Numerical and Experimental Design Validation for Optimal Efficiency Distribution compatible to Frequent Operating Range of Interior PMSM

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***Abstract*—The numerical design methodology based on Finite Element Method(FEM) combined with Maximum Torque Per Ampere(MTPA) is applied for the optimal efficiency distribution of Interior Buried PM Synchronous Motor(IPMSM) compatible to the frequent operating range. FEM-based computation of dominant losses in the whole operating area of IPMSM is numerically carried out. The proposed design considering the MTPA and shape optimization is experimentally verified by the static and transient dynamo tests. As a result, it is found that IPMSM having the optimal efficiency distribution is favorably effective as a design target for the efficient Electric Vehicle(EV) in that experimental results for the efficiency of IPMSM are distributed in most frequent operating area.**

***Index Terms*—Computational electromagnetics, Permanent magnet machines, System testing, Energy efficiency.**

I. INTRODUCTION

Increasingly, the development of EVs using the electric machine is dramatically occurred in that EV has better fuel economy and less emissions superior to the conventional engine-based vehicle. The importance for the efficiency of the main propulsion system is getting greater. One of the attractive candidates is to apply the remarkably efficient IPMSM which has high efficiency and torque density characteristics. Also, the efficiency of IPMSM in main operating range of EV is significantly associated with fuel economy [1].

Hence, the numerical and experimental design validation of IPMSM considering the most frequent operating range is necessary to improve the fuel economy of EV. In addition, the design reliability for IPMSM can be achieved by the performance evaluation in the static and transient state. Especially, the transient motor test based on real world driving cycles is proposed to analyze dynamic characteristics and control accuracy for IPMSM of EV [2] [3].

In this paper, the vehicle simulation for EV, with regard to real-world driving cycles, is applied to obtain the speed and torque profile. Using these profiles, the operating distribution of IPMSM is accurately analyzed. The design with MTPA coupled with FEM is executed to reduce the dominant losses. The static and transient dynamo tests are performed to verify the target performance of IPMSM [4].

Effectiveness of the proposed design and test method with goal of the optimal efficiency distribution within the most frequent operating range on the basis of electric vehicle simulation is supported by the numerical and experimental results [5].

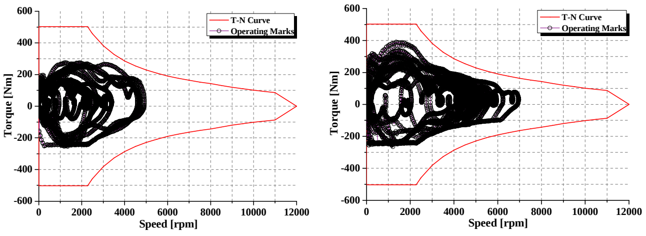
II. ANALYSIS OF MAIN OPERATING RANGE FOR IPMSM

In order to analyze the main operating range of IPMSM, Manhattan and Braunschweig mode are selected as real-world driving cycles. The selected real-world driving cycles, are utilized for the electric vehicle simulation. The specifications for driving modes are shown in Table I.

TABLE I
SPECIFICATIONS OF REAL-WORLD DRIVING MODES

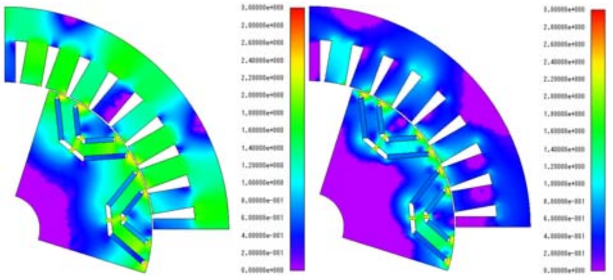
Section	Manhattan Mode	Braunschweig Mode
Nationality	US	EU
Distance(km)	3.325	10.873
Max. Speed(km/h)	40.6	58.2
Avg. Speed(km/h)	11.0	22.5
Max. Acceleration/(m/s2)	1.92	2.42
Max. Deceleration(m/s2)	-2.37	-3.58

The simulation considering the vehicle dynamics and real-world driving modes is performed to analyze the main operating range. The motoring and regenerating operation points for IPMSM are marked in Fig. 1. The characteristics of the speed and torque for the motor drive system are used for performing the transient test.



(a) Manhattan Mode (b) Braunschweig Mode

Fig. 1. Operating marks of IPMSM for EV



(a) Flux density at 2000rpm (b) Flux density at 11000rpm

Fig. 2. Comparison of the flux density distribution

III. MODELING OF IPMSM FOR OPTIMAL EFFICIENCY DISTRIBUTION USING MTPA COUPLED WITH FEM

Nonlinear magneto-static FEM in the whole operating points is carried out for the numerical analysis of IPMSM. FEM based-design of IPMSM combined with MTPA is executed for the efficiency enhancement. The torque and d-q flux linkage at each current amplitude and angle for IPMSM based on MTPA are analyzed to compute the minimum input current.

The flux density distribution at the constant torque and power region is depicted in Fig. 2. It is found that the flux density at the constant power region with flux weakening control is lower than the flux density at constant torque region. Therefore, the accurate analysis for the iron loss dependent on the flux density and frequency of IPMSM is the mainly significant subject because iron loss is dominantly caused by nonlinear saturation characteristics.

Hence, dominant losses such as the copper and iron loss are computed by electromagnetic analysis. In order to accomplish the advanced efficiency distribution, not only the copper loss using FEM-based MTPA is minimized, but the iron loss is reduced by shape optimization of IPMSM.

In particular, the optimal shape design of IPMSM in magnet and teeth is performed to reduce the iron losses in that almost all the generated iron losses are located in the surface of the teeth and rotor.

IV. EVALUATION OF IPMSM BASED ON DYNAMO TEST

The static and transient experiment for IPMSM is performed to verify the performance and optimal efficiency distribution. The layout for the dynamo test consists of the motor, inverter, dynamo, control board and power analyzer, which is shown in Fig. 3.

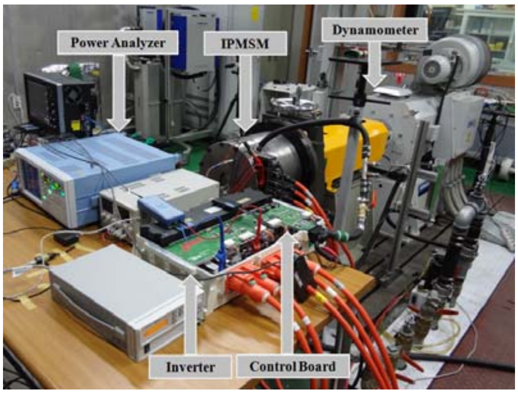
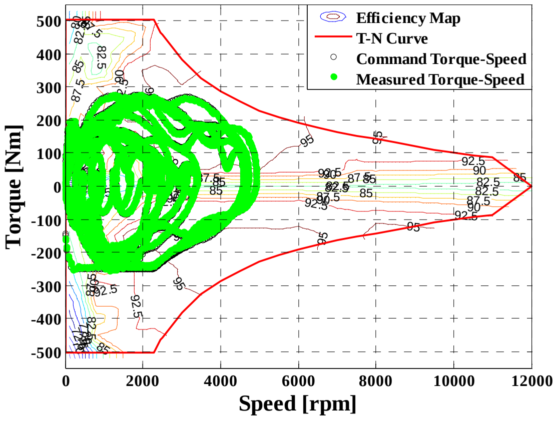
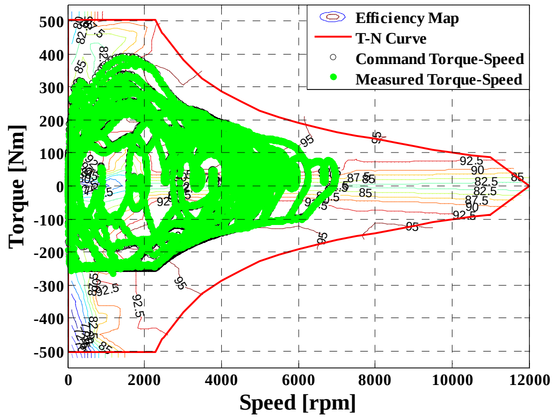


Fig. 3. Experimental setup for validation

As it can be known in Fig. 4, it has been found that the proposed IPMSM and inverter have the well-developed design and control response in that the measured torque according to time is exactly followed to the reference torque command in the transient test. The experimental result for the efficiency of IPMSM through dynamo test is achieved, which is distributed from 90% to 95.3% in most frequent operating area. It makes certain that the proposed design method for the efficient IPMSM is confirmed by the static and transient tests in that the optimal efficiency distribution for IPMSM is matched with the mainly operating range of IPMSM.



(a) Manhattan Mode



(b) Braunschweig Mode

Fig. 4.Transient test results(Measured versus command torque and speed)

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