Loading Field Analysis on PMAC Servo Motor

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Abstract–**The permanent magnet AC (PMAC) servo motor is widely used in the fields requiring the ultimately high performance. Such as good dynamics, low torque pulsation and noise, etc. Hence, how to get the assured output torque plays a dominant role in servo motor design. In PMAC servo motor using $i_d = 0$ control strategy, the electromagnetic power is only related to current and back emf. Back emf is taken by the flux produced by PM. But, because of the armature reaction's effect, the flux produced by PM is different from that in the open-circuit condition. In this paper, a method has been developed for separating the fields produced by PM and winding current under any specified load condition. The technique is based on a 2-dimensional finite element analysis. Then a 10-pole / 9-slot PMAC servo motor's field is analyzed using this method. This method is applicable to other PM motors.**

I. INTRODUCTION

The permanent magnet AC (PMAC) servo motor is widely used in semiconductor, biotechnology, pharmaceutical, etc. These applications require the ultimate performance – good dynamics, low torque pulsation and noise. These are straightly related with output torque of the motor. In PMAC servo motor using $i_d = 0$ control strategy, the electromagnetic torque is only related to current and back emf. The vector graph is shown in Fig. 1, the electromagnetic power in three phases is obtained as:

$$P_{em} = 3E_0 I_1 \tag{1}$$

To get the assured output torque, it is necessary to analyze the field distribution under any specified load condition. Although several papers have been published on the calculation of the air gap magnetic field of brushless dc motors, e.g., [1], [2], [3], none has concerned specifically on the analysis of PM synchronous machines' magnetic field on load. Paper [1] has analyzed the magnetic field distribution in PM brushless dc motors. But, by assuming infinite permeability for the stator and rotor iron, the analysis is reduced to a linear problem, and the field distribution under load condition is obtained by superposition of the open-circuit and armature reaction field components. However, laminated steel plates' permeability is nonlinear.

In this paper, a novel method is introduced to analyze the field distribution on load considering nonlinear nature of permeability. The method is applicable to other discretional PM motors. The field of PMAC servo motor on load is analyzed based on this method. The analytical results are well agreed with simulating ones.

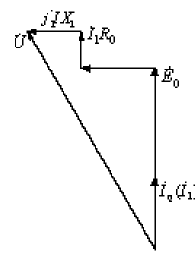

Fig. 1. Vector graph of PMAC servo motor using $i_d = 0$ control strategy

II. OPEN CIRCUIT AND ARMATRUE REACTION FIELD

Loading fields include the field produced by PM and the field by armature current. By assuming linear permeability of the stator and rotor iron, the loading field distribution can be obtained by calculation of the open circuit and armature reaction field respectively [4~8], i.e.,

$$B_{load} = B_{open} + B_{armature} \tag{2}$$

Where B_{load}, B_{open}, $B_{armature}$ are the fields of loading, open circuit, and armature reaction, respectively.

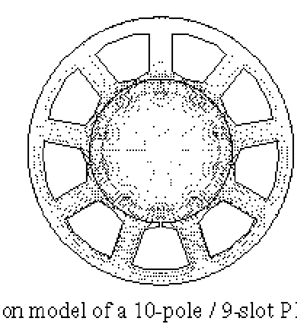

Fig. 2. Calculation model of a 10-pole / 9-slot PMAC servo motor.

The open circuit field distribution that is produced by the magnets can be calculated by software of finite element analyze, and ANSOFT is one of them. A calculation model of a 10-pole / 9-slot PMAC servo motor is depicted in Fig. 2. The field distribution of one tooth with different rotor positions is shown in Fig. 3.

In a similar manner, the armature reaction field distribution is calculated by the stator windings when the relatively permeability of PM is constant. The field distribution is shown in Fig. 4.

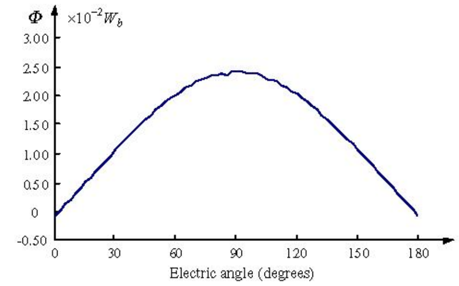

Fig. 3. Field distribution of open circuit with different rotor positions.

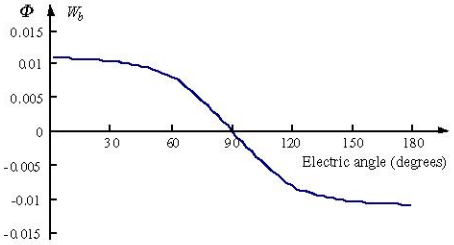

Fig. 4. Field distribution of armature reaction with different time.

To obtain the magnetic field distribution under any load condition and commutation strategy, it is necessary to predetermine the relative position of the open circuit and armature reaction field. In PM synchronous AC servo motor, the control strategy of $i_d = 0$ is widely used. The field distribution in one tooth is shown in Fig. 5, curve 1 is the superposition of the open circuit field and armature reaction field, curve 2 is corresponding simulative result on load.

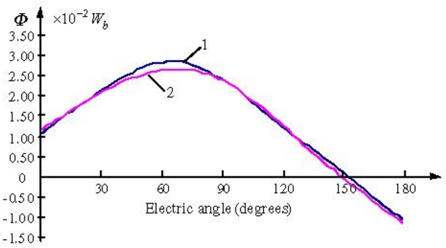

Fig.5. Field distribution in one tooth. 1. Superposition of the open circuit and armature reaction field components. 2. Simulative result on load.

Fig. 4 shows that curve 1 differs from curve 2 which is caused by the nonlinear characteristic of the reluctance. Especially, the values on curve 2 near the peak value are lower than those of curve 1 due to the saturation of magnetic circuit. How to separate the fields that is produced by PM and by winding current on load is the emphasis of this paper.

III. SEPARATE FIELD OF PM ON LOAD USING THE METHOD OF SMALL SIGNAL

How to obtain the back emf under load condition is a critical issue to study the output power. Then, the method of small signal is used to solve the problem as discussed below.

Small signal method is based on the following assumptions:

1. The reluctance does not vary when the magnetic excitation changes a little;

2. The excitation magnitude is proportional to the remained magnetic density when a PM is used as an excitation;

3. The excitation magnitude is proportional to the current when the armature current is used as an excitation.

By the above assumptions, when there is a little change of magnetic excitation ΔT, the change of teeth's flux density calculated by finite element analyze is $\Delta\Phi$. Then the PM's contribution to magnetic flux of tooth can be given as:

$$\Phi = \frac{T\Delta\Phi}{\Delta T} \tag{3}$$

That is the principle of small signal method. There still exists some error using this method. It is because that with the increase of PM excitation, the magnetic circuit becomes saturated, which leads to increase slow-down of tooth flux density. That is to say PM flux density's increase has a nonlinear characteristic, as shown in Fig. 6. It is obvious that there will be serious error when using an origin-crossed straight line whose slope is determined by the slope of a point on the curve to simulate the curve's nonlinear increase.

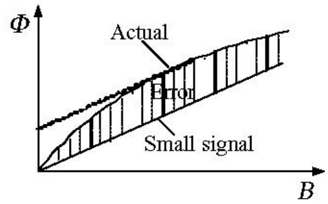

Fig. 6. Nonlinear characteristic of the flux density increase with PM excitation

The field of tooth includes that produced by PM and by winding current. Then there are two methods of field's calculation using small signal. The first is to directly calculate the field produced by PM using small signal, and the second is to subtract the field produced by winding current from the total field. In this paper the means combining the both is used.

Assuming winding current is I_b , and remainder magnetic flux density of PM is B_b. When winding current I and remainder magnetic flux density B are synchronously ascending with the basic value I_b and B_b, the saturation of magnetic circuit is uniform. So the field that is produced by I and B will be proportionably climbed, as shown in Fig. 7, i.e.,

$$g(\frac{I}{I_b}) = k\ f(\frac{B}{B_b}) \tag{4}$$

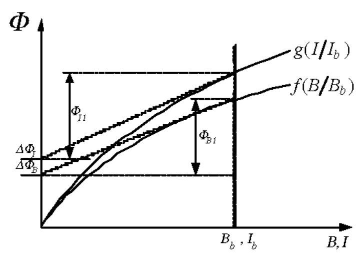

Fig. 7. Proportionably rise of the field that is produced by I and B

Using the method of small signal, the field produced by I and B is calculated as:

$$\Phi_{I1} = g'(1) \tag{5}$$

$$\Phi_{B1} = f'(1) \tag{6}$$

$$g'(\frac{I}{I_b}) = k\ f'(\frac{B}{B_b}) \tag{7}$$

Where Φ_{I1} and Φ_{B1} are the calculative magnetic fields produced by winding current and by PM using small signal.

From Fig. 7, the field produced by B is given by:

$$\Phi_B = \Phi_{B1} + \Delta\Phi_B \tag{8}$$

and

$$\Phi_B = g(1) + f(1) - \Phi_{I1} - \Delta\Phi_I \tag{9}$$

Where Φ_B is the field produced by PM on load, $\Delta\Phi_I$ and $\Delta\Phi_B$ are the correct value.

By consideration of the expressions in (5), (6) and (7), the relation of $\Delta\Phi_{I1}$ and $\Delta\Phi_{B1}$ may be obtained by:

$$\Delta\Phi_{I1} = g(1) - g'(1) = k\ [f(1) - f'(1)] = k\ \Delta\Phi_{B1} \tag{10}$$

Hence the field produced by PM can be deduced from (8), (9) and (10) as:

$$\Phi_B = \frac{g(1) + f(1) - \Phi_{I1} + k\Phi_{B1}}{k+1} \tag{11}$$

In equation (11), $g(1)+f(1)$ can be got by finite element analyze, Φ_{I1} and Φ_{B1} can be calculated using small signal. According to equation (5), (6) and (7), k is obtained as:

$$k = \frac{\Phi_{I1}}{\Phi_{B1}} \tag{12}$$

In above equation, when Φ_{B1} is going to zero, the significant error will come forth. To reduce the error, the open circuit and armature reaction field can be used to replace $f(1)$ and $g(1)$. So k is given by:

$$k = \frac{g(1)}{f(1)} \approx \frac{B_{armature}}{B_{open}} \quad (B_{open} \quad 0) \tag{13}$$

$$\Phi_B = \Phi_{B1} \qquad (B_{open} = 0) \tag{14}$$

IV. CALCULATION RESULT

The method using small signal is applicable to other discretional PM motors. In this paper, a 10-pole / 9-slot PMAC servo motor is calculated. The calculation model is shown in Fig. 2. The parameter of the motor is listed in Tab.1.

Tab. 1. 10-pole / 9-slot PMAC servo motor

Rated power	400 *W*	Pole	10
Rated speed	3000 *r/min*	Slot	9
Outer dia.	80 *mm*	Type of PM	N35SH

The field produced by PM is calculated using small signal under specified load condition, and the winding current i is 0, I_N and $3I_N$ (I_N is rated current) respectively. The result is shown in Fig. 8. The fundamental of the result is shown in Fig. 9.

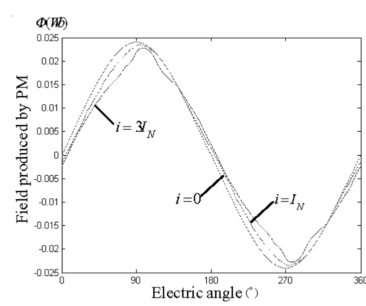

Fig.8. Field produced by PM under specified load condition

From Fig. 9, it can be seen that with the currents increase, the fundamental magnitude of the tooth's flux, which is produced by the PM, decreases gradually as well as some phase excursion. Those are caused by the armature effect. So the output torque coefficient will be decreased. When the winging current is changed from I_N to $3I_N$, the calculative output torque coefficient using small signal has been reduced 8.3%, and the result using electromagnetism simulation is 11.6%. But, assuming linear permeability of the stator and rotor iron, the change of output torque coefficient is zero.

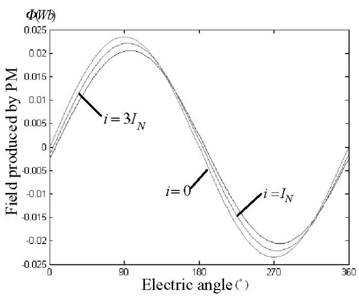

Fig. 9. Fundamental of the field produced by PM under specified load conduction

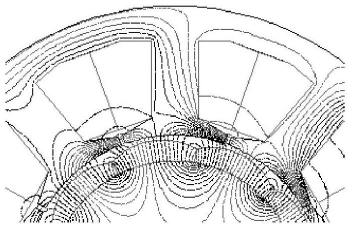

Fig. 10. Distribution plot of magnetic density around tooth area with load

Fig. 10 shows the distribution plot of magnetic density in tooth with load. Fig. 10 shows a serious saturation of the right side of tooth, while the left side of tooth is still in the linear range of magnetization curve. This conclusion is also suitable to all the teeth of the motor. It is the partial situation of the motor that causes the phase excursion. To increase the power output, encoder must be install with a little offset.

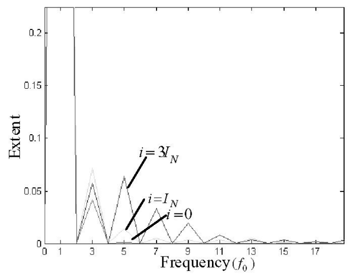

Fig. 11. Amplitude frequency response characteristics of PM flux

Fig.11 is the amplitude frequency response characteristics of PM flux. It shows that with the increase of current, 5th and 7th order harmonic increase obviously, and these will lead to a larger ripple of the electromagnetic torque, which will introduce vibration and noise. But, the result that is calculated using small signal can't be used to quantitative analysis torque ripple.

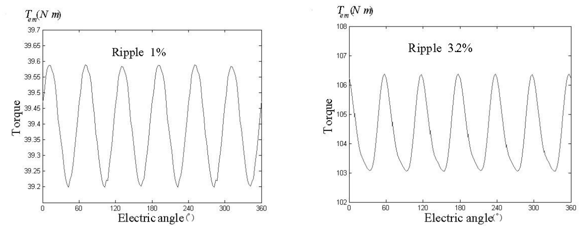

Fig. 12. Simulation result of torque ripple.
(a) $i = I_N$. (b) $i = 3I_N$.

Fig.12 gives the simulation result of torque ripple. It mainly consists 6th order ripple which is mainly produced by 5th and 7th order harmonic. So measures must be taken to retain such ripple especially for the servo system. Then, 5th or 7th order harmonic current can be infused to reduce 6th order ripple.

V. CONCLUSION

A method has been developed for separating the field produced by PM and winding current under any specified load condition. Results shows that, with the increase of currents, fundamental magnitude of the tooth's flux, which is produced by the PM, decreases gradually, as well as some phase excursion. Simulation results proved the analysis. This method is applicable to other PM motors.

REFERENCES

[1] A.K. Wallace, R. Spee, and L. G. Martin, "Current harmonics and acoustic noise in AC adjustable-speed drives," IEEE Trans. Industrial Apple., vol. 26, pp. 267-273, 1990.

[2] N. Boules, "Prediction of no -load flux density distribution in permanent magnet machines," IEEE Trans. Industri al Appl., vol. IA-21, pp. 633-643, 1985.

[3] Z. Q. Zhu, D. Howe, E. Bolte, "Instantaneous magnetic filed distribution in brushless permanent magnet dc motors, part IV: Magnetic field on load," IEEE Trans. Magn., vol. 29, no. 1, pp. 152-158, 1993.

[4] Z. Q. Zhu, D. Howe, E. Bolte, "Instantaneous magnetic filed distribution in brushless permanent magnet dc motors, part : Open-circuit field," IEEE Trans. Magn., vol. 29, no. 1, pp. 124-135, 1993.

[5] Z. Q. Zhu, D. Howe, E. Bolte, "Instantaneous magnetic filed distribution in brushless permanent magnet dc motors, part II: Armature-reaction field," IEEE Trans. Magn., vol. 29, no. 1, pp. 136-142, 1993.

[6] Z. Q. Zhu, D. Howe, E. Bolte, "Instantaneous magnetic filed distribution in brushless permanent magnet dc motors, part III: Effect of stator slotting," IEEE Trans. Magn., vol. 29, no. 1, pp. 143-151, 1993.

[7] U. Kim and D.K.lieu, "Magnetic field calculation in permanent magnet motors with rotor eccentricity: Without slotting effect," this issue, pp. 2243 -2252, 1998.

[8] U. Kim and D.K.lieu, "Magnetic field calculation in permanent magnet motors with rotor eccentricity: With slotting effect considered," this issue, pp. 2243 -2252, 1998.