Study of Efficiency Characteristics of Interior Permanent Magnet Synchronous Motors

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This paper presents an effective method for calculating the current excitations for optimal operating condition of interior permanent magnet (IPM) synchronous machines for traction application. The relationships between torque, current amplitude, and current angle during optimal operation are studied. For a given torque and speed command, the steps of searching for the ideal current excitations can be simplified using a script developed in ANSYS Maxwell, which significantly accelerates the process of evaluating performance and creating efficiency map of an IPM machine.

***Index Terms*— Efficiency map, flux weakening (FW), interior permanent magnet (IPM) machine, maximum torque per ampere (MTPA).**

I. Introduction

INTERIOR permanent magnet (IPM) synchronous machine is preferred in electric vehicle (EV) traction system for its high power density and high efficiency. The traction motor in EV has to bear frequent start, stop, acceleration, and deceleration. This means the motor is desired to have high efficiency over a wide speed range [1].

Efficiency map is a common tool to describe the total efficiency and performance of a motor in the operating envelope [2]. For each operating case (torque and speed), the excitation (current amplitude and angle) must be defined before evaluating its efficiency performance. However, searching for the excitation to output required torque and developing the efficiency map for a given IPM machine can be very time-consuming.

Methods are proposed in the literature for creating efficiency maps. In [4], the efficiency map is produced from a time-domain 2-D finite element analysis (FEA) model, currents of d-axis and q-axis are calculated with multi-objective optimization and a script for ANSYS Maxwell is developed. The efficiency map of a permanent magnet synchronous machine is calculated with nameplate data in [5]. However, the iron loss is roughly estimated, and the method is not suitable for machines under flux weakening (FW) operation. In [6], the nonlinear motor control equations for synchronous motors are derived and adopted to calculate the efficiency map.

In this paper, the relationships between the given torque/speed command and current excitation for optimal operation are summarized. Therefore, the process of searching for the optimal excitation for each operating case can be simplified. A script in ANSYS Maxwell has been developed to automatically find optimal current excitations. The excitations are used to evaluate the efficiency performance of an IPM traction motor with FEA. With this method, the efficiency map of the IPM machine can be obtained rapidly. The effectiveness of the proposed method is validated by comparing efficiency maps based on FEA results and experimental results of an IPM machine.

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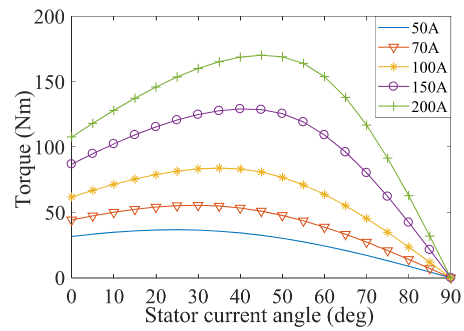

Fig. 1. Variation of the machine's torque with stator current angle.

II. IPM Machine Analysis

The IPM motor in TOYOTA Camry 2007 Hybrid Synergy Drive system [7] has been set as the target machine for this paper. The 2-D finite element (FE) electromagnetic model of the machine is established in ANSYS Maxwell. The motor has 48 slots and 8 poles. The maximum speed is 14 000 r/min and the peak power is 70 kW. Neodymium iron boron (NdFeB) magnets are assembled in the rotor in "V" shape.

Maximum torque per ampere (MTPA) control strategy is adopted below the base speed. FW is used when the speed exceeds the base speed. FW aims at using the minimum amplitude of phase current to provide the maximum torque for any given speed within the voltage constraint set by the inverter.

The variation of the motor's torque with stator current angle is shown in Fig. 1. For any given current amplitude, torque is a function of current angle. This means that there exists one current excitation with the minimum amplitude to produce

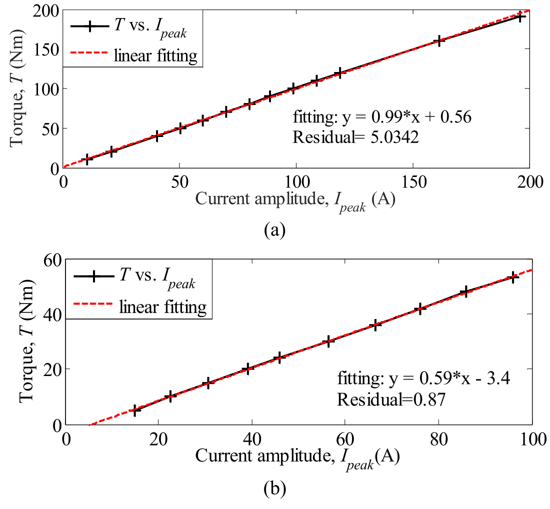

Fig. 2. Relationship between torque (T) and amplitude (I_{peak}) of the optimal current excitations. (a) 1000 r/min. (b) 9000 r/min.

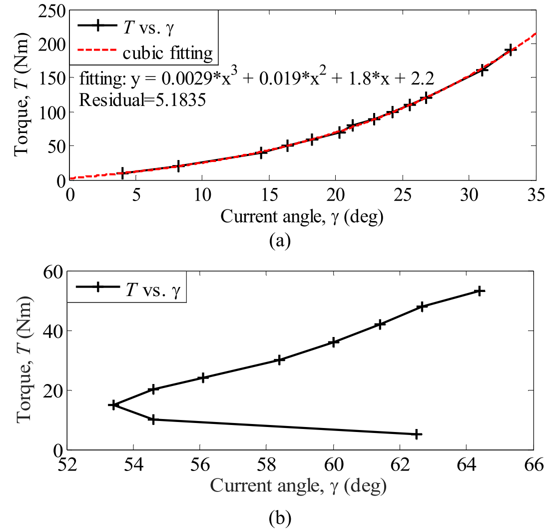

Fig. 3. Relationship between torque (T) and current angle (γ) of the optimal current excitations. (a) 1000 r/min. (b) 9000 r/min.

certain torque at a speed and this excitation is regarded as "the optimal current excitation" in this paper.

A number of optimal current excitations of the IPM machine have been searched at several typical speeds in ANSYS Maxwell with brute force method. The essence of this searching method is listing a series of candidate excitations and pick out the one with minimum current amplitude. For a given torque and speed combination, current amplitude and angle are parameterized and swept until the minimum current is found. In the analysis, back electromotive force is approximately considered as the phase voltage of stator winding. The line voltage must be constrained under the dc bus voltage limit of the inverter. In Figs. 2–6, 11, and 12, torque is denoted as T; current amplitude is denoted as I_{peak}; and current angle is denoted as γ.

For the optimal current excitations of operating cases at a given speed, some conclusions can be drawn.

1) The relationship between torque and optimal current amplitude is almost linear regardless of speed. For instance, $T - I_{\mathrm{peak}}$ curves of 1000 and 9000 r/min are plotted in Fig. 2(a) and (b), respectively. Both of the curves can be well fitted with a linear function.
2) The relationship between torque and optimal current angle can be well fitted by a cubic polynomial if the speed is below a certain value. As the speed exceeds the value, the relationship is no longer monotonic. $T - \gamma$ curves of 1000 and 9000 r/min are plotted in Fig. 3(a) and (b), respectively. $T-\gamma$ curve of 1000 r/min can be well fitted with a cubic function, whereas T–γ curve of 9000 r/min is no longer monotonic.

The gradient of T–I_{peak} curve decreases when large current flows in the stator winding. This phenomenon is the result of magnetic saturation. The values of the d-axis inductance L_d and the q-axis inductance L_q decrease as stator current increases. In this paper, the error of fitting satisfies the engineering precision demand.

Relationships between the speed and optimal current excitations are also explored. For each given torque, the relationship

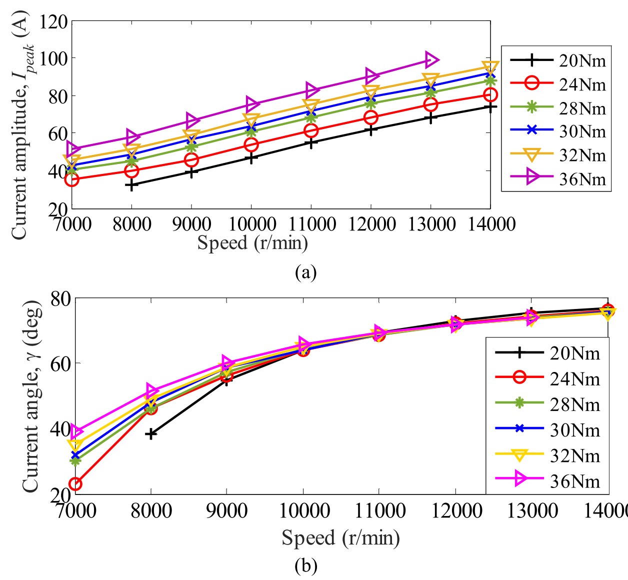

Fig. 4. Relationships between speed and optimal current excitations. (a) Current amplitude (I_{peak})-speed curves. (b) Current angle (γ)-speed curves.

between optimal current amplitude I_{peak} and speed is near linear, as shown in Fig. 4(a). In Fig. 4(b), the trends between optimal current angle γ and speed are the same regardless of torque values.

III. Automatic Calculation of Optimal Current Excitations

Based on the conclusions in Section II, a method to simplify the search process of optimal current excitations is summarized with a script for ANSYS Maxwell. A simplified flowchart of the script is shown in Fig. 5.

The introduction of execution steps is as follows.

1) Set an initiative speed (e.g., 1000 r/min) and pick a few of current values (e.g., 20, 50, 100, and 200 A) in ANSYS Maxwell. Analyze corresponding optimal current angle values at this speed with step searching.

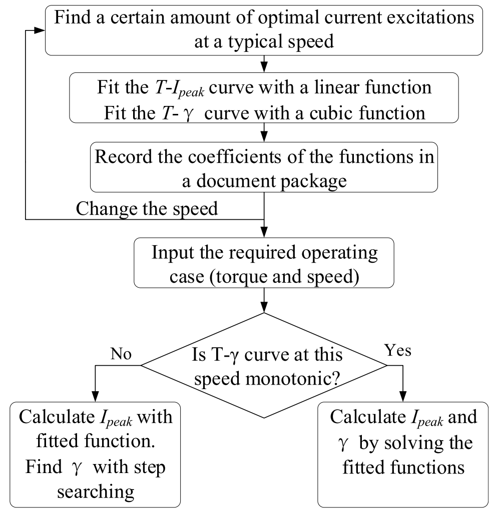

Fig. 5. Flowchart of the script.

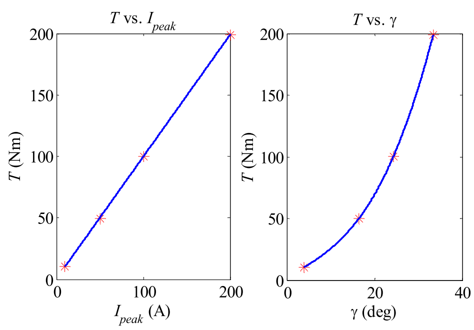

Fig. 6. Automatic fitting process in MATLAB at 1000 r/min.

2) Call MATLAB. Fit $T - I_{\text{peak}}$ curve of optimal current excitations with a linear function and fit T–γ curve with a cubic function. Record the coefficients of the fitted functions in a document package. For example, the fitting process at 1000 r/min of the motor is shown in Fig. 6. The fitted function of T–I_{peak} curve is $y = 0.997x + 0.2713$; the fitted function of T–γ curve is $y = 0.00465x^3 - 0.066653x^2 + 2.9612x - 1.2922$.
3) Process and record the data of other typical speeds (2000, 3000 r/min, etc.) with steps (1) and (2). Obtain the optimal current excitations and record the coefficients of the fitted functions of each analyzed speed in the document package.
4) For an arbitrary torque at a certain speed, the corresponding optimal current amplitude and current angle can be obtained immediately by solving the recorded fitted equations reversely. If $T - \gamma$ curve is not monotonic at this speed, the current amplitude still can be calculated with the fitted T–I_{peak} function, whereas the current angle will be found by step searching. Newton interpolation will be adopted if the characteristic data of the required speed have not been analyzed before, e.g., once the data for 1000 and 2000 r/min are created, the data for the speed of 1500 r/min can be readily collected.

Select a certain amount of operating cases and calculate corresponding losses and efficiency. Hence, the efficiency map can be created.

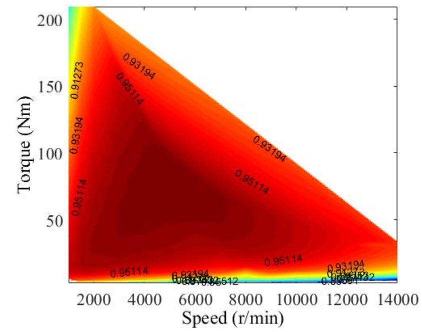

Fig. 7. Calculated efficiency map of the motor in Camry 2007 Hybrid Synergy Drive system.

In this paper, efficiency of 240 operating cases within the torque–speed envelope is calculated to plot the efficiency map of the motor in Camry 2007 Hybrid Synergy Drive system, as shown in Fig. 7. The efficiency of an operating case is estimated as

$$\eta = \frac{P_{\text{mech}}}{P_{\text{mech}} + P_{\text{loss}}} = \frac{T \cdot \Omega}{T \cdot \Omega + P_{\text{loss}}} \tag{1}$$

where P_{mech} represents the mechanical power of the motor; T represents the torque; Ω represents the angular speed of rotor; and P_{loss} represents the sum of losses. The average value of the torque waveform of FE calculation results is regarded as the torque T. Iron losses, eddy current loss in permanent magnets, dc copper loss, and bearing loss are considered. Bearing loss is calculated with

$$P_{\text{bearing}} = k_m G_a n / 1000 \tag{2}$$

where k_m is a constant, three is adopted as the value in this paper; G_a represents the weight of rotor; and n represents the speed. Iron losses and magnet loss are calculated with FEA. After setting B–P curves of the lamination material and the resistivity of permanent magnets in ANSYS Maxwell, the losses in the iron cores and eddy current loss in the magnets can be calculated. In the calculation of copper loss, the phase resistance of the winding is calculated with slot fill factor and winding configuration. The copper temperature is set at 100 °C in this paper.

The CPU of the computer in this paper is Intel-Xeon E5-1620 at 3.50 GHz and the RAM is 32 GB. The execution time of the brute force method consists of computer calculation time and manual data processing time. The average computer calculation time for searching the optimal excitation for an operating case with brute force method is approximately 30 min. Therefore, the total computer calculation time for searching the excitations of the operating cases in the efficiency map with brute force method will be nearly $30 \times 240 = 7200$ min. As for the script, the execution time only consists of computer calculation time because the data is processed automatically. The average time for searching an optimal excitation with step searching is approximately 30 min. To determine the fitted polynomials at low speeds, 32 optimal excitations are found by step searching. For the speeds whose T–γ curves are not monotonic, 48 optimal excitations are found with step searching. The total execution

Fig. 8. Experiment bench.

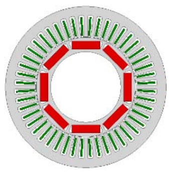

Fig. 9. 2-D FEA model of the experimental IPM machine.

TABLE I
PARAMETERS OF THE EXPERIMENTAL IPM MOTOR

Parameters	Values
Outer diameter of stator	205mm
Inner diameter of stator	128mm
Air gap length	0.75mm
Stator stack length	127mm
Number of slots	48
Number of poles	8
Peak power	60kW
Maximum speed	8000r/min

time for searching the excitations of the operating cases in this efficiency map with the script is nearly $30 \times (32+48) = 2400$ min.

IV. EXPERIMENT AND VERIFICATION

The method developed earlier is applied to a prototype machine to evaluate the validity. An IPM machine for EV traction application was designed and fabricated. The experiment bench has been established as shown in Fig. 8. The 2-D FE electromagnetic model of the IPM motor in ANSYS Maxwell is shown in Fig. 9. The NdFeB magnets are assembled in the rotor as "—" type. Some parameters of the machine are listed in Table I.

MTPA and FW are adopted control strategies for this IPM machine. The block diagram of the controller in the experiment is shown in Fig. 10. Several optimal current excitations of the machine are calculated with the script and with brute force method, respectively. Corresponding T–I_{peak} and T–γ curves at 1000 and 5000 r/min are compared, as shown in Figs. 11 and 12. The similar results of the two methods prove the feasibility of the script. In the simulation, 100 excitations are searched by the script. The efficiency of each case is calculated with (1) and the efficiency map is shown in Fig. 13(a).

In the experiment, the ratio of output power to input power of the motor is considered as efficiency. The shaft torque of the motor is obtained with the dynamometer. The product of shaft torque and angular speed of rotor is regarded as the output power. The input power is obtained by the power analyzer in the test system. The IPM machine was operated at 80 operating cases in the experiment. The efficiency map obtained by the experiment is shown in Fig. 13(b). The efficiency regions in the two efficiency maps are similar. The good correspondence between the two efficiency maps proves the accuracy of automatic calculation with the script.

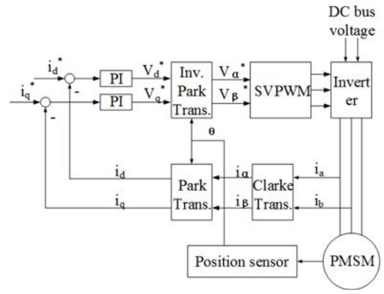

Fig. 10. Block diagram of controller for the motor.

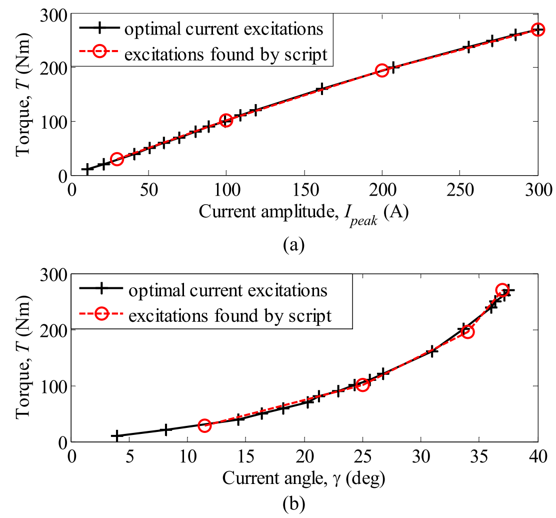

Fig. 11. Comparison of optimal current excitations found with brute force method and script, respectively, at 1000 r/min. (a) T–I_{peak} curve. (b) T–γ curve.

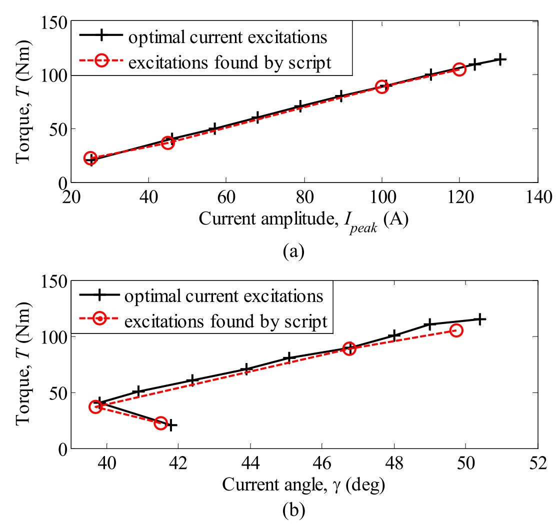

Fig. 12. Comparison of optimal excitations found with brute force method and script, respectively, at 5000 r/min. (a) T–I_{peak} curve. (b) T–γ curve.

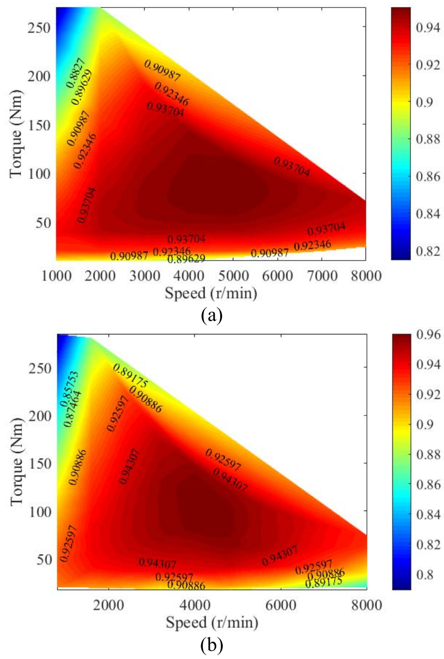

Fig. 13. Efficiency maps of the prototype IPM machine. (a) Simulated with the excitations calculated by the script. (b) Experimental results.

V. Conclusion

A study has been conducted to simplify the steps of searching for the optimal current excitations of IPM machines. The rules between operating cases and corresponding optimal excitations have been summarized with the research of the motor in TOYOTA Camry 2007 Hybrid Synergy Drive system. A script based on the rules is developed for ANSYS Maxwell to search for optimal excitations automatically. Efficiency of each operating case in the operating envelope can be evaluated by FEA. Therefore, the process of creating an efficiency map is accelerated significantly.

The proposed method is applied to a prototype machine and a certain amount of optimal excitations are found by the script. Corresponding efficiency map is created and compared to the one created with the experimental results. The good correspondence between the efficiency maps proves the validity of the script.

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References

[1] Z. Q. Zhu and D. Howe, "Electrical machines and drives for electric, hybrid, and fuel cell vehicles," *Proc. IEEE*, vol. 95, no. 4, pp. 746–765, Apr. 2007.

[2] S. S. Williamson, A. Emadi, and K. Rajashekara, "Comprehensive efficiency modeling of electric traction motor drives for hybrid electric vehicle propulsion applications," *IEEE Trans. Veh. Technol.*, vol. 56, no. 4, pp. 1561–1572, Jul. 2007.

[3] S. S. Williamson, S. M. Lukic, and A. Emadi, "Comprehensive drive train efficiency analysis of hybrid electric and fuel cell vehicles based on motor-controller efficiency modeling," *IEEE Trans. Power Electron.*, vol. 21, no. 3, pp. 730–740, May 2006.

[4] E. Dlala *et al.*, "Efficiency map simulations for an interior PM motor with experimental comparison and investigation of magnet size reduction," in *Proc. Int. Electr. Mach. Drives Conf. (IEMDC)*, May 2013, pp. 23–29.

[5] M. Novak, J. Novak, Z. Novak, J. Chysky, and O. Sivkov, "Efficiency mapping of a 100 kW PMSM for traction applications," in *Proc. 26th Int. Symp. Ind. Electron.*, Jul. 2017, pp. 290–295.

[6] M. H. Mohammadi and D. A. Lowther, "A computational study of efficiency map calculation for synchronous AC motor drives including cross-coupling and saturation effects," *IEEE Trans. Magn.*, vol. 53, no. 6, Jun. 2017, Art. no. 8103704.

[7] T. A. Burress *et al.*, "Evaluation of the 2007 Toyota Camry hybrid synergy drive system," Oak Ridge Nat. Lab., Oak Ridge, TN, USA, 2008.

[8] G. P. Qiu and M. Qiu, *Design and Application Technology of Permanent Magnet DC Motor*. Beijing, China: Machine Press, 2009.

[9] G. Bertotti, "General properties of power losses in soft ferromagnetic materials," *IEEE Trans. Magn.*, vol. MAG-24, no. 1, pp. 621–630, Jan. 1988.