive constant $\varepsilon > 0$.

$$f_k = \begin{cases} -1 & \text{if } e_k < -\varepsilon \\ 0 & \text{if } |e_k| < \varepsilon \\ 1 & \text{if } e_k > \varepsilon \end{cases} \quad (14)$$

A short-circuit fault of the switch S_k is detected if $f_k = 1$. Similarly, an open-circuit fault is detected if $f_k = -1$ and the

defective switch is thus located. In normal operation, the signature of the fault $f_k = 0$ for $k = 1, 2, 3$. The signatures of the different single faults are given in Table 1.

4 Simulation results

The proposed method for the detection of faults is implemented by numerical simulations. The converter parameters are given in Table 2.

The evolutions of the measured and the estimated outputs for the case of an open-circuit fault affecting the switch S_1 at $t = 0.06$ s is shown in Fig. 2.

The evolutions of the measured and the estimated outputs for the case of short-circuit fault affecting the switch S_1 at $t = 0.06$ s is shown in Fig. 3.

Table 2 Parallel multi-cell converter parameters

Parameter	Value
r_L	0.1 Ω
L	100 μH
C	100 μF
R	0.06 Ω
E	12 V

Fig. 2 Measured and estimated output for the open-circuit fault switch S_1 at $t = 0.06$ s

Table 1 Fault signatures in case of single fault

Type of fault	Faulty switch	Fault signature (f_1, f_2, f_3)
Open-circuit Switch Fault	S_1	$(-1, 0, 0)$
	S_2	$(0, -1, 0)$
	S_3	$(0, 0, -1)$
Short-circuit Switch Fault	S_1	$(1, 0, 0)$
	S_2	$(0, 1, 0)$
	S_3	$(0, 0, 1)$
No fault	—	$(0, 0, 0)$

Fig. 3 Measured and estimated output for the short-circuit fault switch S_1 at $t=0.06$ s

Fig. 4 Estimation error for the open-circuit fault switch S_1

The residuals generated for these two cases of single faults are illustrated in Figs. 4 and 5 respectively.

Figure 6 illustrates the evolutions of the measured and the estimated outputs for the case of two open-circuit faults in S_2 at $t=0.06$ s and S_3 at $t=0.07$ s. In this case, residual signals are shown in Fig. 7.

Figure 8 represents the evolutions of the measured and the estimated outputs for the case of short-circuit faults affecting S_1 at $t=0.06$ s and S_2 at $t=0.07$ s. In this case, residual signals are shown in Fig. 9.

The different fault signatures are obtained by comparing the residuals e_1 , e_2 , and e_3 to $\varepsilon=0.1$ A.

5 Discussion

In the case of a single switch fault, it can be shown that the occurrence of an open or short-circuit fault in one of the switches causes an alteration in the output voltage and the phase currents. When the observation error of the latter exceeds the predefined threshold ε the signature value corresponding to the switch S_1 in the case of a single open-circuit fault becomes $f_1 = -1$. Similarly, the signature value to the switch S_1 in the case of a single short-circuit fault becomes $f_1 = 1$. However, the observation error in phase 2 and phase 3 are $f_2 = f_3 = 0$. Consequently, the fault is detected and isolated once one signature fault

Fig. 5 Estimation error for the short-circuit fault switch S_1

Fig. 6 Measured and estimated output for two open-circuit faults in switch S_3 at $t=0.06$ s and S_2 at $t=0.065$ s

Fig. 8 Measured and estimated output for two short-circuit faults in switch S_1 at $t=0.06$ s and switch S_2 at $t=0.07$ s

Fig. 7 Estimation error for two open-circuit faults in switch S_3 at $t=0.06$ s and switch S_2 at $t=0.065$ s

Fig. 9 Estimation error for two short-circuit faults in switch S_1 at $t=0.06$ s and S_2 at $t=0.07$ s

component is different from zero and the type of fault and the faulty switch are hence identified.

In the case of two open-circuit faults, it can be seen in Fig. 8 that the value of the residual e_3 surpasses the threshold after the occurrence of the fault at $t = 0.06$ s. Moreover, the fault indicator becomes $f_3 = -1$ yet the value of the indicators f_2 and f_1 remain zero and hence the fault is detected and isolated. After we introduced another open circuit-fault in S_2 at $t = 0.065$ s the value of the fault indicator f_2 moves from 0 to -1 thus the fault is detected and isolated.

Likewise, in the case of two short-circuit faults the values of the residuals e_1 and e_2 exceed the threshold after the occurrence of the fault at $t = 0.06$ s and $t = 0.07$ s respectively, as depicted in Fig. 9. When the first fault arises, the fault signatures become $f_1 = 1$, $f_2 = 0$, $f_3 = 0$ which indicates a short-circuit fault in the switch S_1 . After the application of the second fault, the value of the fault indicator f_2 changes from 0 to 1 which yields the detection and the isolation of the short-circuit fault in the switch S_2 . However, a peak appears in the residual e_3 which yields a false fault alarm when comparing it to the selected threshold.

According to the undertaken simulations, the time of the detection and isolation is within a range of $1 \mu\text{s}$ i.e. $1/10$ the switching period defined as $10 \mu\text{s}$ which is considered very fast diagnosis time comparing with the results found in [1].

For all the studied cases the detection and the isolation of the faults are ensured and the faulty switches are identified.

When implementing the switched first order sliding mode observer, a saturation function is used instead of sign function to limit the chattering phenomenon that increases the zero-crossing rate and the simulation time. This made the residual signals sensitive to load variations causing false alarms. This problem can be solved by using a higher-order sliding mode observer. Furthermore, a dynamic threshold computation will be used to ensure the robustness against uncertainty and parameter variations

6 Conclusion

In this paper we have developed a diagnostic approach based on first-order sliding mode switched observer. We chose to compare the residuals generated by the observer with a fixed threshold without resorting to the norm function to exploit the information on the sign of each residual. This allowed the detection and localization of single and multiple open and short-circuit switch faults. Moreover,

this method ensured the identification of the fault type and the faulty switch.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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