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Multi-objective Design Optimization of an IPMSM Drive System Based on Loss Minimization Control Strategy

Lin Liu[1], *Student Member, IEEE*, Youguang Guo[1], *Senior Member, IEEE*, Gang Lei[1], *Member, IEEE*,
Wenliang Yin[2], *Member, IEEE*, and Jianguo Zhu[2], *Senior Member, IEEE*

[1]School of Electrical and Data Engineering, University of Technology Sydney, Sydney, NSW 2007, Australia
[2]School of Electrical and Information Engineering, The University of Sydney, Sydney, NSW 2006, Australia

To enhance the optimization and control efficiencies of the interior permanent magnet synchronous motor (IPMSM) drive system for electric vehicles (EVs), an improved multi-objective design optimization strategy at the system level is proposed in this paper. To handle the high dimensional and nonlinear problems for searching Pareto optimal solutions, the multi-level optimization algorithm with approximate models is utilized, by which the computational cost can be greatly reduced. In terms of the typical specifications and requirements of EVs, the maximum torque, minimum torque ripple, and minimum speed overshoot are set as the optimization objectives. For further improving the optimization accuracy and search speed, the objective of minimum loss is achieved through the loss minimization control algorithm instead of being solved in each optimization level, by which the system efficiency is also promoted. Experimental and numerical results show that the proposed approaches can effectively solve the design optimization issues of electric drive systems, and enhance the static and dynamic system performance.

Index Terms—**Electric drive system, interior permanent magnet synchronous motor (IPMSM), multi-objective optimization, system level design optimization, multi-level strategy, loss minimization control**

I. INTRODUCTION

TO develop high-power-density and high-reliability IPMSM drives for EVs, traditional design optimization methods are mostly carried out at the single component level, which benefits the individual component behavior instead of the system level performance [1]. Meanwhile, aiming at the harsh operating conditions, many factors should be considered in the design optimization of IPMSM drive systems, such as torque ripple, losses, efficiency and speed overshoot [2], and hence the multi-objective optimization with system-level optimal performance is desired. Namely, it is significant to develop advanced multi-objective design optimization strategies for the IPMSM drives at system level, rather than directly assembling the individually optimized motor and controller into applications.

For multi-objective optimization, there are many intelligent algorithms to solve the non-inferior Pareto optimums, such as the genetic algorithm, non-dominated sorting genetic algorithm (NSGA), and NSGA II [3]. However, their applications are limited due to the huge computation costs for finite element method (FEM) with high dimensions. To improve the solving efficiency, space mapping methods [4] and space reduction sequential optimization methods [5] were proposed. But the large computation cost still exists in high-dimensional problems, as the design parameters are not fully-simplified.

This paper aims to develop an improved system-level multi-objective design optimization method for the EV IPMSM drive systems. The multi-level strategy with approximate models is used to search the optimums, in which the initial design space can be divided into several subspaces to reduce the calculation burden while ensuring accuracy. Moreover, to further improve the optimization accuracy and efficiency, a loss minimization control is proposed to replace the minimum loss objective, by which the advantages of control parts are exploited to promote the optimal solution scope and the whole system performance.

II. TECHNICAL ROUTES

A. Loss Minimization Control Modeling

System efficiency related to the system losses is an important performance index of IPMSM drive systems which should be optimized. Most studies on this topic take the minimum loss as an optimization objective, but the dominant functions and coupling effects brought by control side are ignored. Therefore, a loss minimization control is used to replace the loss objective, in which the proportional-integral (PI) controller gains are optimized simultaneously to reduce the speed overshoot and torque ripple. The control modeling includes four steps: (i) calculating the system level losses that consist of the iron loss, copper loss, mechanical loss and electronic inverter loss, (ii) converting the system losses as a function of d-axis current (I_d), (iii) calculating the derivative of losses with respect to I_d, and let it equal zero, and (iv) solving the derivative equation to derive the functions of electromagnetic torque (T_e) with respect to I_d and I_q.

The specific control diagram is given as Fig. 1, where ω_m and θ_m are the rotor angular speed and position signal angle. I_{abc} is the stator current in three-phase stationary coordinate system. The reference q-axis and q-axis currents (I_d^* and I_q^*) can be derived by the reference electromagnetic torque (T_e^*) obtained by the difference between the reference and actual speeds. More details of the modeling process will be reported in the full paper.

B. Multi-objective Optimization with Multi-level Strategy

The design optimization of IPMSM drive systems can be divided into two main parts, namely, the design methods with analysis models and the optimization methods with algorithms. To achieve satisfactory system-level performance, the design optimization models of the whole system including the motor and controller are built simultaneously. Considering the EV design requirements, the optimization models are developed as:

$$\min:\begin{cases} f_m(\mathbf{x}_m) = -T_{\max} \\ f_c(\mathbf{x}_c) = \alpha_1 T_{rip} + \alpha_2 n_{os} \end{cases} \quad \text{with,} \quad s.t.:\begin{cases} 0.85 - \eta_m \le 0 \\ 150 - T_{\max} \le 0 \\ I_d - 0.4 \le 0 \\ n_{os} - 0.1 \le 0 \\ \sigma(\eta_s) - 0.005 \le 0 \end{cases} \tag{1}$$

where $\boldsymbol{x}_m$ and $\boldsymbol{x}_c$ are design variables in motor/controller levels. η_m is the motor efficiency. T_{max} and T_{rip} are the maximum torque, and torque ripple, respectively. The speed overshoot (n_{os}) is regarded as dynamic performance. α_1 and α_2 are the weighting factors. σ means the standard deviation of system efficiency (η_s).

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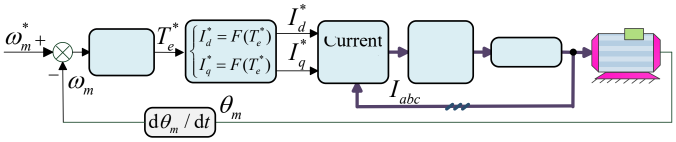


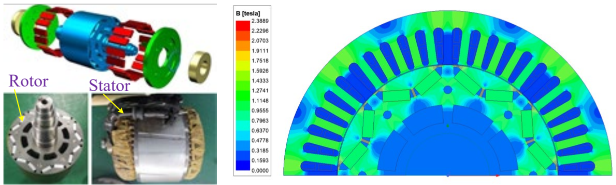
Fig. 1. Block diagram of the proposed loss minimization control.

In this paper, the multi-level strategy [6] is used to improve the solving efficiency.

C. Results and Discussions

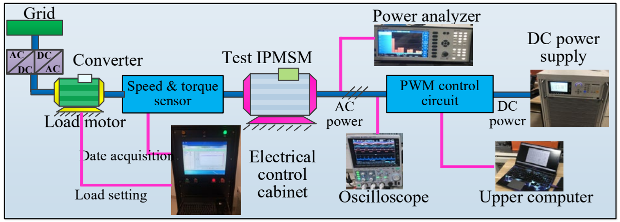
A 48-slot 8-pole V-type IPMSM prototype for driving EVs is tested to verify the proposed approaches. The motor is designed with 20 kW rated power at rated speed 3600 r/min, rated torque 53 Nm, and served by a three-phase inverter. The stator/rotor structures, FEM model and experimental platform setup are shown in Fig. 2. Six design parameters are selected, namely, the slot depth (x_1), pole angle (x_2), PM thickness (x_3), PM width (x_4), and controller integral (x_5) and proportional gains (x_6). Pearson correlation coefficient analysis method [3] is used for subspace divisions. In the subspaces, $\mathbf{X_1}$, $\mathbf{X_2}$ and $\mathbf{X_3}$ contains the highly significant, significant and control parameters of IPMSM drive system, and $\mathbf{X_1} = [x_1, x_2]$; $\mathbf{X_2} = [x_3, x_4]$; $\mathbf{X_3} = [x_5, x_6]$.

Table I shows the optimization results compared with initial parameters of the IPMSM prototype. As seen, all the optimal objectives can be improved by the proposed approaches at rated working condition. The motor efficiency reaches 96.7%, thanks to the designed loss minimization control with the optimized PI gains. Moreover, with the optimal scheme, the maximum output power exceeds 40 kW, the maximum torque increases from 166 to 188 Nm, and the torque ripple decreases from 14.4% to 5.6%.



(a) Stator and rotor structure

(b) FEM model



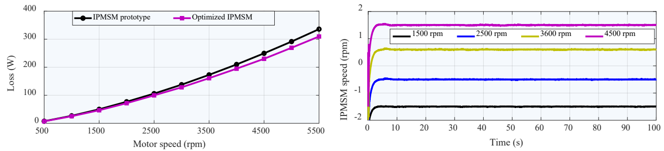
(c) Operating performance of the experimental platform

Fig. 2. Setup of the FEM and integrated experimental platform.

TABLE I

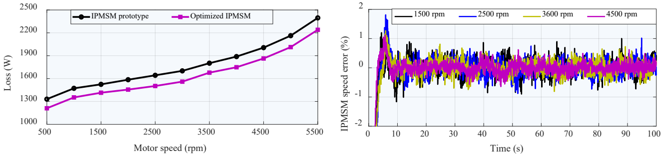
OPTIMIZATION RESULTS COMPARED WITH THE PROTOTYPE

QUANTITY	PARAMETERS	PROTOTYPE	OPTIMIZED RESULT
Design parameter	PM thickness (mm)	6	6.4
	PM width (mm)	33	31.2
	Slot depth (mm)	20	17.2
	Pole angle (deg.)	34	37.8
	Integral gain	1	22
	Proportional gain	1	0.42
Objectives	Stator iron loss (W)	184.7	171.5
	Motor efficiency (%)	96.0	96.7
	Maximum torque (Nm)	166	188
	Torque ripple (%)	14.4	5.6



(a) Cpmparative results of iron losses

(c) Speed tracking curves of the optimized IPMSM



(b) Cpmparative results of the total system losses

(d) Speed tracking errors of IPMSM

Fig. 3. Selected results of loss and speed behaviors

The 2D FEM simulation model is also established with the optimized parameters, by which the comparative analysis of the steady/dynamic state performance is demonstrated. Selected results of loss and speed behaviors are compared in Fig. 3. As seen, the optimized system losses are around 6-9% smaller than those of the experimental platform with field oriented control under different working speeds. The speed overshoots of the optimized IPMSM system are also tiny (less than 1.5%) in the full speed range, while the average steady-state speed errors are always within 1%. The torque and efficiency curves will also be compared in full paper. With the optimized results, the highest cogging torque is about 0.61 Nm, which accounts around 62.3% of the prototype, while the optimized system efficiency is calculated as 91.6%, which is higher than the initial value 90%. Moreover, the computation cost is also cheap (only several seconds) for the proposed three-level optimization strategy.

III. CONCLUSIONS

In this paper, an advanced system-level and multi-objective design optimization model is developed to guarantee the system-level optimal performance of an IPMSM drive system used in EVs. After dividing the design parameters into three subspaces, the multi-level strategy with approximate models is employed to search the optimums for reducing the calculation burden. Moreover, in each optimization level, the minimum loss control is utilized to replace the search of the minimum loss objective for expanding the optimal solution scope and further reducing the computational burden. The proposed approaches are verified through the experimental platform with an IPMSM prototype. Results illustrate well the superiority of the proposed strategies in both the optimization accuracy and efficiency. The performance of the optimized IPMSM drive system is also improved.

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