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Tolerance analysis of electrified vehicles on the motor demagnetization fault: From an energy perspective

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HIGHLIGHTS

- A novel PMSM demagnetization and efficiency estimation framework is established.
- The efficiency reduction pattern under different demagnetization levels is analyzed.
- The impact of demagnetization on the powertrains' energy efficiencies is evaluated.
- A comprehensive comparative study of the energy efficiency is conducted.

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ABSTRACT

Due to possible overheat, abrasion or mechanical vibrations, demagnetization fault is inevitable in permanent magnet synchronous motors (PMSMs), which could greatly decrease the motor's efficiency and hence an electrified vehicle's performance. This paper, from an energy efficiency point of view, proposes to analyze the tolerance ability of different electrified vehicles on motor demagnetization faults, via PMSM flux density degradation modeling, efficiency estimation and dynamic programming (DP) based powertrain energy management. The relationship between different demagnetization levels and resultant motor efficiencies is obtained, and analyzed according to the motor operation area. Demagnetized PMSM is adopted in a pure electric vehicle (PEV), a hybrid electric vehicle (HEV) and a plug-in hybrid electric vehicle (PHEV) for energy efficiency analysis. Tolerance analysis indicates that the powertrain efficiency decrease caused by motor demagnetization is more severe under urban driving conditions, especially with PEV and PHEV configurations compared with HEV. A demagnetization threshold investigation is also given in this paper.

1. Introduction

Permanent magnet synchronous motor (PMSM) has been massively deployed in the electrified vehicle market, including pure electric vehicles (PEVs), hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) [1,2]. Motor operating efficiency is a very important key factor which determines the overall powertrain efficiency of electrified vehicles. However, there are a variety of faults occurring occasionally that might cause the motor's efficiency decrease or even dysfunctionality, such as: bearing faults [3], electrically short/open circuit [4], eccentricity [5], and also demagnetization [6].

Due to physical damage, high temperature stress, inverse magnetic field, high current, or aging, demagnetization faults are becoming inevitable in real operations, and start to attract more and more attentions from the literature [7–9]. PMSM demagnetization faults are ubiquitous in vehicle applications because of the harsh driving conditions [10], and can cause torque reduction and therefore the resultant energy consumption increase. In this case, PMSM demagnetization diagnosis has emerged as a point of concern [11,12]. Many efforts have been made through parameter estimation, equation parity or developing state observers for this purpose. Underwood etc. estimated the PMSM magnet flux linkage with a novel parameter identification approach [13]. Rosero etc. employed motor current signature analysis and Hilbert-Huang transform to realize demagnetization fault detection [14,15]. Least squares, Choi-Williams distribution and other methods have been validated to be effective in diagnosing the motor demagnetization faults [16–18]. Demagnetization tolerant control and demagnetization analysis with different rotor types are also under

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Nomenclature

i_d, i_q	d, q axis stator currents, respectively, A
v_d, v_q	d, q axis voltage, respectively, V
R_s	stator resistance, Ω
ω_s	the electrical angular speed of rotor flux, rad/s
L_d, L_q	d, q axis inductances, respectively, mH
λ_{af}	flux amplitude, Wb
ω_r	rotor angular speed, rad/s
Te	electric torque, Nm
T_f	load torque, Nm
B	damping coefficient
J	moment of inertia, kg m^2
P	number of pole pairs
θ_r	rotor angular position, rad
ω_r,ω_s,ω_c	angular speed of the ring, sun, and carrier gear, respectively, rad/s
S,R	sun gear radii and ring gear radii, respectively, m
J_{ISG},J_{eng},J_{mot}	inertias of generator, engine and motor, respectively, kg m^2
T_{ISG},T_{mot},T_{eng}	torque of ISG, motor and engine, respectively, Nm
F	internal force on pinion gears of the planetary gear set, N
g_f	gear ratio of the final drive
T_{axle}	torque produced from powertrain on the drive axle, Nm
R_{wheel}	wheel radius, m
V	vehicle velocity, m/s
m	vehicle mass, kg
T_{brake}	friction brake torque, Nm
g	gravitational acceleration, m/s^2
θ	road grade, rad
$(1/2)\rho C_d$	aerodynamic drag resistance
C_r	rolling resistance coefficient
I_{batt}	battery current, A
Q_{max}	battery maximum capacity, C
P_{batt}	battery power, W
P_{tank}	fuel consumption from the tank in terms of power, W
R_{batt}	battery internal resistance, Ω
V_{oc}	open circuit voltage, V
P_{ISG},P_{mot}	ISG and motor shaft powers, respectively, W
η_{inv}	inverter efficiency

consideration in many studies [19–21].

In order to better understand the motor efficiency variation when demagnetization fault happens, various experiments have been conducted to imitate demagnetization. Most of them use permanent magnet demolition method to achieve this target. For example, Cristian etc. removed one of the six magnets conforming the electric machine pole to produce a 16.7% reduction of the overall motor magnetism [22]. Urresty etc. demolished two opposite rotor magnets in a PMSM, and realized 50% of demagnetization [23]. Cristian etc. further refined their research in 2013 by removing only one portion of the magnet to generate an approximate 4% demagnetization [24]. Although the precision is effectively improved, imitating PMSM demagnetization via magnet demolition is very difficult to obtain accurate, thorough and comprehensive results.

To authors' best knowledge, few studies in the literature attempt to model PMSM demagnetization through flux density degradation. Also, the literature lacks a systematical and quantificational study to analyze electrified vehicle's tolerance ability to different PMSM demagnetization degrees. When the motor is inappropriate to continue working in the powertrain due to demagnetization, or whether the motor should be replaced or not are under question now.

This paper proposes to analyze the tolerance level of electrified vehicles on motor demagnetization faults from an energy efficiency perspective. The target vehicles include PEV, conventional HEV and PHEV. The main contributions from this study are,

(1) A novel PMSM demagnetization and efficiency estimation framework is established based on the flux density degradation. Its efficiency reduction pattern under different demagnetization levels is also analyzed;
(2) The demagnetized PMSM is injected into three different electrified vehicles to fully evaluate the impact of demagnetization on the powertrains' energy efficiencies;
(3) A comprehensive comparative study of the energy efficiency is conducted with different powertrain configurations, demagnetization degrees and driving conditions.

Base motor parameters and the efficiency map are validated by experimental data. The PMSM efficiencies under all rotation speeds, output torques and demagnetization levels are estimated. Also, in order to fully reveal the tolerance level of hybrid electric vehicles, dynamic programming (DP) is adopted to determine their optimal powertrain behaviors [25]. DP, model predictive control and equivalent consumption minimization are the mostly developed (P)HEV energy management strategies [26,27]. DP is always used to provide energy management performance benchmarks of HEV [28] and PHEV [29]. Thus, the study and results presented in this paper are able to provide a general reference for research related to electrified vehicle energy management or evaluation.

The remainder of this paper is organized as, Section 2 presents the PMSM and control system model, as well as the flux density degradation based efficiency estimation framework, Section 3 summarizes the electrified vehicle powertrain models, and the DP-based optimal nonlinear energy management strategy for HEVs, Section 4 leads to the simulation results, discussions and analysis, with Section 5 draws the main conclusions of this paper.

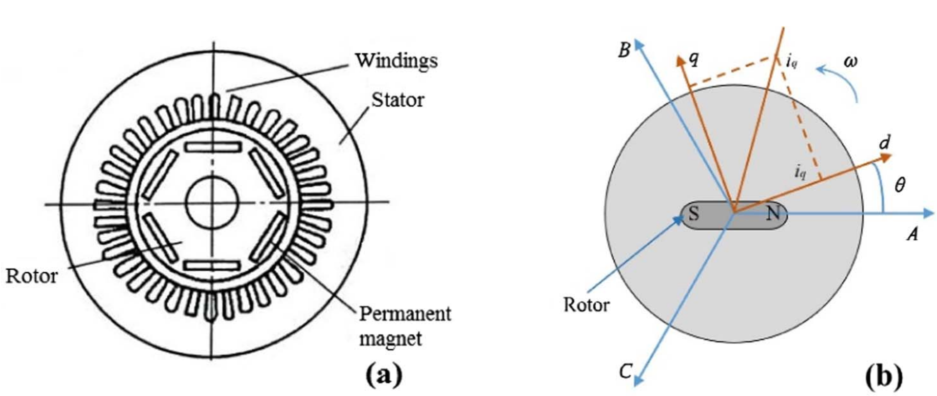

Fig. 1. (a) PMSM structure, and (b) the coordinate systems.