

Hybrid Bond Graph Diagnostic and Localisation - Signal Signature Study of Three-Cell Converter

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Abstract—This paper discusses a localization technique for hybrid systems. It is possible to present the effectiveness of this model-based localization approach by using the example of three-cell converter and its eight operation modes. Based on obtained hybrid bond graph model (HBG), the signal signature for each configuration of the hybrid system was analyzed. The innovative interest of the present paper is the use only one representation (Bond Graph) for modeling and systematic generation of fault indicators based on structural and causal properties of used modeling tool. The transition between modes is achieved by control junctions, which can be activated (on) or deactivated (off). Furthermore, it is possible to substitute to a new model, called diagnostic hybrid bond graph model, where the known variables (i.e., parameters, measurements, sources) are the input of the system and the residuals are the output. Due to the reduced numbers of the measured devices we have no enough information for the system and it is important to define localization procedure for the system. In the second part of this paper signal signature study (SSS) applied for the three-cell converter is offered.

I. INTRODUCTION

This paper is devoted to fault diagnosis and localization of hybrid physical systems involving continuous and discrete phenomena. It stay very difficult task because of the complexity of the monitored system. In the present work, localization procedure based on the Bond-graph (BG) model is used [2], [16], [17] and [12]. For the present dynamic system (three-cell converter), the hybrid bond graph (HBG) model is proposed [5], [6], [7] and [9]. For the hybrid approach, an extension of the traditional BG algorithm, incrementally updating the causal assignment when a mode change occurs. In addition, the HBG model incorporates switching functions, which allow the energy flow to be reconfigured whenever a mode change occurs in the system ([10], [11]). The results improve the model's efficiency, using this HBG approach and causal reassignment.

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The choice of using the HBG modeling approach was motivated by the requirements to apply model-based diagnosis, isolation and localization techniques through fault accommodation tasks to a system with hybrid behavior [2], [5], [8], [13] and [14]. It is very important step to prove the effectiveness of the HBG modeling approach. Here the main objective is to apply this approach to diagnosis, by analyzing the system's fault tolerance in the first part and to fault localization, by using the signal signature study in the second part. The fault detection and isolation (FDI) procedure consists of comparing the system's real behavior with the reference behavior. One of the widely-used FDI approaches is the analytical redundancy relations (ARR) formalism. ARR are static or dynamic constraints of the system's different known variables, obtained through the behavioral model.

The fault localization procedure consists to signal signature study (SSS). This approach involves analyzing the behavior of the nominal and the faulty system. The switch between states is assured by using the LMI control algorithm. The SSS consists to study the signature of the output voltage for the three-cell converter. The signature for the nominal and for the faulty model was obtained (six different signatures equals to the number of the switching devices). For this localization procedure we compare the real-time signal signature to the nominal and we can conclude to the place of outbreak.

This paper is organized as follows. Section 2 describes the HBG for the three-cell converter. Section 3 proposes a diagnosis of this class of hybrid system and presents the technical specification for the fault detection, isolation and identification in order to maintain nominal system operations [3], [4]. Section 4 describes the diagnosis optimization procedure using dedicated software named "FDIpad [1]. Section 5 presents the localization procedure based on the signal signatures analysis. Section 6 offers our conclusions and the perspectives for future research.

II. HYBRID BOND GRAPH BASED-MODEL FOR DIAGNOSIS OF THREE-CELL CONVERTER

The topologie of the system to be monitored consists of: electrical circuit with three binary cells (complementary switches), having two stays (opened or closed) and a load containing a a resistance (R element) and inductance (I element) Fig 1. Using the cells, this hybrid electrical circuit can be presented in 2^p differents simple electrical schemes (states) ([15], [16] and [18]). In the output of the system, there are $(p + 1)$ levels $(0, E/p, E(p - 1)/p, E)$. In this way, the voltage measured in the system output V_s

evolves to p possible levels. Under these conditions, the

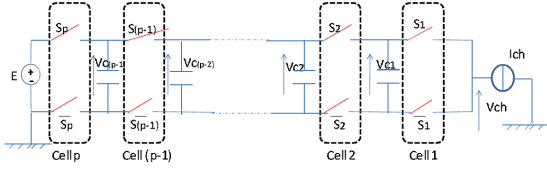


Fig. 1. Multicellular converter (three-cell case)

following property is obtained: The converter has $p - 1$ floating voltage sources and the voltage of the capacity of index k is $\frac{kE}{p}$ (Fig 1). In the case of p cells, the charging current circulates in a floating source only when the cells of adjacent commutation are in different states. In the present work the overlapping operation of a converter with 3 cells was studied.

This hybrid electrical circuit, with eight different simple electrical schemes, is presented in Fig 2, using the three-cell converter. For every state, there is a different voltage (4 levels), measured on the charge boundary points and the transitions between states is presented by the arrows orientation.

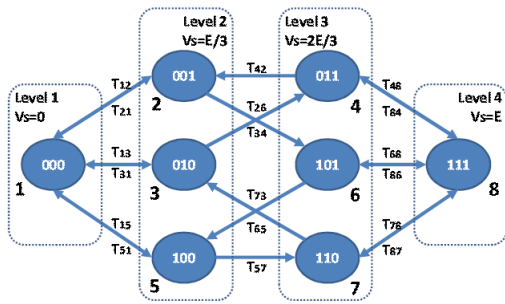


Fig. 2. Multicellular converter (general case)

III. HYBRID BOND GRAPH MODEL FOR THREE-CELL CONVERTER

The Bond Graph (BG) is the graphic modeling approach for hybrid systems. BG have two basic advantages: 1) they model dynamic systems and are very efficient for hybrid dynamic systems, resulting in a unique structural model for all system states; and 2) they are used to diagnose and observe dynamic systems and detect and isolate faults in complex systems. In addition, there are possibilities for optimization tasks when this unique structural model introduced and implemented in a "FDIpad" environment (FDI: Fault Detection and Isolation). The three-cell converter's hybrid nature responds well to the application of the Hybrid Bond Graph (HBG) approach because the traditional BG approach is not appropriate for hybrid systems. The advantages of the HBG are that they include discrete transitions and switching models. Causal dependence is used between the system's inputs and outputs. The obtained results and the methodology of the HBG approach are discussed in previous papers. For

the three-cell converter (Fig 2) the state space model is expressed in equation (1) and (2).

$$\begin{bmatrix} \frac{dV_{C1}}{dt} \\ \frac{dV_{C2}}{dt} \end{bmatrix} = AX + B; X = \begin{bmatrix} V_{C1} \\ V_{C2} \end{bmatrix}; B = \begin{bmatrix} 0 \\ 0 \\ \frac{E}{L} C_{n1} \end{bmatrix} \quad (1)$$

$$A = \begin{bmatrix} 0 & 0 & \frac{1}{C_1}(C_{n2} - C_{n3}) \\ 0 & 0 & \frac{1}{C_2}(C_{n1} - C_{n2}) \\ \frac{-(C_{n2} - C_{n3})}{L} & \frac{-(C_{n1} - C_{n2})}{L} & \frac{-R}{L} \end{bmatrix} \quad (2)$$

The invariant structure of the HBG and the flow/effort relations for all modes are obtained using causality rules (equation 3).

$$\begin{cases} J1 : e_{i-1} = e_i, J1 : f_i = f_{i-1}, \\ J0 : e_i = e_{i-1}, J0 : f_{i-1} = f_i, \end{cases} \quad (3)$$

Using this model approach unique structure for the hybrid three-cell converter was geted as presented in Fig 3.

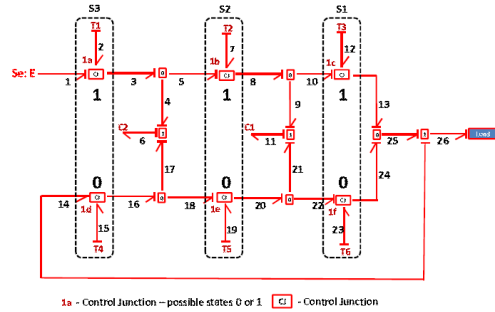


Fig. 3. Hybrid bond graph model for three cell converter

IV. THREE-CELL CONVERTER DIAGNOSIS PROCEDURE

The diagnosis of the hybrid system consists of three steps:

- 1) the detection of faults in the system (Alarm generation);
- 2) the localization of these faults, which can be detected and isolated using Fault Signature Matrix (FSM); and
- 3) the diagnosis to understand how these faults affect the system.

The FDI procedure is presented in Fig 4

V. THREE-CELL CONVERTER DIAGNOSIS PROCEDURE

Most systems are equipped with a limited number of sensors to track the system behavior. That leads to analytical redundancy methods to derive non-local interaction between potential faults and observations. Based on the unique causality structure, it is necessary to obtain global analytical redundancy relations, which describe the hybrid behavior in each state of the system. For the three-cell converter, it is possible to observe the voltage on the capacities De : $Uc1$ and De : $Uc2$, the voltage on the load De : Us , and the

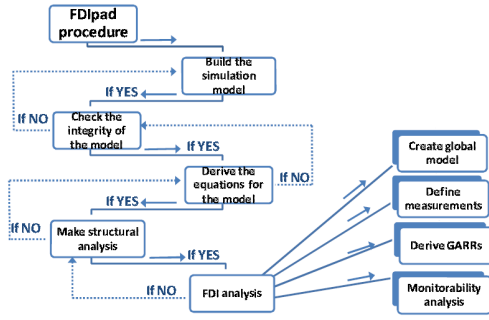


Fig. 4. Fault Detection and Isolation procedure

current on the load $S_f : I_m$.

Using the FDI approach, the system's constraint equations were evaluated. They are more known as Analytical Redundancy Relations (ARR), using known data, sensor data and parameter values of the observed system. These equations can be static or dynamic and represent the compatibility constraints between the variables in the model. They are written only using the known variables (i.e., measurements and sources) (equation 4).

$$ARR =: \begin{cases} MS_e - R D_f : I_m \\ -L \frac{d D_f : I_m}{dt} - \frac{1}{C} \int D_f : I_m dt \end{cases} \quad (4)$$

The verification consists to check the consistency of the system and if there are some faults detected, there will be an inconsistency in one of the equations. The numerical values of these ARR represent the residues, which help to isolate the detected faults in the system. More information about the process and the operation system can be had by dealing with more than one equation. For hybrid systems Global ARR (GARR) equations were established. "Global" means that there are a set of constraint relations for all the operating modes. There are 4 steps in this diagnostic approach:

- 1) Describe the model and build a set of the constraints for the components.
- 2) Draw the HBG in derivative causality from the physical systems while the system's initial conditions are unknown.
- 3) Write the conservative law for the junction 0 $\sum i_i = 0$ and the junction 1 ($\sum U_i = 0$)
- 4) Generate the ARR candidates from the conservative law equations (step 3), to eliminate the unknown variables by using a covering causal path from unknown to known (De, Df, Se, Sf). This results in an oriented graph (4).

The constraint matrices were introduced for all the states of the hybrid system and each element in the electrical circuit. The parameters (i.e., $\alpha, \beta, \gamma, \delta, \eta$ and μ (4)) are Boolean variables and present the constraint on each controlled junctions S_i and $\bar{S}_i, i = \{1, 3\}$.

The GARRs (5), (6) and (7) were established for the hybrid model (equations (1) and (2)) of the converter. There

is more than one GARR for the hybrid system; in this way, it is possible to detect problems not only in the cells but also in the measurement devices.

$$GARR_1 = \begin{cases} \alpha S_e : E - D_e : U_s \\ -(\alpha \eta \frac{1}{C_1} \int (S_f : i_m) dt + (u_{C1_0})) \\ +(\beta \delta \frac{1}{C_1} \int (S_f : i_m) dt + (u_{C1_0})) \\ -(\mu \beta \frac{1}{C_2} \int (S_f : i_m) dt + (u_{C2_0})) \\ +(\gamma \eta \frac{1}{C_2} \int (S_f : i_m) dt + (u_{C2_0})) \end{cases} \quad (5)$$

$$GARR_2 = \begin{cases} \alpha S_e : E - D_e : U_s \\ -(\alpha \eta S_e : U_{C_2}) \\ +(\beta \delta S_e : U_{C_2}) \\ -(\mu \beta S_e : U_{C_1}) \\ +(\gamma \eta S_e : U_{C_1}) \end{cases} \quad (6)$$

$$GARR_3 = \begin{cases} S_f : i_m - \alpha \frac{1}{L} (S_e : E) - \frac{R}{L} \int (S_f : i_m) dt \\ -(\alpha \eta \frac{1}{L} ((S_e : U_{C_2}) dt + (u_{C2_0})) \\ +(\beta \delta \frac{1}{L} ((S_e : U_{C_2}) dt + (u_{C2_0})) \\ -(\mu \beta \frac{1}{L} ((S_e : U_{C_1}) dt + (u_{C1_0})) \\ +(\gamma \eta \frac{1}{L} \int (S_f : i_m) dt + (u_{C1_0})) \end{cases} \quad (7)$$

This GARR structure builds the Fault Signature Matrix (FSM) for the hybrid system. Table II. This structure provides the sensitivity of the residues to the potential fault in the process. For the hybrid system matrix, there are the following parameters: D - fault detection, I - fault isolation, $GARR_i$ - set of all the GARR. The princip consists in the following: the residual is equal to 1 if the system is sensible to fault and equal to 0 otherwise. The General Analysis of the fault detection and isolation procedure is presented in Table tb:1.

TABLE I
GENERAL ANALYSIS OF THE FAULT DETECTION AND ISOLATION PROCEDURE

Mode _i	Detection	Isolation
S_e	Mode:100,101,110,111	Mode:100,101,110,111
C_1	Mode:001,010,101,110	Mode:001,010,101,110
C_2	Mode:010,011,100,101	Mode:010,011,100,101
R	All mode	All mode
L	All mode	All mode

VI. LOCALISATION PROCEDURE - SIGNAL SIGNATURE STUDY

The general view of the localisation procedure (LP) for the three-cell converter is presented in Fig 5. For the simulation model [], LP consists to study the signal signature and the behavior of the system.

The study consists in the follow two parts: *i*) study and analyze of the nominal model. It concludes to observe the load voltage, the load currency and the voltage on the capacitors. In the real system the capture devices are only on load level. That reduces the possibilities to define the place of outbreak; *ii*) Using the computational simulation model, fault on each of the switches (fault model study) was simulated. Six different load voltage signatures are obtained. The difference between the nominal model signal signature

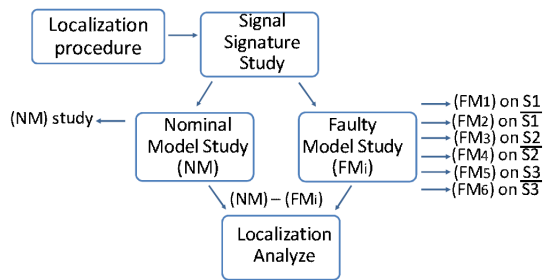


Fig. 5. Organization of LP

and the faulty model signal signature show us the outbreak point. For the simulation procedure LMI control is applied, assuring the switch between the 8 states. The control assures the states ON and OFF of the three-cells as shown in the follow Fig 6.

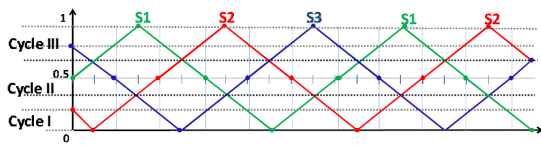


Fig. 6. Cycles of switch between states for the three-cell converter

Based on this control signal, three cycles following one after the other are shown in Fig 7. The first and the third cycles are complementary. The three cycles of switching between states and the three-cell states are presented in Fig 8, Fig 9 and Fig 10.

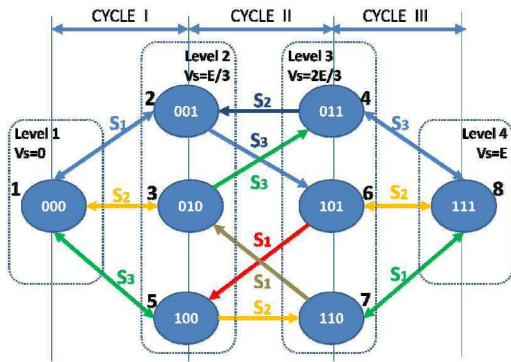


Fig. 7. Cycles of switch between states for the three-cell converter

VII. CASE STUDY

In the following the SSS procedure and the conclusion concerning the localization of the errors for the system are presented.

Nominal model SSS: for the nominal model, under the three cycles conditions under the pulse-width modulation control (8) and for the follow system parameters $C_1 = 40 \cdot 10^{-6}[F]$; $C_2 = 40 \cdot 10^{-6}[F]$; $L = 5 \cdot 10^{-3}[H]$; $R = 10[\Omega]$; $E = 1500[V]$; $I_{sref} = 30[A]$, the obtained results for voltage and current on the load are presented in Fig 11.

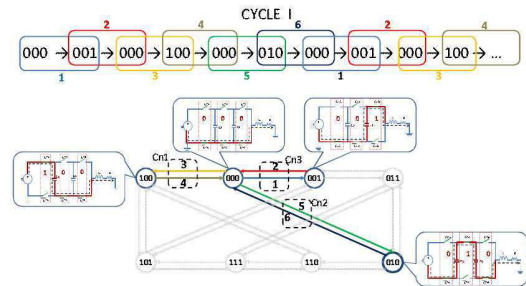


Fig. 8. Cycle 1 of switch between states

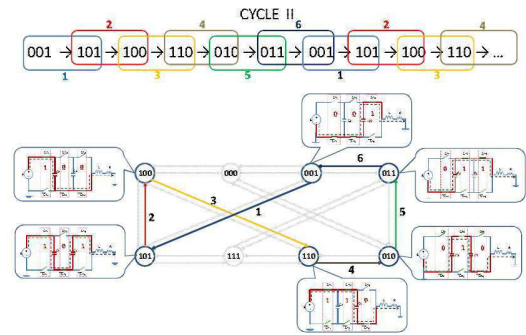


Fig. 9. Cycle 2 of switch between states

$$\left\{ \begin{aligned} V_{C1ref} &= \frac{1}{3}E[V] ; V_{C2ref} = \frac{2}{3}E[V] ; I_{Sref} = 30[A] \end{aligned} \right. \quad (8)$$

Fault model SSS: This physical system is submitted of high temperatures. They can provoke block in level of the cell contacts. The second study in this paper consists to test the fault system (for the six contacts) following the cycles of changing between states. The results for the load measurements (U_s and I_s) are shown in Fig 13. The SSS analyze is presented in Fig 12. The following can be concluded: there is two groups of system behavior - when one of the contacts S_i is blocked on ON state (open) - negatives values of the load voltage and current. Otherwise, if S_i is blocked in OFF state, then values for the load voltage and current is down to zero.

For the three-cell converter the fault model cycle block

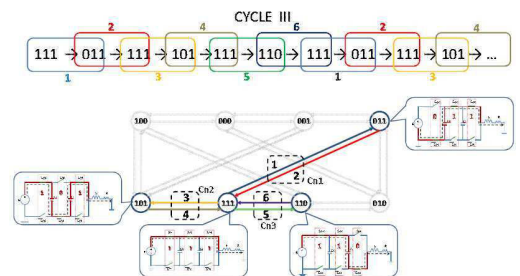


Fig. 10. Cycle 3 of switch between states

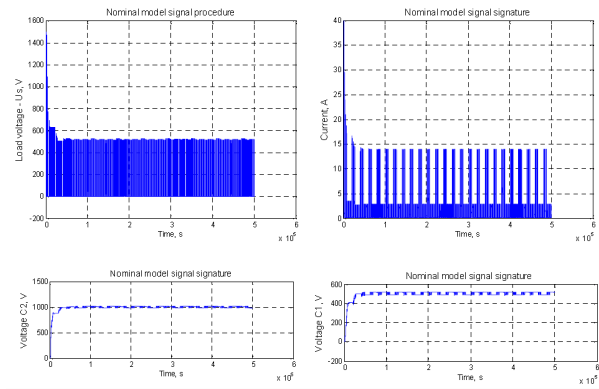


Fig. 11. Nominal model SSS

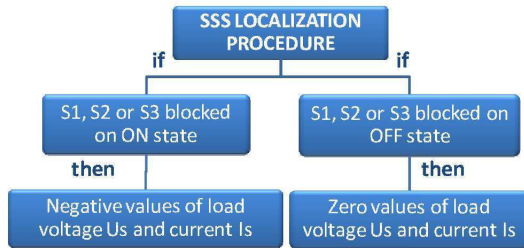


Fig. 12. Synthesis of SSS

diagram, when S_1 stay blocked on OFF state, is shown in Fig 14.

The localization procedure consists to find also the faulty cell. For the considered case study the voltage on the capacitors is observed. Using this data the right outbreak point for the system can be concluded. For the different cells the voltage on the capacitors is shown in Fig 15 for the OFF blocked cells and in Fig 16 for ON blocked cells.

VIII. CONCLUSIONS

In this paper, the causality properties were analyzed, with the aim to localize faults in the system. Based on

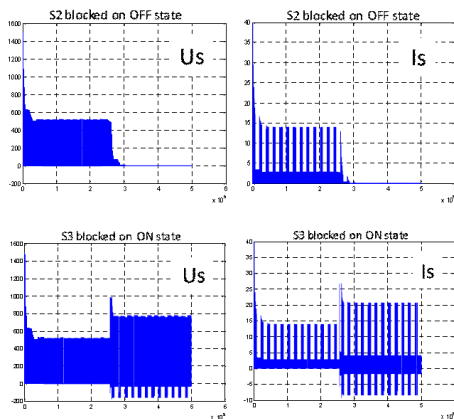


Fig. 13. Fault model SSS

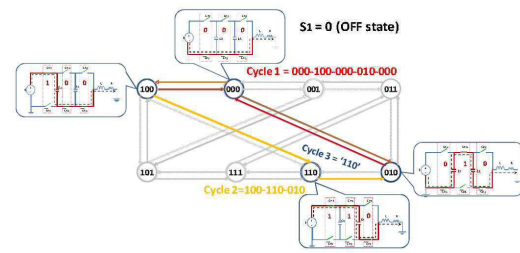


Fig. 14. S_1 in OFF state - fault model cycle block diagram

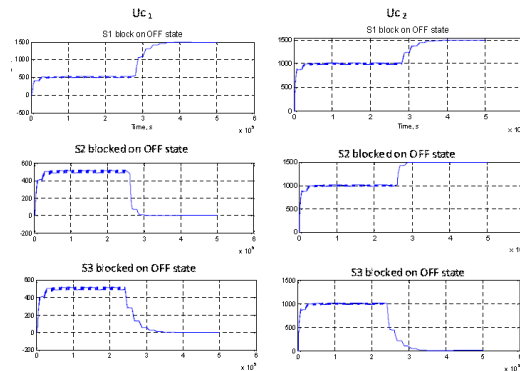


Fig. 15. Fault model SSS for OFF blocked cells

these properties, SSS for the HBG model to the three-cell converter was proposed. The obtained residual model can be implemented in real-time applications to provide a decision support system, including the fault detection, isolation and localization capabilities. For the study case the system behavior was observed and conclusion methodology to localizing the fault was proposed. This LP serves as a state observer using the SSS. For this reason a comparing analysis is proposed of the nominal model behavior and the system behavior under perturbations. In case of errors in the system a residual (for the FDI procedure) are observed and a difference in the signal signature (for the LP).

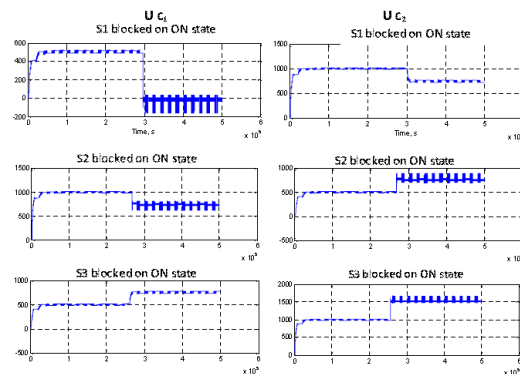


Fig. 16. Fault model SSS for ON blocked cells

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