An Integrated Approach to Parametric and Discrete Fault Diagnosis in Hybrid Systems

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1 Fault Diagnosis of Electrical Power Systems

Fault diagnosis is crucial for ensuring the safe operation of complex engineering systems. Faults and degradations need to be quickly identified so that corrective actions can avoid catastrophic situations. Most real-world, embedded systems are hybrid in nature. In such systems, hybrid models have to be employed for correct tracking and diagnosis. The majority of hybrid systems diagnosis work, however, has focused on either discrete or parametric fault diagnosis. In contrast, we present an integrated model-based approach to diagnosing both parametric and discrete faults in hybrid systems. This extends our previous work in diagnosis of parametric faults in hybrid systems [1,2] by including discrete faults, resulting in a unified hybrid diagnosis methodology. We demonstrate our approach using experimental results performed on a complex electrical power system.

The Advanced Diagnostics and Prognostics Testbed (ADAPT) [3], deployed at NASA Ames Research Center, is functionally representative of a spacecraft's electrical power system. Over fifty relays and circuit breakers configure the system into different modes of operation. Therefore, the system behavior is naturally hybrid. Parametric faults, such as changes in resistance and inductance values, can occur in the components. Discrete faults, such as relays becoming stuck, may also occur. We consider a subset of ADAPT that involves a battery discharging to two parallel DC loads, as shown in Fig. 1, which includes two relays (Sw_1 and Sw_2) and one circuit breaker (CB). The selected sensors measure the battery voltage, $V_B(t)$, the currents through the loads, $I_{L1}(t)$ and $I_{L2}(t)$, and the on/off position of the circuit breaker, $P_{CB}(t)$.

Hybrid System Modeling. We develop component-based models of hybrid physical systems using hybrid bond graphs (HBGs) [4]. Bond graphs define an energy-based, multi-domain, topological modeling scheme for dynamic systems. HBGs extend bond graphs by allowing switching behavior of components, defined through a *control specification* (CSPEC), modeled as a finite automaton [4,2]. The state transitions may be attributed to controlled or autonomous events, and the output of the CSPEC determines the component state.

We focus on the diagnosis of single, abrupt, persistent faults in hybrid systems, and classify these faults as either (*i*) *parametric faults*, or (*ii*) *discrete*

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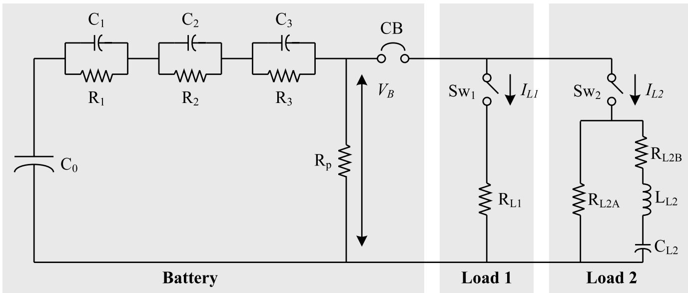

Fig. 1. Electric circuit equivalent for the battery system

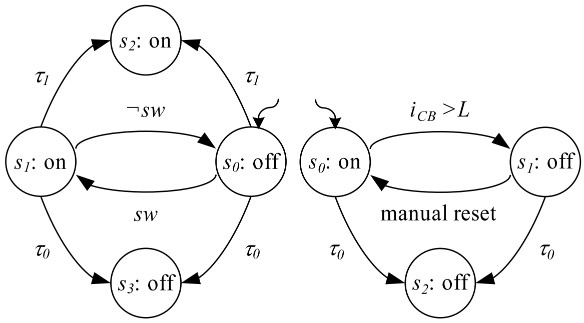

Fig. 2. Relay (left) and circuit breaker (right) CSPECs for ADAPT

faults. Parametric faults cover partial failures or degradations in system components, and are modeled as an unexpected change in the value of a system parameter in the model. For example, the load resistance R_{L1} may increase or decrease. Discrete faults are modeled as a discrepancy between the actual and expected mode of a switching element. Discrete faults in ADAPT include switch malfunctions. For example, a switch may be commanded to close, but remain stuck open. Also, it may unexpectedly open or close without a command. Because the switching behavior in HBGs is captured by CSPECs, we model discrete faults as unobservable fault events in the CSPEC.

Example CSPECs for ADAPT are given in Fig. 2, with the state outputs shown. The relay CSPEC (Fig. 2, left) includes fault events τ_0 and τ_1. Event τ_1, corresponding to the relay being stuck on, causes a transition to the stuck on state, s_2. If the relay was previously off, then this fault manifests in the measurements immediately, because it switches off by itself. Otherwise, it will only manifest when sw becomes true, i.e., it becomes stuck on. The case is similar for the τ_1 event. For the circuit breaker CSPEC (Fig. 2, right), only the stuck off fault, τ_0, is appropriate, and the behavior is similar. The circuit breaker may switch off due to its current, i_{CB} exceeding the limit L, which is nominal behavior, or may switch off due to a fault.

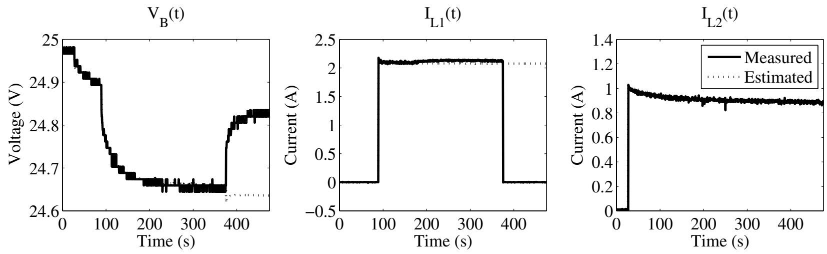

Fig. 3. Sw_1 opens

Hybrid Diagnosis Approach. Our method for integrated diagnosis of parametric and discrete faults in hybrid systems extends the Hybrid TRANSCEND [2] approach for diagnosing single, abrupt, parametric faults in hybrid systems. The diagnosis is based on analysis of fault transients to establish the fault and the mode in which it occurs [1]. We extend this analysis to discrete faults, and augment the approach to handle both parametric and discrete faults. When a fault is detected, the estimated system mode may be incorrect. We compute possible modes of fault occurrence and use the extended diagnosis model to hypothesize parameter deviations as well as discrete fault events that are consistent with the observed measurements. For each possible fault, we predict future measurement deviations. When a new deviation occurs, we check consistency of the fault candidates. Because mode changes may change the predictions, we update our candidates to the possible true system modes. Inconsistent candidates are dropped, and consistent candidates are retained. Details may be found in [5].

Experimental Results. We demonstrate our algorithms on discrete faults injected into the actual system. Our set of possible faults includes parametric faults in the battery and loads (C_0^-, R_1^+, R_{L1}^+, R_{L1}^-, R_{L2A}^+, R_{L2A}^-), sensor faults (V_B^+, V_B^-, I_{L1}^+, I_{L1}^-, I_{L2}^+, I_{L2}^-, P_{CB}^+, P_{CB}^-), and discrete faults in the switches ($Sw_1.off$, $Sw_1.on$, $Sw_2.off$, $Sw_2.on$, $CB.off$). We denote the system mode by q_{ijk} where i is the mode of Sw_1, j is the mode of Sw_2, and k is the mode of CB. We first consider an unexpected switch fault. Within the first 100 s, both loads are brought online. At 375.5 s, Sw_1 switches off by itself. Fig. 3 shows the measured and estimated outputs. As a result, $I_{L1}(t)$ goes immediately to zero, and $V_B(t)$ increases. The fault is detected at 376.0 s, and the symbol generator reports a decrease in $I_{L1}(t)$. Because P_{CB} does not immediately change, the only possible mode of fault occurrence is q_{111}, so the initial fault set is $\{(I_{L1}^-, q_{111}), (R_1^+, q_{111})),$ $(R_{L1}^+, q_{111})), (R_{L2A}^+, q_{111})), (R_{L2A}^-, q_{111})), (Sw_1.off, , q_{011})\}$. At 376.5 s, the symbol generator reports an increase in $V_B(t)$, thus eliminating the sensor fault as a candidate. At 378.5 s, the symbol generator reports that I_{L1} went to zero. Since only $Sw_1.off$ may cause this behavior, it is correctly isolated.

Next, we consider a stuck switch fault. At 414.0 s, Sw_1 is commanded off but remains on. Fig. 4 shows the outputs. The estimated system mode is q_{011}, but the actual system mode is q_{111}, and $\hat{I}_{L1}(t)$ goes to zero, while $I_{L1}(t)$ remains

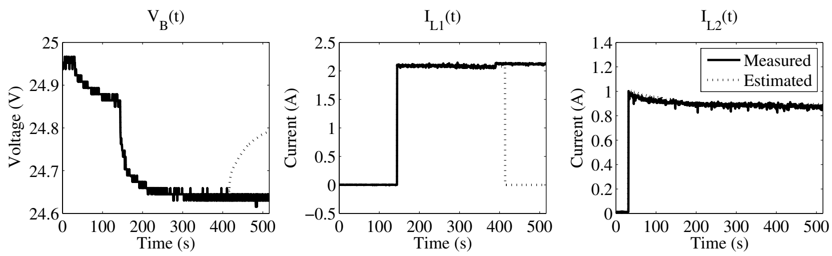

Fig. 4. Sw_1 gets stuck closed

nonzero. The fault is detected at 416.0 s, and the symbol generator reports that $I_{L1}(t)$ has increased. Because the expected mode is q_{011}, the only reason for the current to deviate is due to a discrete fault or a sensor fault, so the initial hypothesis set is $\{(I_{L1}^-, q_{011}), (Sw_1.on, q_{111})\}$. At 418.5 s, the symbol generator reports that $I_{L1}(t)$ became nonzero when expected to be zero. Because sensor faults are also allowed to cause discrete behavior, both faults are retained. At 419.5 s, we observe a decrease in $V_B(t)$, and since I_{L1}^- cannot cause this, $Sw_1.on$ is isolated as the true fault. Additional experiments have shown correct fault isolation, with ambiguities resulting only for certain types of sensor faults [5].

Acknowledgments

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