Analytical Redundancy Relations from Bond Graphs of Hybrid System Models

W. Borutzky

Bonn-Rhein-Sieg University of Applied Sciences, D-53754 Sankt Augustin, Germany

***Abstract*—This paper picks up on one of the ways reported in the literature to represent hybrid models of engineering systems by bond graphs with *static* causalities. The representation of a switching device by means of a modulated transformer (MTF) controlled by a Boolean variable in conjunction with a resistor has been used so far to build a model for simulation. In this paper, it is shown that it can also constitute an approach to bond graph based quantitative fault detection and isolation in hybrid system models. Advantages are that Analytical Redundancy Relations (ARRs) do not need to be derived again after a switch state has changed. ARRs obtained from the bond graph are valid for all system modes. Furthermore, no adaption of the standard sequential causality assignment procedure (SCAP) with respect to fault detection and isolation (FDI) is needed.**

It is shown that the approach proposed in this paper can produce the same ARRs given by Low et. al. for a network example reproduced in Fig. 1. Moreover, its usefulness is illustrated in a small case study by application to a switching circuit from the realm of power electronic systems. The approach, however, is not limited to FDI of such systems. Analytically checked simulation results give confidence in the approach.

***Keywords*—Hybrid models, FDI, ARRs, bond graphs with system operation mode independent causalities, power electronic systems, averaged bond graph models.**

I. Introduction

Depending on the application, it is justified and convient to model fast state transitions as instantaneous discrete events giving rise to hybrid system models encompassing time continuous state transitions and discrete events. Bond graph representations of such hybrid models have been considered for a long time and various approaches have been reported in the literature. Early proposals have been to represent switches considered non-ideal by means of a modulated transformer controlled by a Boolean variable in conjunction with a resistor accounting for the small ON-resistance of the switch [1–3]. Other approaches also aiming at an *invariant* causality assignment independent from system modes have been the use of sinks of fixed causality switching off degrees of freedom [4], or the use of a Petri net representing system modes and discrete changes between them along with a set of bond graphs with standard elements modelling the time continuous behaviour in each identified system mode [5]. Also, in order to account for ideal switching in a bond graph with time-invariant causalities, so-called switched power junctions (SPJs) have been introduced more recently [6, 7].

Bond graph representations of hybrid models allowing for *variable* causalities are based on (ideal) switches [8–11] (switched bond graphs), or junctions controlled by a local automaton [12, 13]. Bond graphs with such controlled junctions are usually called hybrid bond graphs.

Moreover, early publications such as [14] have given rise to an increasing interest in bond graph model based quantitative fault diagnosis resulting in remarkable achievements during recent years [15–21]. Due to the nature of bond graphs, the focus has been mainly on fault detection and isolation (FDI) in systems represented by time continuous models. In [22], hybrid bond graphs are used for fault diagnosis in systems represented by hybrid models. As switching on or off controlled junctions entails at least a partial reassignment of causalities in a bond graph and affects the generation of Analytical Redundancy Relations (ARRs), a modification of the causality assignment procedure with respect to FDI has been recently proposed by Low and his co-workers [23–25]. They term the result a Diagnostic Hybrid Bond Graph.

In this paper, bond graph based FDI in hybrid models does not start from controlled junctions that entail either a dynamical reassignment of causality or a modification of the SCAP. Instead, conceptual switches are represented by transformers with Boolean modulus in conjunction with a resistor and by applying the unchanged standard Sequential Causality Assignment Procedure (SCAP) to the bond graph. As a result, ARRs derived from the bond graph with invariant causalities hold for all system modes. It is shown that derivation of equations leads to the same ARRs given by Low et. al. for an example [23].

Clearly, the representation of switching devices by a transformer with Boolean modulus and a resistor is not limited to electronically implemented switches and may be used for switching devices in other energy domains as well, e.g. for hydraulic check valves. Furthermore, suitable formulation of derived equations may enable the ON resistance of switches to be set to zero turning them into ideal switches.

The paper is organised as follows. The following section briefly revisits bond graph model based fault detection and isolation. Subsequently, the derivation of ARRs from a bond graph of a hybrid model is considered. The approach is illustrated by application to a simple buck converter example. Simulation results are verified by some analytical evaluation. The conclusion summarises the advantages of the approach.

II. Bond Graph Model-based Fault Detection and Isolation

Fault detection and isolation clearly needs fault indicators. In a bond graph model based approach, the sum of efforts or flows respectively at junctions can provide them. In a bond graph model of a non-faulty system, evaluation of these sums results in values called residuals that are equal or close to zero due to numerical inaccuracies. If nonlinearities in the model permit, unknown variables in these equations can be replaced by inputs and known variables. That is, the result is a constraint relation between known variables usually termed Analytical Redundancy Relations (ARRs). Output variables of a bond graph model are often indicated by detector elements. In the context of FDI, these sensed variables are considered known variables. Accordingly, the causality of detectors in inverted. Furthermore, in order to be independent of initial values of energy stores, Samantaray et al. suggested to assign derivative causality as preferred causality to energy stores [21] and have termed the resulting bond graph diagnostic bond graph.

If values of the known variables in an ARR have been obtained by measurements of a real process or from another behavioural bond graph model accounting for possible faults in the process, then the residual of the ARR is likely to be different from zero over time due to noise in measurement, to parameter uncertainties or due to the occurrence of a fault. Noise in measurement can be suppressed by appropriate filtering before measured values are used in a diagnostic model. If the residual exceeds certain thresholds, then this event indicates that a fault has occurred in one of the system's components. As more than one system component usually contribute to an ARR, it is not clear in which component the indicated fault has happened. The information of which components are involved in an ARR is called the signature of the residual. Residuals with different signature are called structurally independent. Their number is equal to the number of sensors added to a system [21]. However, the set of ARRs is not unique. The information of which system component contributes to which residual is usually expressed in a Fault Signature Matrix (FSM) [26]. Its diagonal part directly indicates single faults that can be isolated. For isolation of simultaneous faults, parameter estimation by means of least squares optimisation has been used [20]. In this paper, the single fault hypothesis is adopted.

III. Derivation of ARRs from a Bond Graph of a Hybrid Model

In this paper, switches in hybrid models are represented in a bond graph by means of a transformer modulated by a Boolean variable and a resistor with statically assigned conductance causality as has been initially proposed by Ducreux, Dauphin-Tanguy and Rombaut for bond graph modelling of power electronic circuits [2]. The advantage of this approach is that the hybrid model is represented by one single bond graph and application of the SCAP results in causalities that hold for all physically feasible combinations of switch states. From such a bond graph of a hybrid model, ARRs can be derived in the same way as from a bond graph of a time continuous model.

For illustration, the network example used by Low et. al. in [23] is adopted. It is shown that the approach in this paper leads to the same ARRs given in [23]. Fig. 1 displays the circuit diagram and Fig. 2 an associated bond graph. As can be seen from the bond graph in Fig. 2, detector causalities have been inverted and *derivative* causality has been assigned to energy stores as proposed by Samantaray et al. [20]. although

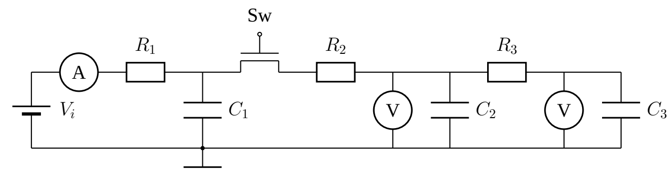

Figure 1. Network with a switch (cf. [23])

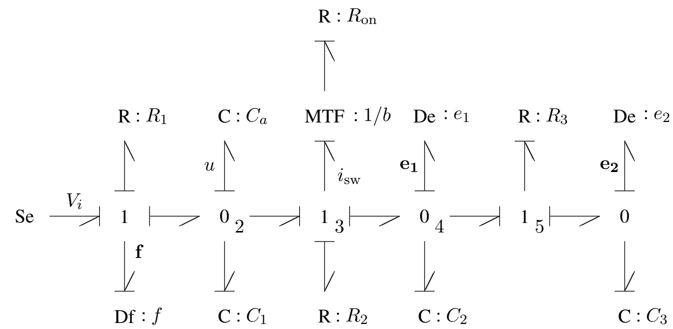

Figure 2. Bond graph of the network in Fig. 1

this is not necessary for the derivation of ARRs expressed in terms of the derivatives of energy storage variables instead of their integral. The auxiliary capacitor $\mathrm{C} : C_a$ in integral causality with a small capacitance C_a has been added to resolve the causal conflict at junction 0_2. In its constitutive relation solved for its current, C_a is considered small so that the current vanishes. In the formulation of equations, the parameter of an auxiliary storage element used for resolving a causality conflict at a junction is set to zero. That is, the auxiliary storage elements will not lead to a set of stiff model equations with regard to simulation performed for a numerical evaluation of residuals.

For comparison, Fig. 3 reproduces the diagnostic hybrid bond graph given by Low et al. in [23]. In that diagnostic hybrid bond graph, junction 1_3 is a controlled junction accounting for the connection and the disconnection of circuit nodes by the pass transistor modelled as a switch. The resistor $\mathrm{R} : R_{\mathrm{p2}}$ is an artificial resistor resolving the causal conflict at junction 0_4 similar to the auxiliary capacitor $\mathrm{C} : C_a$ in the bond graph of Fig. 2.

In [23], ARRs are derived from the junctions $0_2, 0_4, 1_5$. In general, ARRs are obtained from the balance equation of those junctions to which a detector has been attached that represent a real sensor. According to the choice made in [23], summation of flows at junction 0_2 of the bond graph in Fig. 2 yields for

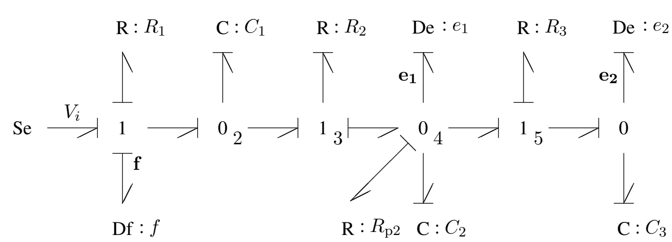

Figure 3. Diagnostic hybrid bond graph of the network (cf. [23])

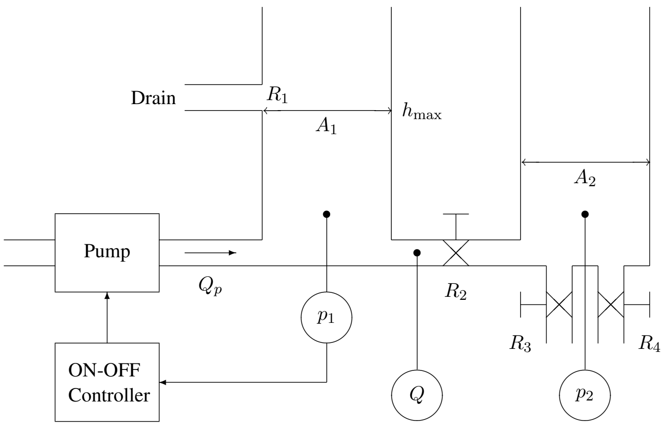

Figure 4. Two tank system (cf. [25])

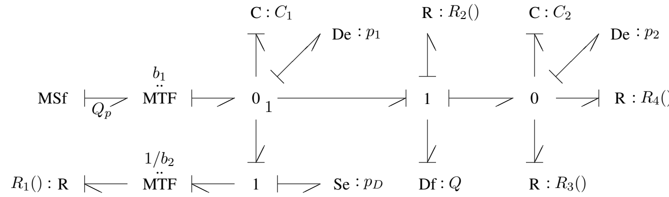

Figure 5. Bond graph with Boolean controlled MTFs of the two tank system

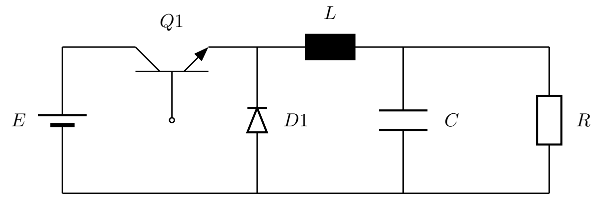

Figure 6. Schematic of the DC-DC buck converter circuit

the residual r_1

$$r_1 = f - C_1\dot{u} - i_{\mathrm{sw}} - C_a\dot{u} \ . \tag{1}$$

As C_a is assumed very small, the term $C_a\dot{u}$ can be neglected in (1). Due to the conductance causality of the ON resistance $R : R_{\mathrm{on}}$ the constitutive relation of the switch takes the form

$$i_{\mathrm{sw}} = \frac{b^2}{R_{\mathrm{on}} + b^2 R_2}(u - e_1) \tag{2}$$

where $b \in \{0, 1\}$. Finally, the voltage u is determined from the sum of efforts at the left 1-junction

$$u = V_i - R_1 f \ . \tag{3}$$

As a result, the ARR for r_1 reads

$$\begin{aligned} r_1 &= f - C_1\frac{d}{dt}(V_i - R_1 f) \\ &\quad - \frac{b^2}{R_{\mathrm{on}} + b^2 R_2}(V_i - R_1 f - e_1) \ . \end{aligned} \tag{4}$$

Likewise, summation of flows at junction 0_4 and of efforts at junction 1_5 respectively and elimination of unknown variables according causal paths in the bond graph gives the ARRs

$$r_2 = i_{\mathrm{sw}} - C_2\dot{e}_1 - C_3\dot{e}_2 \tag{5}$$

$$r_3 = e_1 - R_3 C_3 \dot{e}_2 - e_2 \ . \tag{6}$$

These results are identical to the ones reported in [23] if R_{on} is neglected in the ON mode of the switch.

Clearly, the derivation of ARRs from bond graphs in which elements modelled as switches are represented by a Boolean controlled MFT in conjunction with a resistor in conductance causality is not limited to electronic circuits with switching elements. In [25], Low et. al. consider a hydraulic two tank system in which an ON-OFF controller ensures that the fluid level in the tank connected to the pump does not exceed a certain level. This tank has got a drain to prevent an overflow in case the controller fails (cf. Fig. 4). Fig. 5 displays a bond graph with Boolean controlled MTFs of that system. The residual r_1 derived from the bond graph in Fig. 5 reads

$$r_1 = b_1 Q_p - C_1\dot{p}_1 - b_2 k_1\sqrt{b_2|p_1 - p_2|} - Q \tag{7}$$

where k_1 is a constant, $b_2 = 0$ for $p_1 \leq p_D$ and $b_2 = 1$ for $p_1 > p_D$ (overflow).

IV. Case Study

Beyond the result of the previous section, FDI in a DC-DC buck converter circuit [16] is considered in a small case study in order to show that bond graph modelling based on the representation of switches by modulated transformers and the use of the standard SCAP can well support FDI in hybrid system models and produces correct result.

Fig. 6 shows the circuit schematic of the buck converter. A bond graph of the buck converter is displayed in Fig. 7. Again, the capacitor $C : C_a$ has been attached to junction 0_2 to resolve the causal conflict at that junction caused by the fixed conductance causality of the ON resistors of the switches. Physically, it can be justified by the small capacitance of the circuit node against ground.

Assume that the inductor current i_L and the voltage drop across the capacitor u_C are measured. Accordingly, Fig. 8

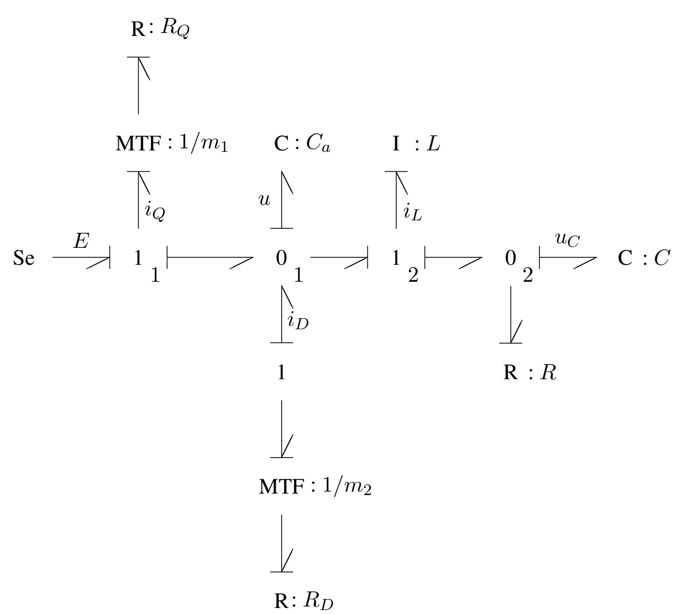

Figure 7. Bond graph of the DC-DC buck converter circuit (cf. Garcia, 1997)

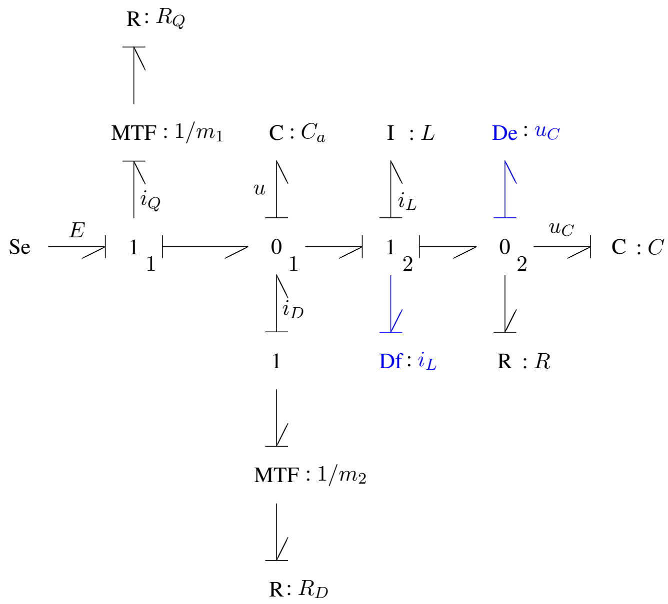

Figure 8. Diagnostic bond graph of the DC-DC buck converter circuit

TABLE I
FAULT SIGNATURE MATRIX OF THE BUCK CONVERTER WITH SENSORS Df : i_L AND De : u_C

Component	Parameter/ Output	r_1	r_2	D_b	I_b
Supply of signal m_1	m_1	1	0	1	0
Switch Q	R_Q	$m_1 = 1$	0	$m_1 = 1$	0
Diode D	R_D	$m_2 = 1$	0	$m_2 = 1$	0
Inductor	L	1	0	1	0
Capacitor	C	0	1	1	0
Resistor	R	0	1	1	0
Sensor of i_L	i_L	1	1	1	0
Sensor of u_C	u_C	1	1	1	0

depicts the diagnostic bond graph. From the diagnostic bond graph, the following two ARRs can be derived

$$1_2: \quad r_1 = u - L\frac{di_L}{dt} - u_C \tag{8}$$

$$0_2: \quad r_2 = i_L - C\dot{u}_C - \frac{1}{R}u_C \tag{9}$$

where

$$u = k m_1^2 E - k R_Q i_L \tag{10}$$

and

$$k := \frac{R_D}{m_1^2 R_D + m_2^2 R_Q} \tag{11}$$

with $m_2 = 1 - m_1$.

With these two residuals the structural fault signature matrix in Table I can be set up. Clearly, a fault in the pass transistor or in the diode can only be detected when these elements are active. This is indicated in the first additional column with the heading D_b. As can be seen from the last column with the heading I_b, no fault can be isolated given the two sensors. However, isolability can be improved by adding more sensors.

TABLE II
PARAMETERS OF THE BUCK CONVERTER

Parameter	Value	Units
E	100	V
R_{on}	0.1	Ω
L	50	mH
C	50	μF
R	50	Ω
T	10^{-3}	s
α	0.7	-

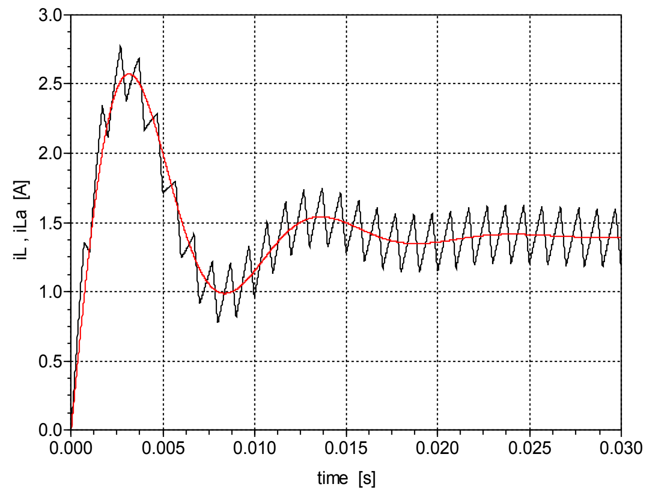

Figure 9. Time evolution of the inductor current i_L for the case of a non-faulty operation

A. Non-Faulty Behaviour

Neglecting the capacitance C_a, the following two state equations can be derived from the bond graph in Fig. 7.

$$\frac{di_L}{dt} = \frac{1}{L}[u - u_c] \tag{12a}$$

$$\frac{du_C}{dt} = \frac{1}{C}\left[i_L - \frac{u_C}{R}\right] \tag{12b}$$

Given the parameters listed in Table II, and assuming that $R_Q = R_D = R_{\text{on}}$, Fig. 9 shows the time evolution of the current i_L through the inductor and of its mean value i_{La} for the case of a non-faulty operation of the buck converter. In Table II, T denotes the duty cycle of the signal switching the pass transistor Q1 on and off and α the duty ratio. The transistor is on for the period αT, while it is off for the remaining part $(1-\alpha)T$ of the period.

For $R_Q = R_D = R_{\text{on}}$, the dynamic equations of the average inductor current i_{La} and the the average voltage u_{Ca} read

$$\frac{di_{La}}{dt} = \frac{1}{L}[\alpha E - R_{\text{on}} i_{La} - u_{Ca}] \tag{13a}$$

$$\frac{du_{Ca}}{dt} = \frac{1}{C}\left[i_{La} - \frac{u_{Ca}}{R}\right]. \tag{13b}$$

Fig. 10 shows a bond graph of the average model.

B. Fault Scenario 1

As one of the possible fault scenarios, consider the case that the signal controlling the switch Q is not properly supplied for

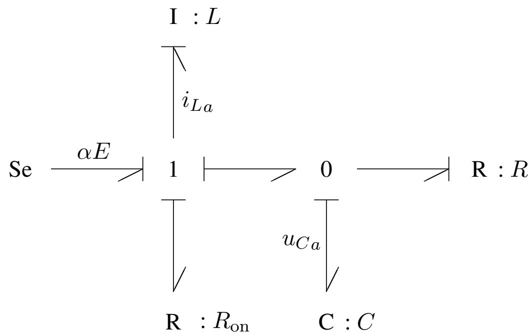

Figure 10. Bond graph of the average model

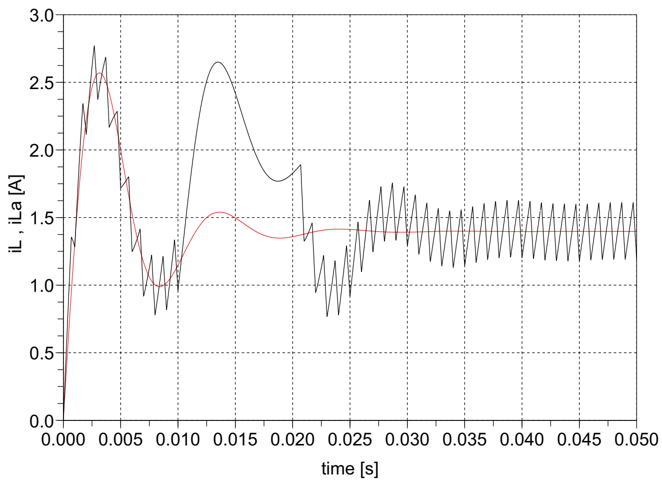

Figure 11. Faulty time evolution of the inductor current due to a temporarily permanently closed switch

some period of time. Let the switch be permanently closed for the time interval $[0.01s, 0.02s]$ and assume that this is the only fault. By consequence, the diode is permanently off during that interval. Fig. 11 shows the faulty time history of the current i_L. As to be expected from the fault signature matrix, this single fault is indicated by the time evolution of residual r_1 (cf. Fig. 12). For the residual r_1, an analytical expression can be found and used for verification of the result obtained by simulation. Let

$$\tilde{k} \quad = \quad \frac{\tilde{R}_D}{\tilde{m}_1^2 \tilde{R}_D + \tilde{m}_2^2 \tilde{R}_Q} \tag{14}$$

with the tilde denoting possibly disturbed variables or parameters. Then, the expression for r_1 reads

$$r_1 \quad = \quad (\tilde{k}\tilde{m}_1^2 - k m_1^2)E - (\tilde{k} - k)R_Q i_L \, . \tag{15}$$

A permanent closure of the switch Q1 during the time interval under consideration means $\tilde{m}_1 = 1$, while in the non-faulty system model, m_1 switches values between 0 and 1. Thus, for $\tilde{m}_1 = 1, \tilde{m}_2 = 0$ and $m_1 = 1, m_2 = 0$ the residual r_1 becomes zero. For $\tilde{m}_1 = 1, \tilde{m}_2 = 0$ and $m_1 = 0, m_2 = 1$, the expression for r_1 reduces to E. That is, during the time interval $[0.01s, 0.02s]$, the value of r_1 oscillates between zero and $E = 100V$ as displayed in Fig. 12.

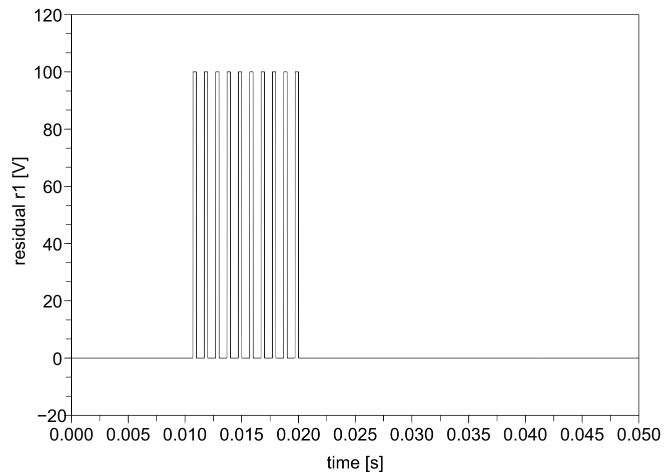

Figure 12. Residual r_1 indicating the temporary permanent closure of the switch

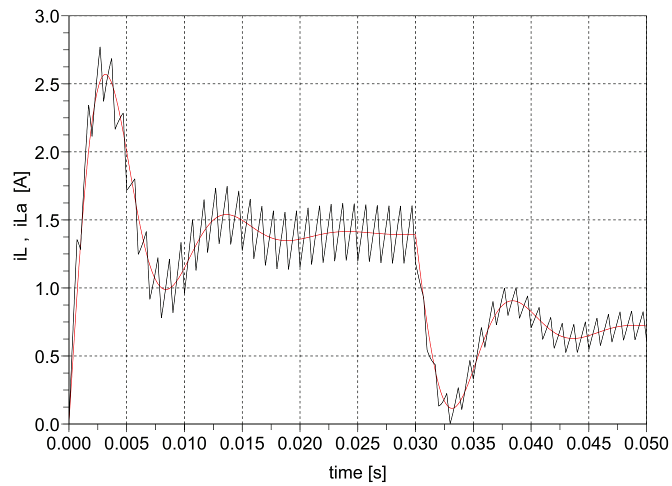

Figure 13. Faulty time evolution of the inductor current in case 2

C. Fault Scenario 2

In a second fault scenario, the diode is considered to be permanently conducting as of a time instant $t_3 = 0.03s$. That is, $\tilde{m}_1 = m_1$, $\tilde{m}_2 = 1$. Fig. 13 shows the faulty time history of the current $\tilde{i}_L$ along with its mean value for this case. For $t > t_3$, the state equations read

$$L\frac{d\tilde{i}_L}{dt} \quad = \quad \frac{R_D m_1^2}{m_1^2 R_D + R_Q}E - \frac{R_D}{m_1^2 R_D + R_Q}R_Q \tilde{i}_L - \tilde{u}_C \tag{16a}$$

$$C\frac{d\tilde{u}_C}{dt} \quad = \quad \tilde{i}_L - \frac{\tilde{u}_C}{R} \, . \tag{16b}$$

From these equations, the mean values $\tilde{i}_{La}$, $\tilde{u}_{Ca}$ for $t \to \infty$ can be computed. For $R_Q = R_D = R_{\text{on}}$, these values are $\tilde{u}_{Ca} = 35V$ and $\tilde{i}_{La} = 0.7A$ in accordance with Figures 13 and 14. This fault occurring for $t > t_3$ is indicated by the time evolution of residual r_1 in Fig. 15 as to be expected from the FSM. Again, the simulation result for r_1 can be checked analytically. Let $t > t_3$ and $R_Q = R_D = R_{\text{on}}$. In this case,

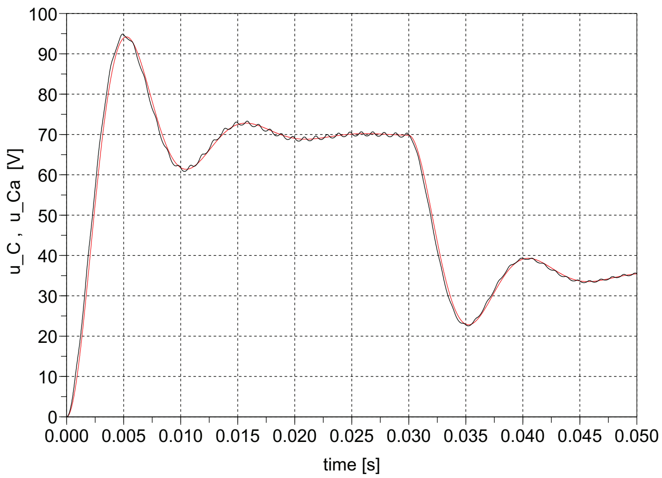

Figure 14. Faulty time evolution of the voltage across the capacitor in case 2

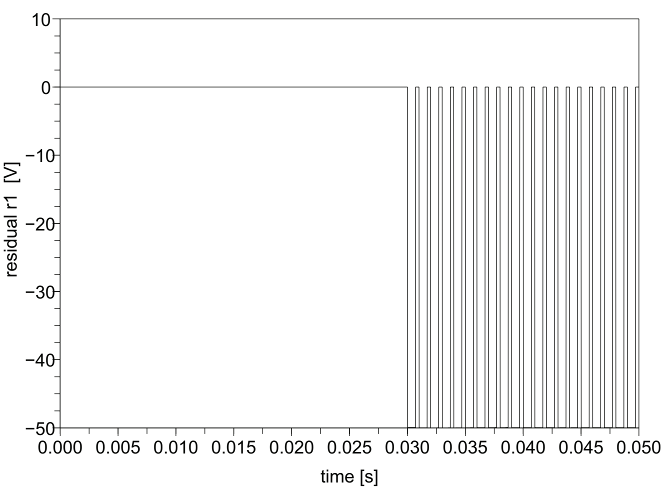

Figure 15. Residual r_1 in case 2

(15) then reduces to

$$r_1 = -\frac{m_1^4}{m_1^2+1}E + \frac{m_1^2}{m_1^2+1}R_Q i_L \ . \qquad (17)$$

As the ON resistance R_{on} is small, R_Q is neglected in (17). As a result, it can be seen that r_1 oscillates between zero ($m_1 = 0$) and the value $-E/2 = -50V$ in case $m_1 = 1$.

V. Conclusion

Aiming at a bond graph based derivation of ARRs for hybrid models, this paper picks up on a proposal known for a long time to represent switches by a transformer modulated by a Boolean variable and a resistor in fixed conductance causality accounting for its ON resistance. This representation has been used to come up with a model for the purpose of simulation. The paper demonstrates that this representation can well constitute an approach to bond graph based quantitative FDI of hybrid models offering the following advantages.

- Computational causalities once assigned are independent of system modes. There is no need for adjusting causalities after a change from one system operation mode to another.

  This means that neither model equations nor ARRs need to be derived again after a discrete change of a system mode.
- There is no need for a special version of the SCAP as has been proposed for bond graphs with controlled junctions in [23].
- Existing bond graph software such as SYMBOLS [27] could be used to generate a single set of ARRs. As these ARRs include Boolean variables, there is not one single FSM but a set. Detection and isolation of faults become system mode dependent. (In [23], they are called Global ARRs.)

Causal conflicts at junctions may require auxiliary storage elements with a small parameter value to be attached. However, in the derivation of equations from a diagnostic bond graph with storage elements in preferred derivative causality, the parameter of these auxiliary storage elements can be set to zero so that the additional storage elements will not lead to a set of stiff model equations with regard to simulation performed for a numerical evaluation of residuals. If it is decided to keep the small ON resistance of the switch model, i.e. switching devices are not represented by ideal switches, then small time constants may result.

It is shown that the approach in this paper can come up with the same ARRs given in [23] for a network example. Moreover, the approach has been applied to a switching circuit. Simulation results obtained with Scilab [28] have been analytically checked giving rise to confidence in this approach.

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Wolfgang Borutzky is a professor for Modelling and Simulation of Engineering Systems at Bonn-Rhein-Sieg University of Applied Sciences, Germany. He obtained his Diploma Degree in Mathematics in 1979 and his Doctoral Degree in Mechanical Engineering in 1985 both from the Technical University of Braunschweig, Germany. He was a visiting professor at Twente University in Enschede, The Netherlands (1993), at the University of Arizona in Tucson, Arizona, U.S.A (1996) and at École Centrale de Lille, France (2001, 2002). Since 2008 he is also an Associate Professor of Electrical Engineering and Information Technology at the University of Dubrovnik, Croatia.

His main scientific interests include modelling and simulation methodologies for multidisciplinary systems, especially Bond Graph based as well as object oriented modelling; modelling, simulation, control and diagnosis of mechatronic systems, modelling languages, software design for modelling and simulation of continuous, as well as hybrid systems, scientific computing, numerical algorithms and software design for (parallel) continuous system simulation.

Dr. Borutzky has published extensively in major international conferences on Modelling and Simulation and in refereed scientific journals. He is the author of a Springer monograph on Bond Graph Modelling and the editor and a co-author of a Springer compilation text on Bond Graph Modelling of Engineering Systems with contributions from experts in various fields from all over the world. He was also the guest editor and a cou-author of two special journal issues on bond graph modelling.

Since 1990 he has served in many international scientific conferences on Modelling and Simulation in various capacities, in 2005 as Assistant General Chair of the European Conference on Modelling and Simulation (EMCS) in Riga, Latvia and as General Chair of the ECMS 2006 in Sankt Augustin, Germany. In 2009, he was an invited speaker of the IASTED Conference on Modelling, Simulation and Identification (MSI 2009) in Beijing, China and in 2010 he was one of the invited keynote speakers to the Conference on Power Control and Optimisation (PCO 2010) in Kuching, Malaysia. He has also served as an invited external examiner of Ph.D. theses in France, India and Pakistan.

Dr. Borutzky is a member of ASIM, a member of the IASTED Technical Committee on Modelling and Simulation and a senior member of SCS. During the 2004-2006 biennium he served on the SCS Board of Directors. From 2005 to 2007 he served on the Board of the European Council for Modelling and Simulation. He is also active as a member of the Editorial Board of some major modelling and simulation related journals. Currently, he is again an Associate Editor of the journal Simulation: Transactions of the Society for Modeling and Simulation International.

E-mail address: wolfgang.borutzky@h-brs.de, web-page: http://www2.inf.fh-brs.de/∼wborut2m/