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A New Method for Estimating Permanent Magnet Synchronous Machine Parameters

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ABSTRACT

This paper presents a new method for estimating equivalent circuit parameters of a permanent magnet synchronous machine. Previous methods for finding equivalent circuit parameters are based on magnetostatic finite element analysis. Magnetostatic finite element analysis doesn't consider operation frequency. At higher frequencies machine parameters might vary due to skin effect contribution. The new method is based on transient finite element analysis. Therefore it can take operation frequency into account. The new method needs four finite element transient analysis; one no load analysis and three loading analysis. Test results are gathered in a set of three non-linear equations. By solving this set of three equations, equivalent circuit parameters of the permanent magnet synchronous machine will be found. A typical solid rotor permanent magnet machine is chosen for case study. It is shown the proposed method is simple and accurate.

KEYWORDS: Equivalent circuit parameters, Finite element method, Permanent Magnet Machine, Transient.

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1. INTRODUCTION

Using permanent magnet (PM) excitation in electric machinery has some advantages over electrical excitation. Main advantages are augmentation in efficiency and reduction in machine volume [1]-[4]. Therefore permanent magnet synchronous machines (PMSMs) are being popular and widely used. For good exploitation of a PMSM, it is necessary to know its equivalent circuit parameters accurately.

A few works have been done on obtaining equivalent circuit parameters of PMSMs [5]-[8]. All of that works are relatively complicate, and can't operation frequency into account. Although inductance/resistance calculation methods ignoring frequency effects are valid at low frequencies, the frequency enhancement leads to inductance/resistance increase which consequently leads to differences between theoretical and experimental results. Therefore it is crucial to have realistic and validated models that could take the frequency into account.

This paper presents a new easy, but accurate method for parameters identification of a PMSM. The new method uses transient finite element analysis (FEA), so it can consider effects of operation frequency in calculation of equivalent circuit parameters. The new method needs four transient FEA; one no load analysis and three loading analysis. Test results are gathered in a set of three non-linear equations. By solving this set of three equations, equivalent circuit parameters of the PMSM will be found.

In this paper first, the basis of the new method is described. Based on equivalent circuit of a PMSM and its phasor diagram, an equation is derived. By using this equation and four transient FEA results, it is possible to find PMSM equivalent circuit parameters. FEA include one no-load analysis and three load analysis. A typical solid rotor PMSM is chosen for case study. Performance characteristics of the machine are computed by obtained equivalent circuit parameters.

The proposed method is easy to implement and can take operation frequency into account, because it uses transient FEA results.

2. Equivalent Circuit of a Three Phase PMSM

Fig. 1 shows per phase equivalent circuit of a three phase PMSM in generator mode.

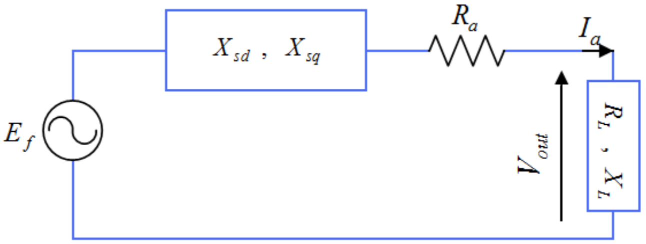

Fig.1. Per phase equivalent circuit of a PMSM in generator mode.

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In Fig. 1, X_{sd} and X_{sq} are d- and q-axis components of synchronous reactance, respectively. I_a , V_{out}, R_L, and X_L are the one phase current of the armature winding, per phase output voltage of the machine, load resistance connected to one phase of the armature winding, and load reactance connected to one phase of the armature winding, respectively. The induced electromotive force of the armature winding due to the fundamental flux linkage of PMs in the air-gap is depicted by E_f.
The phasor diagram of Fig. 1 is shown in Fig. 2. I_{ad} and I_{aq} are the projections of the armature current I_a on the d- and q-axes, respectively.

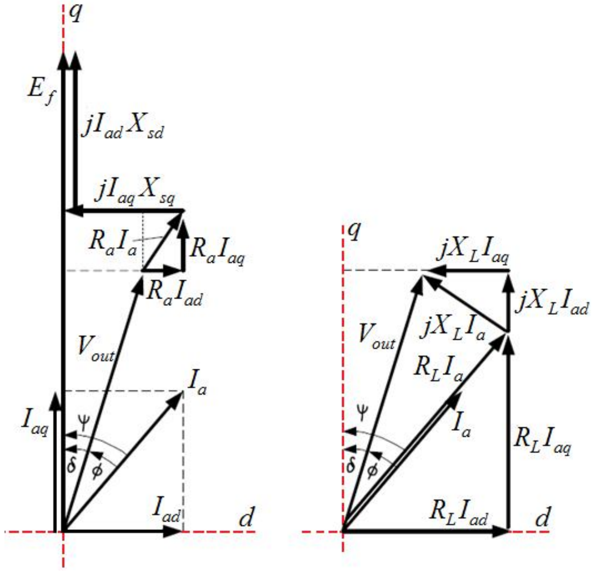


Fig.2. Phasor diagram of one phase of the PMSM in the generator mode loaded with RL load.

The associated output voltage projections on the d- and q-axes are [9]-[10]

$$\begin{aligned} V_{out}\sin\delta &= I_{aq}X_{sq} - R_a I_{ad} \\ V_{out}\cos\delta &= E_f - I_{ad}X_{sd} - I_{aq}R_a \end{aligned} \tag{1}$$

and

$$\begin{aligned} V_{out}\sin\delta &= I_{ad}R_L - I_{aq}X_L \\ V_{out}\cos\delta &= I_{aq}R_L + I_{ad}X_L \end{aligned} \tag{2}$$

where the load angle δ is the angle between the output voltage V_{out} and EMF E_f. Combining (1) and (2), the d- and q-axes currents, independent of the load angle δ, are determined by

$$I_{ad} = \frac{E_f\left(X_{sq}+X_L\right)}{\left(R_L+R_a\right)^2+\left(X_L+X_{sd}\right)\left(X_{sq}+X_L\right)} \tag{3}$$

$$I_{aq} = \frac{E_f\left(R_L+R_a\right)}{\left(R_L+R_a\right)^2+\left(X_L+X_{sd}\right)\left(X_{sq}+X_L\right)} \tag{4}$$

The per phase output electrical power of the PMSM is

$$P_{out} = E_f I_{aq} - I_{ad}I_{aq}\left(X_{sd}-X_{sq}\right) - R_a I_a^2 \tag{5}$$

The internal electromagnetic power of the PMSM, P_{elm}, is sum of the stator winding losses, defined by $\Delta P_{lw} = 3R_aI_a^2$, and stator core losses, defined by ΔP_{lFe}, and output power, $3P_{out}$.

$$\begin{aligned} P_{elm} &= 3P_{out} + \Delta P_{lw} + \Delta P_{lFe} \\ &= 3\left[E_f I_{aq} - I_{ad}I_{aq}\left(X_{sd}-X_{sq}\right)\right] + \Delta P_{lFe} \end{aligned} \tag{6}$$

Stator core losses can be calculated if the amplitude and the frequency of time varying magnetic flux in the stator cores are known. Efficiency is defined as

$$\eta = \frac{3P_{out}}{P_{elm} + \Delta P_{rot} + \Delta P_{str}} \tag{7}$$

where ΔP_{rot} and ΔP_{str} are rotational losses and stray losses, respectively.
Combing (3) and (4) with considering following relation

$$I_a^2 = I_{ad}^2 + I_{aq}^2 \tag{8}$$

gives

$$I_a^2 \left[\left(R_L + R_a\right)^2 + X_{sd}\, X_{sq} \right]^2 = E_f^2 \left[X_{sq}^2 + \left(R_L + R_a\right)^2 \right] \quad (9)$$

For obtaining (9) it is assumed X_L=0. Using (9) and four test results on the PMSM, equivalent circuit parameters of the PMSM are determined.

3. Case Study

A typical solid rotor PMSM is chosen for case study. Fig. 3 shows 2D view of the solid rotor PMSM.

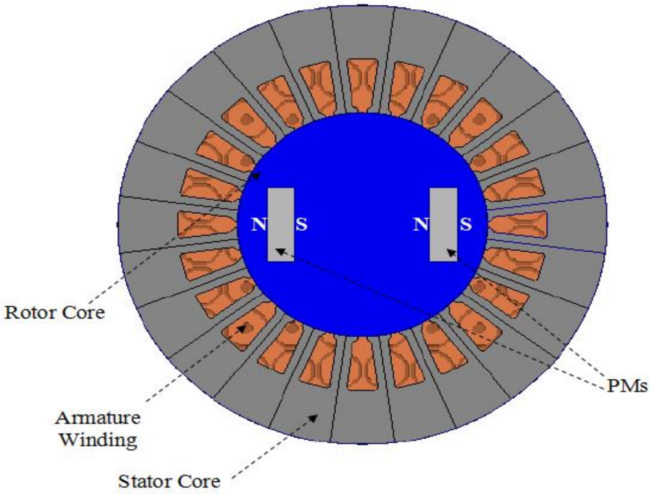
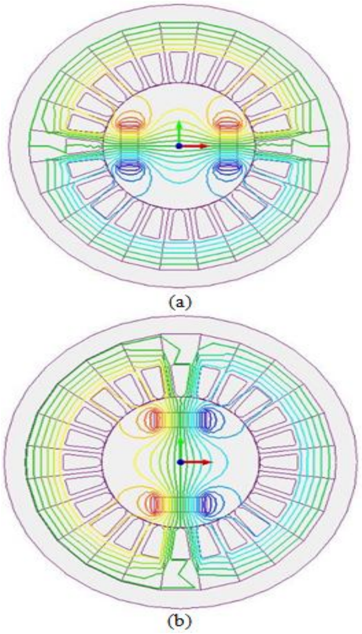


Fig.3. 2D view of the solid rotor PMSM.

The stator core is fabricated by laminated steel sheets. PMs are rare earth NdFeB magnets, and the directions of PMs are shown in Fig. 3. Armature winding is a three phase, two pole winding.

Here, the rotor is rotated with the fixed speed 3000 rpm. The rotation of the rotor causes magnetic fluxes change in the stator core and voltage induction in the armature windings. Induced voltages and currents are oscillating with the time. The proposed method for identification of PMSM equivalent circuit parameters needs four separate 2D transient FEA. One 2D transient FEA with high impedance load to determination of E_f, and three other 2D transient FEA with arbitrary finite impedance loads to determination of the corresponding I_a. All transient (time-stepping) analyses must be continued until the output voltages, V_{out}, and load currents, I_a, reach to their steady state values.

Fig. 4 shows flux lines in no load analysis at t=0 second and t=0.005 second. Fig. 5 shows flux lines with load R_L=10Ω and X_L=0Ω, at t=0 second and t=0.005 second. Effect of load current is shown in Fig. 5(b).


(a)

(b)

Fig.4. Flux lines in no load transient finite element analysis at (a) t=0 second, and (b) t=0.005 second.

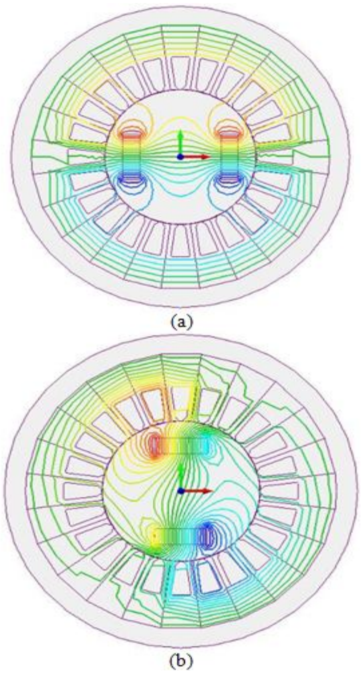


Fig.5. Flux lines in load analysis with R_L=10Ω at (a) t=0 second, and (b) t=0.005 second.

Fig. 6 illustrates waveform of steady state E_f obtained by using a 2D transient FEA. Fourier analysis on Fig. 6 at steady state gives: peak of fundamental component =83.5 V, and THD=29.5%.

Steady state load currents for R_L=5, 8 and 10 ohm are shown in Fig. 7. Because of rectangular shape of PMs, output waveforms contain harmonics. Fourier analysis results on Fig. 7 waveforms are given in Table I.

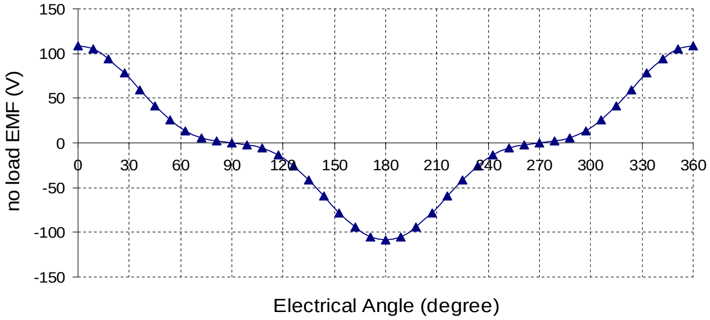


Fig.6. Waveforms of steady state E_f obtained by using 2D transient FEA.

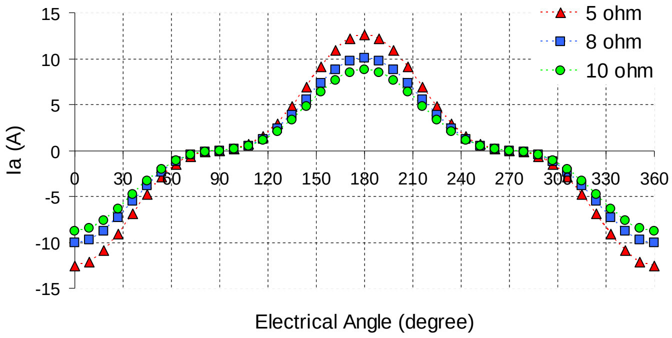


Fig.7. Steady state load current waveforms for three resistive loads obtained by using 2D transient FEA.

TABLE I
Fourier Analysis Results on Load Current Waveforms

R_L (Ω)	**Fundamental of I_a (A)**	**THD (%)**
5	9.6894	29.5
8	7.7679	29.5
10	6.749	29.5

Now, identification of the equivalent circuit parameters of the TFPMDG with the aid of 2D transient FEA results is explained. Putting results of Table I into (9), it leads to the following non-linear systems of three equations in the three unknowns R_a, X_{sd} and X_{sq}

$$\begin{cases} \left(\frac{9.6894}{\sqrt{2}}\right)^2 \left[(5+R_a)^2 + X_{sd}X_{sq}\right]^2 = \left(\frac{83.5}{\sqrt{2}}\right)^2 \left[X_{sq}^2 + (5+R_a)^2\right] \\ \left(\frac{7.7679}{\sqrt{2}}\right)^2 \left[(8+R_a)^2 + X_{sd}X_{sq}\right]^2 = \left(\frac{83.5}{\sqrt{2}}\right)^2 \left[X_{sq}^2 + (8+R_a)^2\right] \\ \left(\frac{6.749}{\sqrt{2}}\right)^2 \left[(10+R_a)^2 + X_{sd}X_{sq}\right]^2 = \left(\frac{83.5}{\sqrt{2}}\right)^2 \left[X_{sq}^2 + (10+R_a)^2\right] \end{cases} \tag{10}$$

Solving (10) is done by using a computer program based on Gauss-Newton method [11]. Results of proposed method for generator equivalent circuit parameters identification are given in Table II.
Note that in (10) R_a is assumed unknown, because of skin effect due to AC current should be considered.

TABLE II
Equivalent Circuit Parameters of The Solid Rotor PMSM Obtained by Using The New Method

E_f (V)	59.0434
X_{sd} (Ω)	6.7316
X_{sq} (Ω)	6.7163
R_a (Ω)	0.3805

By using Table II results and presented relations in section II, it is possible to calculate machine characteristics. Fig. 8 shows the variation of output voltage versus load current. Fig. 9 illustrates the output power versus load current. In Fig. 10, the variation of efficiency versus load current is depicted.

Because the proposed method uses transient FEA results, so the proposed method can consider frequency effects in estimation of PMSM parameters. In previous works effects of frequency just considered in armature resistance by using an approximate coefficient [5]-[8].

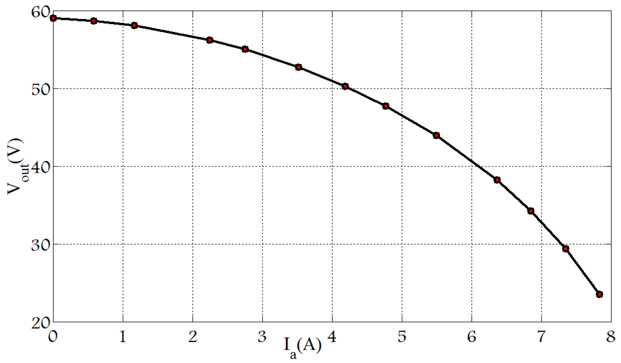


Fig.8. Variation of output voltage versus load current.

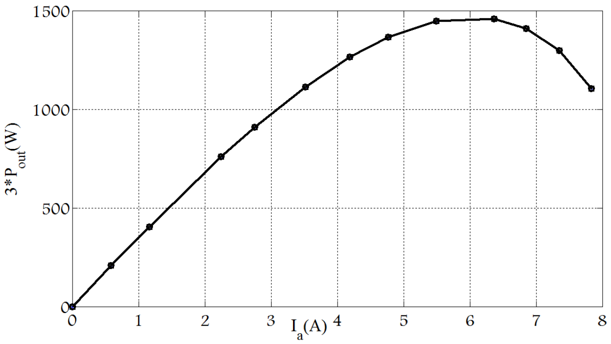


Fig.9. Variation of three phase output power versus load current.

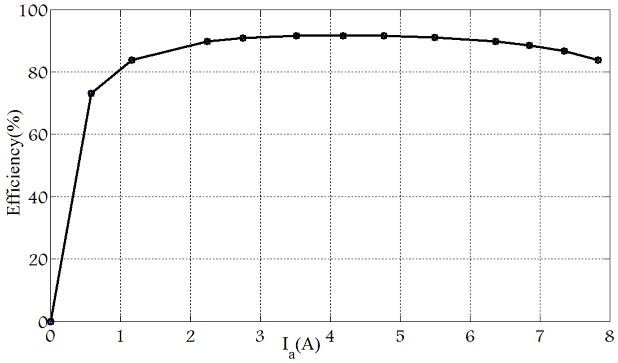


Fig.10. Variation of efficiency versus load current.

4. Conclusion

This paper presented a new method in modeling PMSM with high precision. The new method needs four simple tests in generator mode. A typical solid rotor PMSM is chosen as a case study. Four tests were done by 2D transient FEA, and equivalent circuit parameters of the solid rotor PMSM were found. One benefit of the new method is its capability for modeling of PMSM in any arbitrary frequency. Note that previous methods for modeling of PMSM don’t consider effects of frequency in PMSM modeling. The new method can be used for equivalent circuit parameters identification for any type of synchronous machines by taking operation frequency into account.

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