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Efficiency Optimization of a Permanent-Magnet Hybrid Brushless Machine Using DC Field Current Control

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This paper proposes a new efficiency optimization approach for a new kind of permanent-magnet hybrid brushless (PMHB) machine. The key is to propose the self-searching control (SSC) for the PMHB machine in such a way that the input power at the given load and speed can be progressively minimized by tuning the dc field current. A loss analysis of the machine is given to justify the use of dc field current as the control parameter. Detailed experimental results confirm that the proposed approach can effectively accomplish the desired efficiency optimization.

Index Terms—Efficiency optimization, field current control, permanent-magnet (PM) machine, self-searching control (SSC).

I. INTRODUCTION

WITH ever-increasing concern on energy efficiency, various efficiency optimization approaches have been developed for electric machines, including the permanent-magnet (PM) brushless machines [1] which inherently have relatively high efficiency [2]. Basically, such approaches are loss-model referencing, model-free self-searching, or even both of them [3]. Although self-searching control (SSC) takes advantage of model-free self-searching, which is insensitive to parameter variations and is easy-to-implement, it still relies on using the $d-q$ coordinate transformation to perform flux control. Recently, a new class of PM hybrid brushless (PMHB) machines [4]–[6] has been developed which offers the distinct feature of simple flux control.

The purpose of this paper is to propose the SSC for efficiency optimization of the PMHB machine. The key is to use the dc field windings of the PMHB machine to online tune the air-gap flux, and consequently adjust the input power under the given load and speed. Hence, the advantages of SSC can be retained while there is no need to use the complicated $d-q$ coordinate transformation.

II. PRINCIPLE OF EFFICIENCY OPTIMIZATION

Fig. 1 shows the newly developed PMHB machine. It is composed of a solid-iron outer rotor with 24 salient poles, and a double-layered stator in which the outer stator has 36 salient poles wound with armature windings, while the inner stator has installed both PMs and dc field windings for hybrid-field excitation. The air bridge, which is in shunt with each PM, functions to amplify the effect of flux control. Through proper control of the bidirectional dc field current, this machine can realize flexible flux control up to a range of nine times.

The proposed control system for efficiency optimization is depicted in Fig. 2. It can be seen that the dc field current control essentially decouples with the machine operation control, which

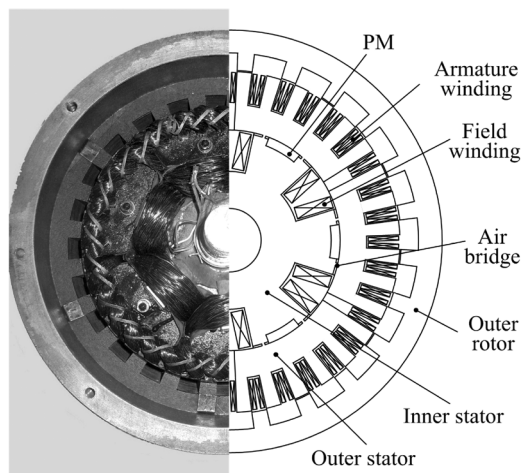


Fig. 1. PMHB machine configuration.

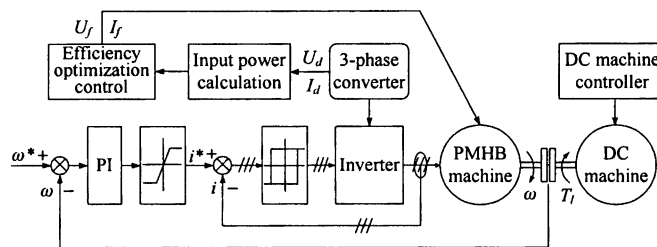


Fig. 2. Proposed control system for efficiency optimization.

makes the efficiency optimization simple and reliable. The key of this efficiency-optimizing control is as follows: when the algorithm starts, it will check the optimal operation record to see whether it has stored the corresponding load torque and speed. If yes, it will retrieve the optimal parameters; if not, it will perform the SSC, namely to online tune the dc field current in such a way that the input power of the whole system can be progressively minimized under the given load and speed. After completing the SSC, the data will be used to update the optimal operation record. Fig. 3 shows the power circuit for dc field current control, which is actually a typical H-bridge converter. Hence, the magnitude of the dc field current can be easily regulated by adjusting the duty cycle of the conductive switches. Also, the direction of the dc field current can be simply controlled

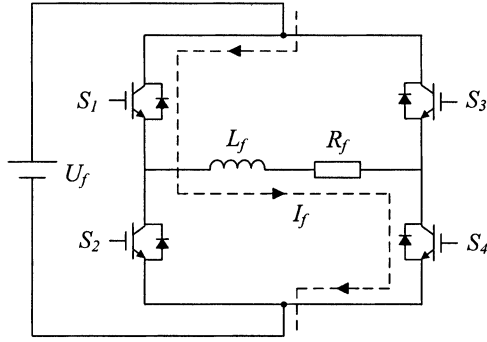


Fig. 3. Power circuit for dc field current control.

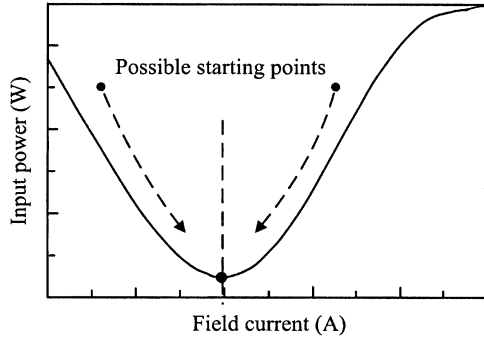


Fig. 4. SSC process for efficiency optimization.

 TABLE I
 SSC PERTURBATION RULE FOR EFFICIENCY OPTIMIZATION

Current perturbation	Change in field current	Change in input power	Next perturbation
Positive	Positive	Negative	Positive
Negative	Negative	Positive	Positive
Positive	Positive	Positive	Negative
Negative	Negative	Negative	Negative

by selecting contrary switches. As compared with other efficiency optimization approaches, the proposed method has the merits of simpler control, easier implementation, and is more cost-effective.

Fig. 4 shows the SSC process for efficiency optimization of the PMHB machine under the given load and speed. If the starting point is from the left-hand side of the minimum input power point, the increment of the dc field current will reduce the input power. In contrast, if the starting point goes from the right-hand side of the minimum input power point, the decrement of the dc field current will reduce the input power. Therefore, if there is a decrease in input power, the subsequent perturbation will be kept unchanged until reaching the minimum input power point; otherwise, the perturbation will be reversed. This perturbation rule is summarized in Table I. Additionally, once the optimal point of a specific condition is obtained, this operation point is memorized and will be used as the initial point for next search or be directly used as the optimal operation point if encountering this condition again. This arrangement can greatly enhance the speed of searching. It should be noted that since the input power is measured on

the dc link, the efficiency optimization is for the entire drive system, including the PMHB machine and power inverter.

III. LOSS ANALYSIS

The major losses of the PMHB machine include the copper losses, iron losses, stray losses, and mechanical losses. The iron losses are composed of the magnetic hysteresis loss and eddy-current loss [7], [8].

The copper losses are due to the stator windings and dc field windings, which can be written by

$$P_{Cu} = mR_a i_a^2 + R_f I_f^2 \quad (1)$$

$$u_a = R_a i_a + L_a \frac{di_a}{dt} + e_a \quad (2)$$

$$e_a = C_e \Phi_\delta n \quad (3)$$

$$\Phi_\delta = k_1 \tau l_a B_\delta \quad (4)$$

where m is the number of phases, R_a the resistance of the phase winding, i_a the current, R_f the resistance of the dc field winding, I_f the field current, u_a the terminal phase voltage, L_a the inductance of the phase end winding, e_a the generated phase electromagnetic field, C_e the coefficient of the phase electromagnetic field, Φ_δ the phase flux linkage, n the machine speed, k_1 the coefficient of the pole arc, τ the pole pitch, l_a the axial length, and B_δ the air-gap flux density. Substituting (3) and (4) in (2), it yields

$$u_a = R_a i_a + L_a \frac{di_a}{dt} + k_1 \tau l_a C_e n B_\delta. \quad (5)$$

From (1) and (5), it can be deduced that the copper losses are mainly governed by the stator current and the field current, while the stator current can be adjusted by changing B_δ which can also be regulated by tuning the field current.

Classically, the iron losses of the teeth and yokes can be expressed as

$$P_{Fe} = k_2 k_3 G_t \left(\frac{f}{50} \right)^{1.3} B_t^2 + k_2 k_3 G_y \left(\frac{f}{50} \right)^{1.3} B_y^2 \quad (6)$$

where k_2 and k_3 are the coefficients of iron losses, G_t and G_y the weights of teeth and yokes, f the supply frequency, and B_t and B_y the flux densities of teeth and yokes. Thus, under the given speed, the iron losses can be adjusted by regulating B_t and B_y , which can also be controlled by tuning the field current.

For higher accuracy, the iron losses can be expressed in terms of the magnetic hysteresis loss and the eddy-current loss. The magnetic hysteresis loss is caused by varying magnetization of ferromagnetic materials, which can be written by

$$P_{Hy} = k_4 G_{Fm} f B_\sigma + k_5 G_{Fm} f B_\sigma^2 \quad (7)$$

where k_4 and k_5 are the coefficients of the materials, G_{Fm} the weight of the ferromagnetic material, and B_σ the flux density of the iron. Hence, under the given speed, the magnetic hysteresis loss varies with B_σ , which can also be adjusted by the field current. On the other hand, the eddy-current loss exists in the iron, which can be described by

$$P_{Ed} = \frac{\pi^2 b^2}{6 \rho_1 \rho_2} G_{Fe} f^2 B_\sigma^2 \quad (8)$$

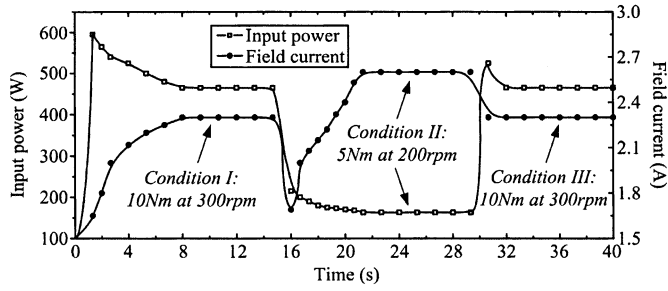


Fig. 5. Measured input power and field current responses with efficiency optimization during flux strengthening.

where b is the thickness of the iron, ρ_1 the resistivity of the iron, ρ_2 the density of the iron, and G_{Fe} the weight of the iron. Thus, under the given speed, the eddy-current loss is related with B_σ , which can also be regulated by the field current.

The stray losses are additional losses caused by the load current due to changes in metallic materials. Such losses are usually quite small and can be expressed as

$$P_{St} = k_6 f^2 i_a^2 \quad (9)$$

where k_6 is the coefficient of stray losses. According to (5), it can be seen that the stray losses can be altered by adjusting B_δ , which can also be changed by tuning the field current.

The mechanical losses are due to friction and windage, which are independent from those electrical variables. In general, they can be written by

$$P_{Me} = k_7 n^2 \quad (10)$$

where k_7 is the coefficient of mechanical losses.

Therefore, except the mechanical losses, all the other losses can be regulated by tuning the field current under the given load and speed. Hence, the optimal efficiency of the PMHB machine can be expressed as

$$\eta_{opt} = \left(1 - \frac{P_{loss_opt}}{P_{out} + P_{loss_opt}} \right) \times 100\% \quad (11)$$

where $P_{loss} = \sum(P_{Cu} + P_{Fe} + P_{St} + P_{Me})$ is the total losses, and η_{opt} is the optimal efficiency.

IV. RESULTS

The proposed efficiency optimization of the PMHB machine has been prototyped for experimentation. This PMHB machine is mechanically coupled with a dc machine. By connecting with a four-quadrant programmable power supply, this dc machine operates as a dynamometer which can real-time control the rotor speed and load torque.

First, the proposed efficiency optimization of the PMHB machine is assessed during flux strengthening. Fig. 5 shows the measured input power and field current responses under different loads and speeds. It can be seen that in Condition I (10 Nm at 300 rpm), the field current gradually increases until the input power progressively reaches the minimum of 465 W. When the operation is suddenly changed to Condition II (5 Nm at 200 rpm), a new search is activated. Consequently, the input

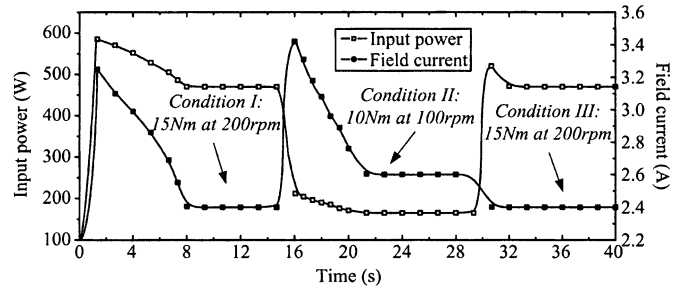


Fig. 6. Measured input power and field current responses with efficiency optimization during flux weakening.

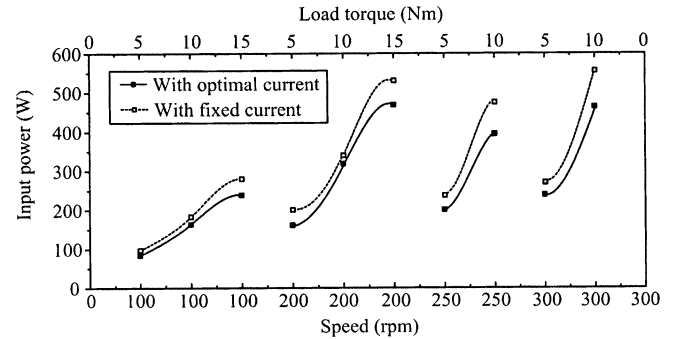


Fig. 7. Measured input power characteristics with and without efficiency optimization.

power is minimized to 163 W with the optimal field current of 2.6 A. When the operation is suddenly switched to Condition III which is actually the same as Condition I, the initial operation point is directly retrieved from the memory. So, it virtually takes no time to achieve the minimum input power of 465 W. Hence, it verifies that the proposed SSC method can effectively find the optimal operation point during flux strengthening for the PMHB machine under different loads and speeds.

Second, the proposed efficiency optimization is evaluated during flux weakening. Fig. 6 shows the measured input power and field current responses under different loads and speeds. It can be found that in Condition I (15 Nm at 200 rpm), the field current decreases until the input power gradually arrives at the minimum of 470 W with the optimal current of 2.4 A. While the operation is suddenly changed to Condition II (10 Nm at 100 rpm), another new search is triggered. Then, the input power is minimized to 165 W. When the operation suddenly returns to the same case as Condition I, the initial operation point is directly retrieved from the memory. Thus, it quickly settles at the minimum input power of 470 W. Hence, it further verifies the effectiveness of the proposed SSC.

Third, in order to evaluate the validity of the proposed efficiency optimization, the input power characteristics of the PMHB machine with the use of optimal field current and a fixed field current of 2 A are compared as shown in Fig. 7. It can be seen that under any sets of rotor speed and load torque, the input power with the optimal field current is always less than that with the fixed field current. The corresponding percentage reduction in input power is also plotted in Fig. 8. It can be seen that the input power reduction spans from 5.9% to 18.5%, and

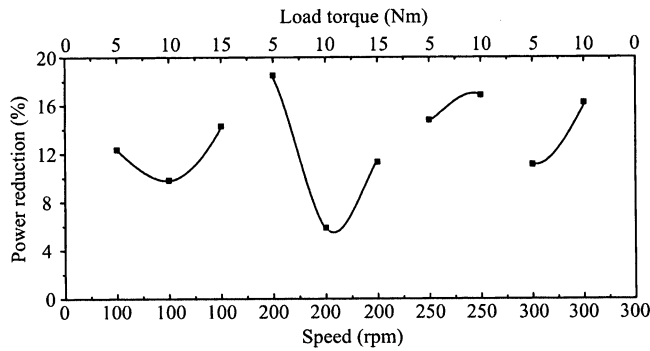


Fig. 8. Measured power reduction characteristics with efficiency optimization.

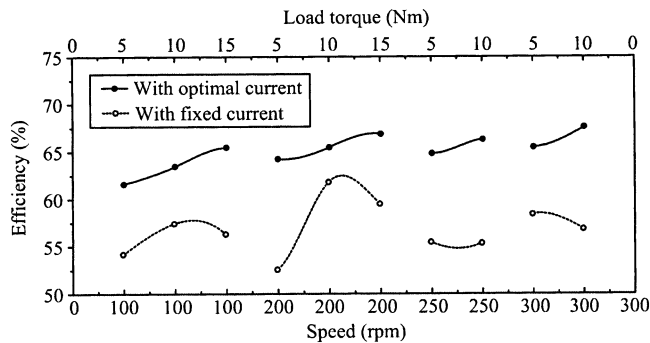


Fig. 9. Measured efficiency characteristics with and without efficiency optimization.

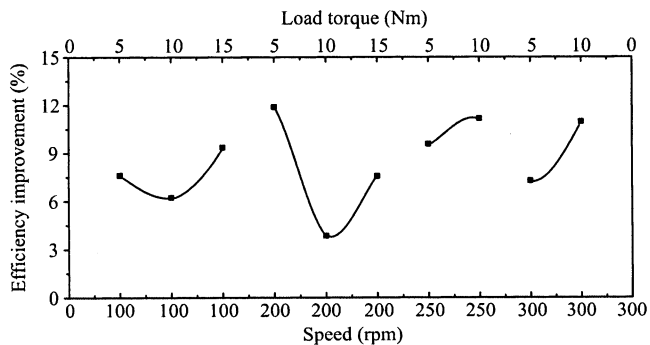


Fig. 10. Measured efficiency improvement characteristics with efficiency optimization.

mostly over 10%. Such reduction is very significant when the power level is elevated to the order of kilowatts.

Fourth, to further assess the efficiency improvement, the measured efficiency characteristics with the optimal field current and a fixed field current of 2 A are also compared as depicted in Fig. 9. It can be found that the efficiency with the optimal current spans from 61.6% to 67.6%, which is much higher than the range of 52.3%–61.5% with the fixed field current. The corresponding efficiency improvement is also shown in Fig. 10.

It can be seen that the efficiency improvement is significant, from 3.9% to 11.9%, and mostly over 7%. Therefore, with the proposed efficiency optimization, the PMHB machine can significantly improve its efficiency, and consequently increase its cost-effectiveness.

Furthermore, it is worthy to note that since the input power is measured at the dc link, the measured efficiency is actually a combined efficiency of the whole system, including the PMHB machine and power inverter. So, the optimal efficiency of over 61.6% under all speeds and loads is attractive for most industrial applications.

V. CONCLUSION

A new efficiency-optimizing approach for the PMHB machine has been proposed and implemented. The loss analysis indicates that various loss components of the machine can be altered by changing the dc field current. So, by simply tuning the dc field current, this machine can online achieve the minimum input power under any given loads and speeds. Detailed experimental results have been given to verify that the proposed approach is effective to achieve the desired optimal efficiency.

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