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Demagnetization monitoring and life extending control for permanent magnet-driven traction systems

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A B S T R A C T

This paper presents a novel scheme of demagnetization monitoring and life extending control for traction systems driven by permanent magnet synchronous motors (PMSMs). Firstly, the offline training is carried to evaluate fatigue damage of insulated gate bipolar transistors (IGBTs) under different flux loss based on *first-principle modeling*. Then an optimal *control law* can be extracted by turning down the power distribution factor of the demagnetizing PMSM until all damages of IGBTs turn to balance. Next, the *similarity-based empirical modeling* is employed to online estimate remaining flux of PMSMs, which is used to update the power distribution factor by referring the optimal control law for the health-oriented autonomous control. The proposed strategy can be demonstrated by a case study of traction drive system coupled with dual-PMSMs. Compared with traditional control strategy, the results show that the novel scheme can not only guarantee traction performance but also extend remaining useful life (RUL) of the system after suffering demagnetization fault.

1. Introduction

Modern vehicles are getting increasingly complex, with continued growth in demands for improving safety and survivability when suffering unexpected faults or failures, which may lead to critical damage, expensive downtime, costly repairs, and even loss of assets and lives [1]. This lack of performance is most often a failure beyond which vehicle system can no longer be used to meet desired performance. Prognostics predicts the future performance of a component by assessing the extent of deviation or degradation of a system from its expected normal operating conditions [2]. Potential uses for prognostics is in condition-based maintenance (CBM). The discipline that links studies of failure mechanisms to system lifecycle management is often referred to as prognostics and health management (PHM). Meanwhile, PHM leads to CBM as a replacement for time-based or scheduled maintenance [3]. Various of PHM strategies [4–8] have been developed in recent years that pertain specifically to the phase of predicting future behavior, including remaining useful life (RUL), on the basis of current operating state and schedule of required maintenance actions to maintain system health [9]. However, most of the developed PHM technology belongs to human-in-the-loop maintenance strategies, which unable satisfy increasing requirements for onboard autonomous control when suffering early damage or health degradation for key components or subsystems during continuous operation.

Furthermore, inspired by biological immune engineering, some researchers recently are increasing attentions on PHM applications into control strategies, such as automated contingency management (ACM) [10,11], engineering immune

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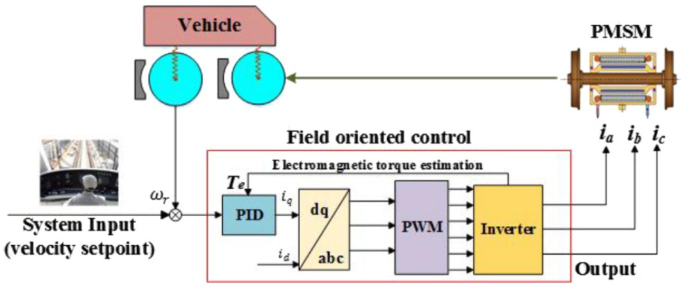

Fig. 1. Basic architecture of traction drive system of PMSM rail vehicles.

system (EIS) [12,13] and fault self-recovery (FSR) [14,15], etc. These health-oriented control strategies aim to optimize available components and control modes so that systems can continue to operate within an acceptable and stable regime [9]. This extending performance in reliability, availability, maintainability and safety (RAMS) can lead to improved life cycle cost (LCC). However, the few existing studies on self-maintenance mainly focus on specific fault modes and operation missions. Slow degradation and condition variations of components are usually neglected, even though they may be vital factors for some key systems. In terms of autonomous ground vehicles, most of the research [16,17] is focused on trajectory planning or mission control areas, seldom attentions are paid on health-oriented control strategy. However, assessing suitability for a mission control is determined only through simple detection, which tends to hide failure and results in an incomplete mission or even accidents. The health of modules affects the realization of corresponding functions and therefore influences mission execution [18].

As far as electric vehicle is considered, its traction drive system has widely use gate-controlled power switches represented as insulated gate bipolar transistors (IGBTs) [19]. The development of high-voltage IGBTs during the past decade has encouraged traction drive manufacturers to choose IGBTs for their newest drive equipment in order to take advantage of their higher switching frequencies and simpler gate drives. Meanwhile, the development of power electronics technology in recent years has realized the inverter control of large-size induction motors. A noteworthy motor is the permanent magnet synchronous motor (PMSM) that has the performance required for traction motors and is more compact, lightweight, and efficient than induction motors so that becomes an ideal selection to develop direct drive traction drive system in railway vehicles [20]. The basic traction architecture for PMSM rail vehicles is shown in Fig. 1, which mainly consists of coupled dual-PMSMs with inverters for each motor, and field-oriented control (FOC) strategy. Such high-performance FOC method can significantly enhance the dynamic performance of traction drive, which make it possible to adjust the dc link voltage supplied to the traction inverters more conveniently than in the catenary supply units. The gate signal controls six IGBTs in an inverter to change speed of the PMSM. This important degree of freedom can be used to control the flux levels in the traction machines as a function of speed and load in combination with pulse width modulation (PWM) inverter control, providing opportunities for enhanced inverter operating characteristics and efficiency [19].

However, due to armature reaction, especially under conditions of operation requiring strong torque, for example, at high loads, during sharp transients or even at high temperature, PMSM traction drive system has the risk of *demagnetization* [21], which will accelerate the cumulative damage of IGBTs and cause failure of inverters at component level, even serious influence to traction drive at system level. The failure propagation mechanism lies that the demagnetization of PMSMs may lead to output torque drop, then the proportion integration differentiation (PID) controller adaptively increases proportion of constant torque in process of traction drive, which causes IGBTs, by the side of faulty PMSM, suffer accelerated fatigue damage due to higher joint temperature. This influence makes the IGBT failure shifts to an earlier time. As IGBTs are usually considered as the most easily damaged elements in a traction drive system, its accelerated failure may reduce remaining useful life (RUL) of the integrated traction drive system.

To cope with this challenge and achieve economic maintenance cost, this research proposes a novel scheme of demagnetization estimation and control reconfiguration for PMSM traction drive systems. The realization of this strategy can not only guarantee traction performance but also extend RUL of the integrated traction drive system after suffering demagnetization fault.

The remaining parts of this paper are organized as follows. Section 2 introduces the thought of health-oriented control, and based on which, a scheme of life extending control is put forward for PMSM traction drive systems that suffer flux loss. In Section 3, the first principle modeling for PMSM traction drive system is developed. And then, the techniques involved in the proposed scheme are given in Section 4. Next, Section 5 describes a simulation experiment to demonstrate the effects of the contributions. Finally, conclusions are presented in Section 6.

2. Scheme

A typical health-oriented control architecture is given in Fig. 2, in which PHM is embedded into various levels of the control hierarchy [22]. At the higher echelons, mission re-planning and midlevel 'intelligent' controls are exercised to safeguard