12. Electric Machines and Drives

Study on Machine Parameter and Performance of Interior Permanent Magnet Motor with Double-layer Permanent Magnet

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Abstract — In this paper, a study on the machine parameter and performance of interior permanent magnet (IPM) motor with double layer rotor structure is presented. The double layer IPM motor is designed basing on a single layer IPM motor. The advantages of multi-layer IPM motor are verified by the analysis of the motor performance. With the help of design of experiment (DOE) and response surface methodology (RSM), the optimized rotor structure with double layer PM is determined effectively. In this study, the efficiency as the object function is emphasized while other parameters and performance are also compared. All the results are confirmed by finite element method.

I. Introduction

Interior permanent magnet(IPM) machines are widely used in vehicle propulsion system for their attractive performance attributes, such as, high efficiency, high torque density, high power density and a long constant power operating range.

In IPM machines, the permanent magnets are buried inside the rotor core. It is not only for avoiding the separation of PM caused by the centrifugal force at high speed, but also for generating hybrid torque production. The reluctance torque due to the IPM rotor saliency effect is produced in addition to the magnet torque.

Single buried layer IPM machine as the familiar designs were the first to be implemented and put into production[1]. And many work of single layer IPM designs, such as flat-shape, V-shape and U-shape design etc, were reported frequently. The single layer IPM motor is the basic and simplest design.

In this paper, multi-layer IPM design approach is applied. Generally, a single layer IPM rotor design can be split into several layers creating a multi-layer IPM design. Comparing with the single layer IPM designs, the multi-layer IPM motors exhibit the beneficial attributes of both synchronous reluctance motor and the PM motor in structure. The increasing of buried PM layer can reduce leakage and improves the rotor saliency trait. Accordingly, other machine parameters and performance characteristics can be improved.

For this study, the IPM models, a prototype single layer design and a redesigned double layer model, are analyzed by using finite element method(FEM), and then their results are compared. The improvement of performances and variation of machine parameters are analyzed. The advantages of multi-layer design over the single layer rotor design are concluded.

II. Model and Design Method

In this study, an existing IPM motor used in hybrid electric vehicle(HEV) propulsion system is introduced as the prototype model firstly. Fig. 1 shows the configuration of this IPM motor model. It has 16-pole and 24-slot. In the rotor part, a single PM layer is buried in each pole. And it has been designed optimally as the V-shape PM structure.

Then, the same amount of PM as that buried in the prototype model is redesign into the multi-layer IPM rotor structure for further improving the IPM motor performance. In the study, the efficiency performance of the IPM motor is chosen as object of optimization.

In the following design process, the double layer IPM rotor structure is chosen because of the considerations such as simplicity for manufacturing, the easiness of inserting PM into the rotor core and the mechanical robustness. Even if, the advantages of the increasing PM layers design can be concluded by analogy[2].

In the double layer design, more design variables are produced after splitting the PM layer and flux barriers, for example, L_{at}, L_{bt}, α_1, α_2, β_1, β_2, as shows in Fig. 2. Consequently, the difficulty of motor design greatly increased. Therefore, firstly, the design of experiment (DOE) analysis is applied to select the lesser but dominant design variables for efficiency improving design. According to a full factorial design (FFD), design variables (L_{bt}, β_2) are proved to have great effect on the efficiency characteristic of this double layer rotor design.

Then, using the selected design variables (L_{bt}, β_2), with the help of response surface methodology (RSM) analysis[3], the optimal model design variables can be determined according to the response of efficiency characteristic with the design variables (L_{bt}, β_2). Fig. 3 shows the response surface of efficiency, from which the optimal configuration is built with ($L_{bt}=12.5mm$, $\beta_2=31.2$). Fig. 4 shows the final designed double layer IPM motor.

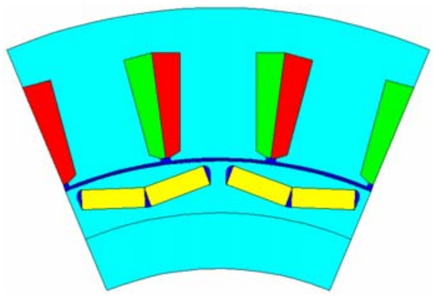


Fig. 1 Prototype single layer V-type IPM motor model

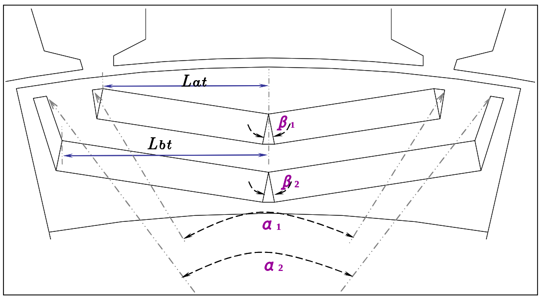


Fig. 2 Design variables in double layer design IPM rotor part

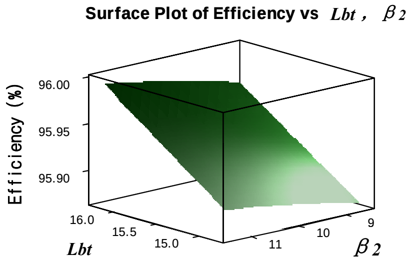


Fig. 3 Response surface of efficiency characteristic with variable (*Lbt*, *β2*)

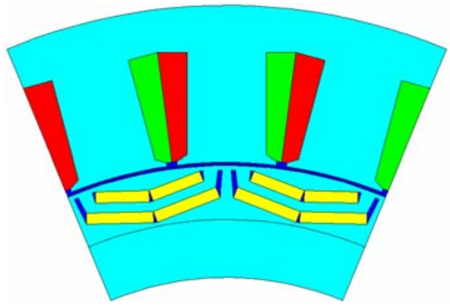
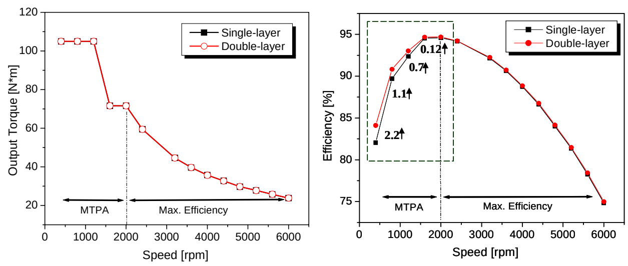


Fig. 4 double layer design VV-shape IPM motor model



(a) (b)

Fig. 5. (a) torque performance; (b) efficiency characteristic comparison

III. Results Comparison and Analysis

The double layer IPM motor model was designed for improving the efficiency characteristic. As the Fig. 5 shows, when the double layer IPM model give the same output torque performance with the prototype model over the full speed range, of that the MTPA control for low speed and Maximum efficiency control for high speed. The efficiency characteristics are compared in Fig. 5(b). The improving of efficiency in the MTPA segment is achieved. It is caused by the increasing of reluctance torque production (Fig. 7(a) shows) due to the reinforcing of saliency effect, which is caused by increasing the q-axis inductance (Fig. 6(a) shows) and reducing the d-axis inductance (Fig. 6(b) shows). On the other hand, the magnetic torque production decreased (Fig. 7(b) shows), which can reduce the copper loss and iron loss in the stator and rotor core. And also, the other performances (such as torque ripple, constant power range) and machine parameters (such as back EMF, cogging torque, etc.) are calculated and compared, the detail analysis in theoretical will be given in the full paper.

IV. Conclusion

In this study, an IPM motor with double layer IPM rotor structure was optimally designed, and the improvement of performance characteristics and machine parameters are discussed through comparing with the prototype single layer IPM motor. By applying the multi-layer IPM design, the benefits of increasing the reluctance torque production while reducing the dependence on magnet torque are emphasized in this study. From the machine performance and a cost standpoint, the multi-layer buried PM design is applicable design approach for achieving preferable performance with lesser magnet quantity in IPM machines.

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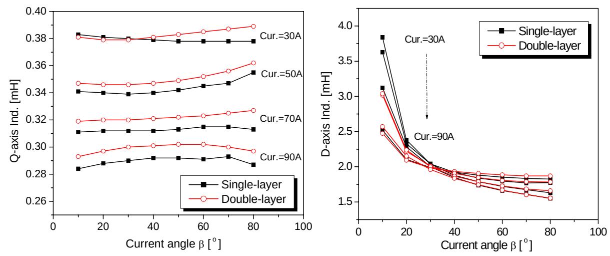
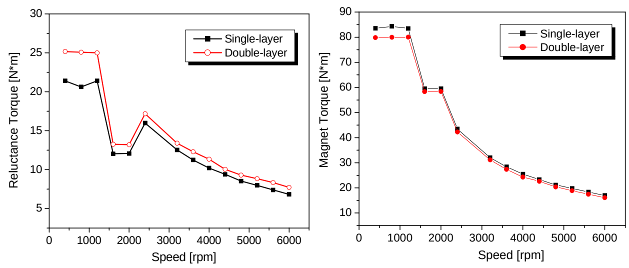


(a) (b)

Fig. 6. Inductance characteristics with current angle
(a) Q-axis inductance *Lq*, (b) D-axis inductance *Ld*



(a) (b)

Fig. 7. Hybrid torque characteristics
(a). reluctance torque production; (b) magnet torque production

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