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IFAC-PapersOnLine 48-15 (2015) 454–461

Functional Safety of Electrified Vehicles Through Model-Based Fault Diagnosis

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Abstract: Functional safety is of great importance for electric and hybrid electric vehicles (EV/HEVs). One way to improve functional safety of EV/HEVs is developing reliable and robust fault diagnosis and fault tolerant control systems so that, once a component failure is detected, effective remedial actions are taken to avoid system failures. Robust fault diagnosis is a necessary precursor to fault tolerant control strategies. In this paper, we use a V-diagram to present a systematic process for conducting automotive fault diagnosis, in connection with fault tolerant control development. We also introduce a diagnostic approach based on structural analysis that can form the basis of fault tolerant control. The structural analysis approach makes it possible to evaluate a system's analytic redundancy by its structural model, using the mathematical model of the system in matrix form, from which it is possible to derive a set of analytic redundant relations for fault detection and isolation. Structural analysis is useful in the early stages of diagnostic design because specific knowledge of the system parameters in numerical form is not required. In the paper, we demonstrate the application of this methodology, and its broad usefulness, by carrying out the design of a diagnostic strategy for an electric vehicle equipped with a permanent magnet synchronous machine (PMSM) drive system. The EV case study focuses on sensor faults, but the methodology is applicable to any component faults.

Keywords: Functional safety, HEV/EVs, Fault diagnosis, Fault tolerant control, Structural analysis

Functional safety is increasingly important in future automobile development such as in electric and hybrid vehicles (EV/HEVs), due to increased complexity and the wide employment of electrical and electronic components. In order to ensure functional safety, the automobile industry has developed its own functional safety standard (ISO 26262), which defines the functional safety requirements and life-cycle management for the safety-related components of automobiles in different phases of the development process Christiaens et al. (2012). One of the effective ways to guarantee functional safety of HEV/EVs is to develop On-board Diagnosis (OBD) design processes that are in compliance with the functional safety standards. Reference Cordoba Arenas et al. (2013) studies the potential faults and failure modes and their consequences for the key components in an electrified powertrain. Faults in any of these electrical or electronic components, for instance a short or open circuit in one of the motor windings, can lead to serious problems in vehicle such as degraded performance, increased noise and vibration, unintended torque requests, and other malfunctions, which could affect the vehicle's functional safety. Therefore, it is extremely important to develop reliable and robust diagnosis and fault tolerant control for electrified powertrains, in order to guarantee safe and reliable operation.

Substantial research work has been conducted in developing fault diagnostic strategies for electric drive systems, which is a key subsystem for any electrified vehicle. We cite, for example, work related to power inverter faults (Meinguet et al., 2013; Mendes and Cardoso, 1999; Peuget et al., 1997), to electric motor faults (Nandi et al., 2005; Cruz and Cardoso, 2001; Bellini et al., 2008; Khan and Azizur Rahman, 2009), and to sensor faults (Grouz et al., 2013; Najafabadi et al., 2011). With more specific focus on fault diagnosis for electric drive systems for automotive applications, for example, reference Lee et al. (2013) studies demagnetization fault diagnosis of permanent magnet

⋆ This paper is based upon work supported by the Department of Energy under Award Number DE-PI0000012. This paper was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

10.1016/j.ifacol.2015.10.065

synchronous machines (PMSMs) used in electric vehicles, and reference Jeong et al. (2005) discusses fault detection for various sensor faults in electric vehicles. However, these references are still about specific faults inside the electric drive system, and do not develop a systematic methodology for automotive fault diagnosis and fault tolerant control. In this paper, we present a methodology that is not specific to any particular type of fault or particular subsystem, but is generally applicable to any automotive system and is consistent with the spirit of the ISO 26262 functional safety standard. In particular, we focus on the use of this methodology for the diagnosis of electric drive system malfunctions in EV/HEV applications, and we illustrate an example of this methodology by considering sensor fault detection.

The use of V-diagrams linking the requirements and specifications of an application to the implementation of algorithms and software in the development of control systems is common practice in the automotive industry. In this paper, we propose an analogous methodology that defines the elements of a V diagram for the development of diagnostic and fault tolerant control systems for electric drives. The proposed V diagram, shown in Fig.1 begins with the diagnostic requirements and works through a model based design methodology that can lead to implementation of algorithms using Software-in-Loop (SIL), Hardware-in-the-Loop (HIL) and eventually in vehicle methods. A central element of this methodology includes: 1) the definition of requirements; 2) the development of detailed plant and fault models that allow us to understand the consequences of different types of faults; 3) A strategy for doing diagnostic system design; and 4) the various steps of implementation of this diagnostic strategy. In earlier papers, the authors have documented hazard analysis, plant and fault models Cordoba Arenas et al. (2013); Zhang et al. (2013). This paper focuses in particular on a methodology for diagnostic algorithm design that is referred to as structural fault detection and isolation.

Structural analysis for fault detection and isolation (FDI) is a methodology that uses the *structural model* of a system to identify the analytic redundant relations (ARRs) of the system in the model to allow us to diagnose faults in the system Blanke and Schröder (2003); Krysander (2006). The importance of this structural methodology is that it does not specifically depend on specific numerical parameters, but it depends on the structure of the model, as is shown later in the paper. Therefore, it is a very appropriate tool in the early stages of the design of a system and of its control, because diagnostic requirements can be identified while the control system development process is still in progress. A further advantage of structural analysis approach is that it decomposes the complex system into smaller subsystems; this decomposition allows for the design of diagnostic algorithms that are more efficient and more easily implementable. Following the structural analysis step, one still needs to develop specific diagnostic algorithms for implementation, a subject that is well understood Isermann (2005); Rizzoni et al. (2009). The choice of specific diagnostic algorithms, for example whether it is based on linear/nonlinear observers, parity equations, or other diagnostic methods, depends on the specifics of the applications and nature of the problem.

In this paper, we show how this methodology can be applied to an automotive electric drive, with the special case of sensor faults in electric drive systems. This is just an example, but it is generally applicable to any automotive systems. Fig. 1 presents the complex interaction between the design of diagnostic and fault tolerant control strategies. In this paper, we focus on the fault diagnosis part, but it should be clear that this methodology is useful for anyone who wishes to design fault tolerant control. On the application side, the paper focuses on a special application: a prototype vehicle developed by the EcoCAR2 team at the Ohio State University Center for Automotive Research. EcoCAR2 is a plug in series-parallel hybrid electric vehicle, as shown in Fig. 2, but we are only focusing on its rear axle drive. The models used in this paper are experimentally validated models that are derived from the EcoCAR2 development process. In this paper, we use these experimentally validated models to demonstrate the methodology. Future work will implement these results in the experimental vehicle.

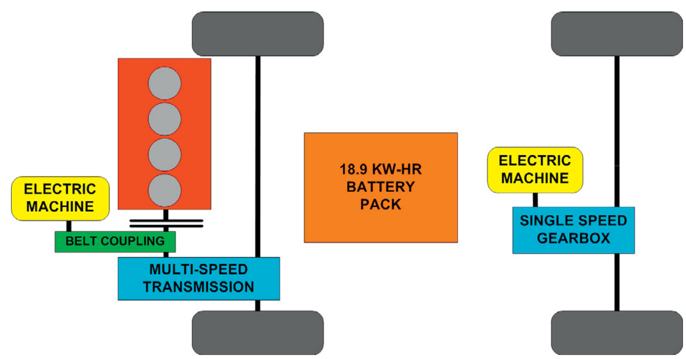

Fig. 2. EcoCAR2 Vehicle Architecture

1. HAZARD ANALYSIS

Cordoba Arenas et al. (2013) conducted a hazard analysis through failure modes and effect analysis (FMEA) for the key components comprising an electrified powertrain. The FMEA identifies the main hazards existing inside each component of an electrified powertrain, from which the diagnostic requirements to ensure safe and reliable operation can be defined.

2. PLANT AND FAULT MODELING

Fig. 3 shows the subsystems and components comprising of an electric vehicle driven by a permanent magnet synchronous machine. The driver pushes the accelerator pedal or brake pedal according to driving demand, a vehicle controller converts the pedal signals (α, β) to a torque reference (T_e^*), which is then converted into a current reference i_q^*. For PMSMs, we usually takes advantage of Field Oriented Control(FOC), in which the d axis current component is set to be zero so that electromagnetic torque is only related to q axis current component, in order to achieve maximum torque to current ratio Pillay and Krishnan (1989). The EM controller is a hysteresis controller where the desired three phase currents (i_a^*, i_b^*, i_c^*) are compared with the measured ones (i_a, i_b, i_c), from which the gate signal commands to the three phase inverter