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Sensorless algorithm for sustaining controllability of IPMSM drive in electric vehicle after resolver fault

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ABSTRACT

This paper presents a sensorless algorithm designated for the emergency control of an interior permanent magnet synchronous motor (IPMSM) drive in electric or hybrid vehicle. Special requirements for emergency-activated sensorless algorithms are defined, and shortcomings of state-of-the-art methods in terms of the considered application are discussed. The proposed emergency-activated algorithm is based on analysing the derivatives of motor phase currents measured over the duration of particular inverter states. The method is computationally simple and does not require additional hardware since the derivatives are measured indirectly. A lag between activating the algorithm upon an emergency flying start and re-establishing the torque controllability is defined. The proposed algorithm was implemented in the controller of a laboratory IPMSM vehicle drive and tested under varying operational conditions, including the emergency activation.

1. Introduction

Contemporary combustion cars are equipped with on-board diagnostics systems (OBDs) (King & Burnham, 2012). Such systems, introduced by U.S. legislative regulations in 1988, initially aimed to detect and indicate engine faults that could cause a significant increase in harmful emissions. Nowadays, OBDs detect almost all major malfunctions in the combustion car's drivetrain. In many cases, OBDs are able to isolate a faulty device and switch into a sub-optimal control mode, which uses the remaining sensors and actuators. It is expected that a similar development of drivetrain diagnostics will soon be implemented in electric vehicles (EVs) and hybrid-electric vehicles (HEVs). Currently, the U.S. Code of Federal Regulations states that a manufacturer has to equip a hybrid car with a monitoring system for the batteries (Akin, Choi, & Toliyat, 2012). It seems to be only a matter of time until legislative regulations will require diagnostics for the other drivetrain components of EVs and HEVs, such as the electric motor, inverter and numerous sensors. Several methods of detecting and isolating the faults of such components have already been proposed (Bourogaoui, Sethom, & Belkhodja, 2017; Farina, Osto, Perizzato, Piroddi & Scattolini, 2015; Foo, Zhang & Vilathgamuwa, 2013; Foster, Cintron-Rivera, & Strangas, 2016; Friedrischková, Vala, & Horák, 2015; Zhou, 2011).

If a fault occurs when driving, the faulty component must be immediately excluded from the drivetrain control. The control algorithm has to switch into the emergency mode in order to maintain vehicle controllability. This is particularly important for cars equipped with in-wheel electric drives where a fault of a single in-wheel drive may disrupt the balance of propulsive or breaking forces generated on individual wheels, which at high traveling speed can lead to the sudden deprivation of vehicle stability (Li, Du, Li, & Zhang, 2015; Nussbaumer, Macek, Ploechl, & Wolbank, 2013).

The majority of modern EVs and HEVs apply permanent magnet synchronous motor (PMSM) traction drives, usually of the interior type (IPMSM) (El-Refaie et al., 2014; Kim et al., 2014). Recently, an intensive research has been conducted on the sensorless control of IPMSM drives. In a case of sensorless control, the rotor-position feedback, required to control the motor's torque, is estimated instead using, for instance, a resolver. Such solution is applied to many industrial applications of these motors. However, the sensorless control has not yet been deployed onto the drives of mass-produced HEVs and EVs. Nevertheless, sensorless control algorithms could be used as a sub-optimal emergency procedure, activated upon the detection of rotor-position sensor failure (Aguirre, Poza, Aldasoro, & Nieva, 2013; Kim, Kim, Kwon, & Lee, 2012).

The requirements for an emergency-activated sensorless control algorithm are found and studied in this paper. Two rotor-position estimators based on the derivatives of motor phase currents (DMPCs) are proposed. The estimator dedicated for medium and high speeds, previously presented in Jarzebowicz (2011) as a sensorless-by-default

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solution, is now supplemented with a new low speed estimator. These two estimators are investigated in terms of their emergency activation ability. They are implemented and tested on a laboratory IPMSM drive, and the results confirm their fast emergency activation and stable operation in traction-specific operational conditions.

2. State of the art

The sensorless control of vehicle drives is troublesome due to their wide range of operational speeds and the demand for uninterrupted torque controllability; therefore, a set of two estimation methods is typically used. At a low speed and standstill, the rotor's position is estimated from the analysis of stator inductances, which vary due to the rotor saliency. An additional high-frequency (HF) signal component, generated by the inverter, is required to measure the inductances (Accetta, Cirrincione, & Pucci, 2012; Kim et al., 2012; Kondo, 2014). At medium and high speeds, an estimation based on the electromotive force (EMF) observer is most convenient (Bifaretti, Iacovone, Rocchi, Tomei, & Verrelli, 2012; Taghavi, Jain, & Williamson, 2011).

The activation of the estimation algorithm during a drive operation, the so-called flying start, is considered in Kim et al. (2012) and Aguirre et al., (2013) where a typical combination of HF injection and EMF observer methods is also used. Aguirre et al. (2013) proposed an additional procedure for the rough estimation of the rotor's position to pre-tune the target estimation algorithm.

Some unconventional approaches to the sensorless control of IPMSM drives have been proposed; however, they do not directly aim at vehicular applications. One of these approaches is based on DMPC analysis. DMPC methods are also referred to as: fundamental excitation (Bolognani, Calligaro, Petrella, & Sterpellone, 2011; Hua, Sumner, Asher, Gao, & Saleh, 2011), PWM transients (Nussbaumer & Wolbank, 2011), current ripples (Paulus & Landsmann, 2012) and current-slope algorithms (Lin, Fu, & Liu, 2011; Wei & Liu, 2012). Recent research on DMPC methods is reviewed over the following paragraphs.

Hosogaya and Kubota propose an algorithm that enables the controller to estimate the rotor speed by analysing the DMPCs calculated for the q-axis (Hosogaya & Kubota, 2012). They suggest that the rotor angle can be estimated as an integral of speed.

Research reported in Lin et al. (2011) concerns an estimation algorithm that analyses current derivatives in order to calculate the rotor's position on the basis of IPMSM saliency. In turn, in Schrodl and Simetzberger (2008) DMPCs are used to estimate the rotor's position from an electromotive force vector.

In Bolognani et al. (2011), an estimator for a wide speed range is presented where the rotor's position is differently estimated in low- and high-speed ranges. Current derivatives are measured by means of Rogowski coils. Narrow inverter states are prolonged to measure the current derivative accurately.

An estimation algorithm for the rotor's position by analysing motor saliency is presented in Hua et al. (2011). The results show good estimation accuracy. However, the solution requires a major amendment to the PWM algorithm as well as hardware upgrades, such as a modification of IGBT gate circuits and an addition of current derivative sensors.

3. Problem statement

The application of the emergency-activated rotor's position estimation algorithm involves special requirements compared with a drive that is sensorless-controlled by default. Such an algorithm:

a) Has to provide a reliable feedback instantly, even if it becomes activated with an unknown initial position and speed.
b) Should not require any hardware upgrades compared with the resolver-based control in order not to increase cost and complexity. This mainly concerns current feedback components, such as transducers and analogue-to-digital converters (ADCs).
c) Should be simple and quickly computed to fit into the time window within a control cycle, which is reserved for emergency algorithms. Since the target drive is expected to consist of numerous emergency algorithms for various malfunctions, these algorithms have to be started on the occurrence of particular faults, leaving the reserved time window idle during normal operation.

As faults are expected to be uncommon and the aim of the emergency algorithm is to sustain vehicle's stability and controllability, sub-optimal solutions are accepted. Therefore, the estimates of the rotor's position are not expected to be as accurate as in typical sensorless drives. Further, a slight decrease in drive performance is admissible. However, the emergency estimation algorithm should be robust to all traction-specific operational conditions in order to assure vehicle's controllability and stability.

As one can see from the review of related papers, only a typical approach of combining the HF injection and EMF observer methods has been considered as a solution to the resolver-fault emergency control of traction drives. The HF injection methods require additional controller resources and hardware filters, which does not comply with the requirement (b). In turn, the inceptive performance of observers is highly affected by the initial values of state variables; therefore, their flying start must be preceded by an initialisation procedure, which does not follow the requirement (a). This problem may be overcome by running the observer constantly in the background; however, this would collide with the requirement (c).

A DMPC-based method can overcome the aforementioned drawbacks. A use of the current derivatives in the motor's mathematical model makes it possible to apply simple estimation equations, which do not consist of integrals; therefore, state-variables initialisation constraints are omitted and the processing time is reduced. At the same time, the estimator does not load the controller until a resolver fault occurs, which maintains the computing overhead for other emergency algorithms. Current derivatives may be measured indirectly by sampling the currents more frequently than a typical control method requires, which discards the requirement of installing di/dt sensors.

In this paper, we propose the DMPC-based algorithm designated for the emergency-mode sensorless control of traction IPMSM drive. The DMPC-based methods are sensitive to measurement disturbances, thus the reported solutions often consist of an advanced current-measuring hardware as well as a sophisticated signal processing in order to provide the rotor's position accurate estimates. Following the special requirements of our application, we propose the method featured by simple computations and lacking hardware amendments. In turn, this method is not expected to be as accurate as the sensorless-by-default solutions, as long as the control stability and fast flying start are ensured.

4. Sensorless control algorithms

The general structure of the control algorithm is shown in Fig. 1. The algorithm is based on the fundamental torque control and voltage modulation methods, which are presented in the following subsection. The controller applies standard motor phase current measures to compute DMPCs, as explained in Section 4.2. The motor mathematical model, presented in Section 4.3, is fundamental for the rotor-position estimators introduced in Sections 4.4 and 4.5. As the algorithms aim to estimate the position of the rotor, the angular speed is computed by differentiation.

4.1. Torque control and voltage modulation methods

A fundamental diagram of the field-oriented control (FOC) algorithm is included in Fig. 1. Motor currents are regulated in the d–q