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Fault detection and isolation for a multi-cellular converter based on sliding mode observer

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Abstract: This paper presents a model-based approach for the fault diagnosis of three-cell power converters. The goal is to design a fault detection and isolation (FDI) scheme which diagnoses parametric and discrete faults. Parametric faults are characterized by abnormal changes in the capacitor value whereas a discrete fault affects a switching element and is characterized by an abrupt deviation of the dynamics of the system. The combined continuous and discrete diagnosers are used to detect and isolate the discrete and the parametric faults. The discrete diagnoser is based on an appropriate decomposition of the hybrid model of the three-cell converter. The continuous diagnoser is based on a set of residuals which enable a comparison between the measured and estimated values of each continuous variable. Some experiments are shown to prove the effectiveness of the proposed scheme.

Keywords: Fault detection and isolation, three-cell power converter, switched system, sliding mode observer.

1. INTRODUCTION

A fault can be defined as a non-permitted deviation of at least one characteristic property of a system or one of its components from its normal or intended behavior. Fault diagnosis is the operation of detecting faults and determining possible candidates that explain their occurrence, which is a crucial step in ensuring the safe operation of complex engineering systems. Indeed, fault occurrence can be extremely detrimental, not only to the equipment and surroundings, but also to the human operator when not detected on time (Daigle et al. (2008)), (Van Gorp et al. (2013)).

For the past decades, switched linear systems have been widely studied in the literature as they are found in various fields such as in manufacturing, power, automotive and chemical process industries. Considering this class of systems, faults can be classified into two categories: parametric faults and discrete faults. Discrete faults influence the operating modes (spontaneous switchings for instance), while parametric faults, which cover partial failures or degradations in system components, change the dynamics of the continuous state (Daigle et al. (2008)).

There have been numerous diagnosis schemes developed in the literature. They can be categorized as analytical model-based approaches and data mining approaches. Analytical model-based approaches exploit the physical knowledge of the system dynamics to construct a mathematical or analytical model using, for example, the bond graph representation of the system, or the governing differential equations (Louajri and Sayed-Mouchaweh (2014)). The corresponding FDI algorithm is usually based on either the analysis of appropriate residuals or an estimation of the fault variables using, for instance, unknown input observers, Kalman filters, parameter identification, etc. Associated to the class of switched systems, some observer-based FDI approaches have been proposed. They can be divided into three categories, depending whether they are able to diagnose only parametric faults, only discrete faults, or both. When no discrete faults are considered, Belkhiat et al. (2011) designed an H_∞ observer to perform parametric fault detection for a linear switched system. A stack of robust Luenberger observers and a discrete algorithm for the diagnosis have been combined to guarantee sensor fault detection and isolation in Belkhiat et al. (2012). In (Louajri and Sayed-Mouchaweh (2014)), (Bayoudh et al. (2008)), some residual signals are used to detect and isolate both continuous and discrete faults. An observer based on a switched extended Kalman filter estimates the continuous state in each operating mode. Another approach, proposed in (Daigle et al. (2008)), (Uzunova et al. (2012)), is based on the design of temporal causal graphs for each normal and faulty mode using a global hybrid bond graph. When measurement deviations, caused by a fault, are detected through residuals, temporal causal graphs help determine the effects that faults will have on the

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measurements. The fault signature is defined as the first non-zero derivative change which can be observed in the residuals. Nevertheless, a common drawback of most of the schemes mentioned above is that they cannot be applied when the system has switching modes in which the state is not fully observable.

The main goal of this paper is to describe an approach for detecting parametric and discrete faults for a three-cell converter. Multicellular converters are used in high power applications since they enable to reduce the switching losses and the electromagnetic interference, improve the harmonic content of the waveforms and increase the robustness properties with respect to the failure of one switch. These properties make multicellular converters a very interesting solution for input current shaping, traction of locomotives, etc. A multicellular converter is based on the association in series of elementary commutation cells. These devices are electrical circuits controlled by switches (transistors, diodes). In order to benefit as much as possible from the large potential of the multicellular structure, theoretical tools for the observation and fault diagnosis of linear switched systems are needed. Indeed, classical tools cannot be applied since some subsystems are not observable in the classical sense. Several failures can affect this system. Floating capacitors and switching components are two examples, which may cause degradations and failures in the multi-cell converter. For instance, a discrete fault can represent a blocked cell or a blocked switch due to a faulty driver. The parametric fault may correspond to an ageing capacitor (Vento et al. (2011)), (Bayoudh et al. (2008)), (Defoort et al. (2011)).

Unlike most existing observer and/or FDI schemes applied to multicellular converters (Van Gorp et al. (2013)), (Bayoudh et al. (2008)), (Uzunova et al. (2012)), this paper considers non-ideal capacitors, by including the equivalent series resistance in the modelling. The contribution of this paper is twofold: (i) an extension of (Louajri and Sayed-Mouchaweh (2014)) is proposed, based on a robust second order sliding mode observer. However, in (Louajri and Sayed-Mouchaweh (2014)), the diagnoser decision is based on three residuals which are computed using ideal signals, without considering the noise affecting the measurement signals. (ii) A combined continuous and discrete diagnoser is proposed to detect and isolate both discrete and parametric faults for the three-cell converter.

The paper is organized as follows. In section 2, the three-cell converter is described together with the discrete and parametric faults considered in our work. Section 3 defines the FDI scheme for the three-cell converter. Some experimental results are described in Section 4. A conclusion and directions for future work are given in Section 5.

2. THREE-CELL CONVERTER

2.1 Modeling of the three-cell converter

The multi-cell converter is a switched system which changes during its operation. Figure 1 shows the topology of a p-cell converter which supplies a passive load composed of a resistor R and an inductor L. Each commutation cell is characterized by a floating capacitor and is controlled by a binary input signal CS_i: $CS_i = 1$ means that the i^{th} cell is conducting, while $CS_i = 0$ means that the i^{th} cell is non-conducting. A structure of multi-cells is adapted to several working modes: (1) a DC/DC mode and (2) a DC/AC mode inverter. To take into account the non- ideal capacitor, the equivalent series resistance (ESR) of each floating capacitor has been included in the model.

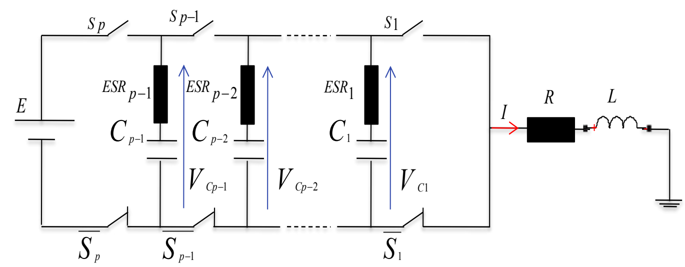

Fig. 1. Multi-cell converter connected to a load RL.

The structure can be modelled by $(p-1)$ dynamical equations related to the evolution of the voltages of the $(p-1)$ floating capacitors and an equation related to the load current.

System (2.1) gives the dynamics of a three-cell converter $(p = 3)$ connected to a load RL:

$$\begin{cases} \dot{V}_{c1} = u_1\left(\frac{I}{C_1} + ESR_1\dot{I}\right) \\ \dot{V}_{c2} = u_2\left(\frac{I}{C_2} + ESR_2\dot{I}\right) \\ \dot{I} = -\frac{R}{L}I - \frac{u_1}{L}V_{C1} - \frac{u_2}{L}V_{C2} + \frac{u_3}{L}E \end{cases} \quad (2.1)$$

where:

$$\begin{cases} u_1 = (CS_2 - CS_1) \\ u_2 = (CS_3 - CS_2). \\ u_3 = CS_3 \end{cases}$$

The dynamic of the three-cell converter can be described in a compact form as a state space equation:

$\dot{X} = A_q X + B_q u$

with: $X = [V_{C1} V_{C2}\ \ I]^T$, $u = E$ and

$$A_q = \begin{bmatrix} \frac{-u_1.ESR_1.u_1}{L} & \frac{-u_1.ESR_1.u_2}{L} & u_1\left(\frac{1}{C_1} - \frac{R.ESR_1}{L}\right) \\ \frac{-u_2.ESR_2.u_1}{L} & \frac{-u_2.ESR_2.u_2}{L} & u_2\left(\frac{1}{C_2} - \frac{R.ESR_2}{L}\right) \\ \frac{-u_1}{L} & \frac{-u_2}{L} & -\frac{R}{L} \end{bmatrix}$$

$$B_q = \begin{bmatrix} \frac{u_1.ESR_1.u_3}{L} \\ \frac{u_2.ESR_2.u_3}{L} \\ \frac{u_3}{L} \end{bmatrix}.$$

Index $q = \{1,2, \ldots ,8\}$ defines the working mode and depends on the 2^3 possible combinations of the binary variables in the triple $(CS_3\ CS_2\ CS_1)$. The eight working modes are listed in Table 2.