The Analytical Analysis of the Rotor Losses in the PMSM Motors

Amin Hassan Zarei, Karim Abbaszadeh, and Kiarash Safari

Abstract— **In the permanent magnet machines (PMSM), the rotor losses overheat the electrical machines, decreasing the rated torque and the total efficiency. It causes a severe demagnetization of the magnets too. The purpose of this paper is to carry out an analytical investigation of the rotor losses in the PMSM. Firstly, the losses in the case of the sinusoidal magnetic field are obtained. Then, it is expanded to the calculation of the losses in the case of the non-sinusoidal magnetic field. Finally, by analyzing the flux density in the yoke of the rotor and comparing it with the previous results, three main parameters which have the most effect on the losses are determined in an analytical way.**

Keywords-Permanent Magnetic Machines, Rotor Losses, Demagnetization, Sinusoidal Magnetic Field, Non-Sinusoidal Magnetic Field, Flux Density

I.INTRODUCTION

Nowadays, the use of high efficiency electrical machines is growing dramatically due to their unique qualities, such as their ability in the energy saving and the protection of environment. The role of the rotor losses in the high-speed electrical machines must be studied with a great attention. Specifically, in the permanent magnet machines (PMSM), the rotor losses overheat the electrical machine, decreasing the rated torque and the total efficiency.

Although, the amount of the rotor loss is usually lower in comparison to the other types of losses, due to the weak transformation of the heat by the rotor, the demagnetization of the permanent can emerge in an obvious way. Furthermore, such losses are increased exponentially by the speed of the rotor which can have an immense effect on determining the maximum speed of a machine, during the process of designing its mechanical structure. By calculating the rotor losses of a PMSM, constructive measures can be taken to modify the motor with lower losses. In this thesis, an analytical approach is used to evaluate the rotor losses in one interior-type permanent-magnet (IPM) machine which is illustrated in Figure 1.

On the other hand, the core losses in a magnetic material emerge when the material is subjected to a time varying magnetic flux density. The core losses can be classified into to different mechanisms: the hysteresis loss and the eddy current loss. The hysteresis loss is because of the energy dissipated in the redirection of the magnetic domains of the material during every flux direction reversal. The eddy current is the circulating current produced in the material by changing the magnetic flux due to the electromagnetic induction. [1] Both hysteresis effect and eddy currents result in the core losses. Therefore, the observation of the variation of the flux density is vital for our research. It is tried in this thesis to analyze the rotor losses from the harmonic point of view. In other words, it is investigated to find the effect of the harmonic contents on the distribution of the rotor losses. In addition, the ways of reducing these losses can be later obtained by studying this research.

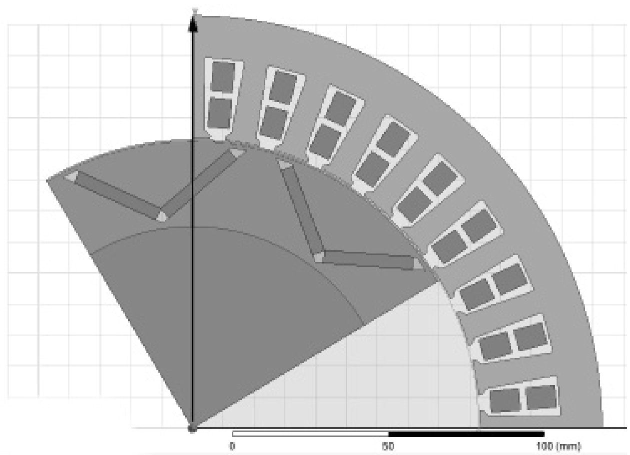

Fig 1. The quarter of the IPM machine

This paper received in July 15,2012,revised in August 8,2012.This work was supported by Department of Electrical Engineering of K.N.T University of Technology in Tehran.
Amin Hassan Zarei has now received some PHD positions in the field of the design of electrical machinery from some German Universities. (Email: amin.zareie@yahoo.com)
Karim Abbaszadeh is an associate Prof. of K.N.Toosi University of Technology. (Email: Abbaszadeh@eetd.kntu.ac.ir)
Kiarash Safari is going to continue his studies for M.sc in design of electrical machinery in Tehran (Email: kiarash.safari@gmail.com)

IPM motors are usually recognized as those motors with minor rotor losses. Because, the rotor is synchronized with the main harmonic component of the air-gap but, due to the presence of the unsynchronized harmonics of the field, losses are produced in the iron and the permanent magnet of the rotor [1 2].On the other hand, although the rotor losses are relatively lower in comparison to the other parts of the motor, they can cause the demagnetization of the permanent magnet because of the weak transformation of the heat in the rotor.
The phenomena which have the main effects on the losses are listed below:
1. The changing of the reluctances in the air-gap because of the slots of the stator [3].
2. The space harmonics produced by the winding of stator [4]
3. The time harmonics produced by the voltage or current source [5]
4. The geometrical shape of rotor (include magnet and bridges).

This paper is organized into 5 sections. Section II calculates the rotor losses of this IPM machine in the case of the sinusoidal and non-sinusoidal magnetic field. Section III focuses on the analysis of the MMF of the stator. Section IV obtains the flux density in the yoke of the rotor and by doing so the major parameters which have an immense effect on the rotor losses are determined. Finally, major paper conclusions are summarized in section V.

II.CALCULATION OF THE ROTOR LOSSES

A Losses in the case of the sinusoidal magnetic field

In the case sinusoidal magnetic field, the general rotor losses are classified into the excess losses and eddy current losses. Its equations are listed in the following page

$$P_{total-sin} = P_{h_{sin}} - P_{eddy_{sin}} = k_h f^a B^a + k_e f^2 B^2 \qquad (1)$$

Where f is the frequency and B is the maximum flux density and a, b the k_h , k_e, are the coefficients of the lamination. The coefficient of eddy current is also calculated in this way:

$$k_e = \frac{k^2 d^2}{6p} \qquad (2)$$

Where ρ and d represent the thickness and the special resistance of the lamination respectively.

Generally, the producers of lamination publish some losses curves in the different equations which can be used in order to obtain the coefficients of the equation of 1.These equations are obtained indirectly from one standard test which is called Epstein. By considering the sinusoidal changing of the magnetic field, some actual effects are ignored which are listed below:

1. Minor loops in the hysteresis losses.[7]
2. Effective dc values in the hysteresis losses[8]
3. The time harmonics in the eddy current

B Losses in the case of the non-sinusoidal field

In this case, the hystersis losses by considering the effect of minor loops are calculated in this way: [9]

$$P_h = P_{h_{sin}} \left(1 + \frac{k}{B} \sum_{i=1}^{N} \Delta B_i \right) \qquad (3)$$

Where N is the numbers of the minor loop and k is a coefficient between 0.6 and 0.7.

Clearly, the present fluxes in the rotor of the PM motors have an average dc value. The changing of fluxes is around this dc value and it can not be ignored. In order to get the correct results, this dc value must be brought in the equations.

Owing to this physical fact that the eddy current losses are proportional to the mean square of the time changing of the flux density, the equation 4-1 can be used in the form of equation of 4-4, in order to consider the effect of all harmonics.

$$P_{eddy} = \frac{k_e}{2\pi^2} MeanSquare\left(\frac{dB}{dt}\right) = k_e f^2 \sum_{h \geq 1} |hB_h|^2 \qquad (4)$$

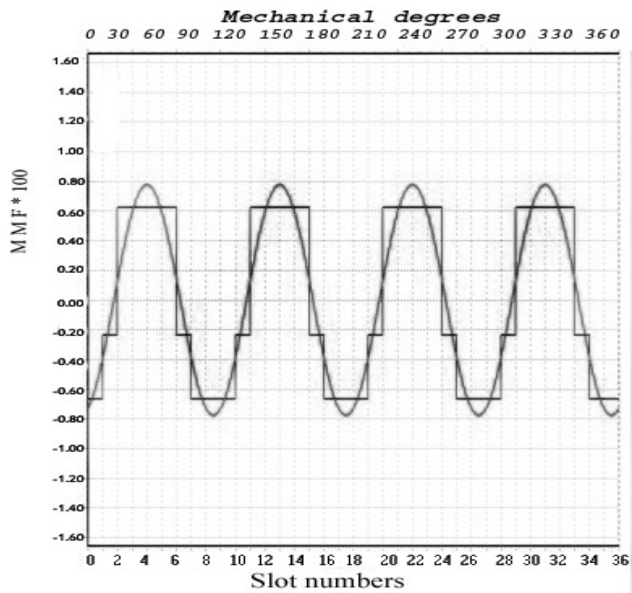

Figure 2 MMF Produced by the PMSM

ISBN: 978-988-19252-4-4
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

where B_h is the amplitude of h^{th} of flux density harmonics. It is obvious that in the above equation Peddy is equal with Peddy_sin by assuming a perfect sinusoidal magnetic field. It is noticeable that the eddy current losses are not related to the minor loop and the value of dc of magnetic field. In addition, in order to calculate the hysteresis and eddy current losses from above equations, the exact value of magnetic flux density in the rotor must also be determined. This field can be obtained from analytical or FE methods.

By increasing the speed and of motor and therefore the improvement of frequency, the value of eddy current losses will become more than the hysteresis losses. Hence, in the following section, the analysis of eddy current losses is investigated in a detailed way.

III.STATOR MMF SLOT HARMONICS

Generally, there is a low value of losses in the case of no open circuit in the stator. Hence, the effect of harmonics which are produced by changing the reluctance of the air-gap can be ignored. In addition, by assuming a sinusoidal power supply ,the MMF of stator which is observed from the rotor frame can be obtained in this way:[9]

$$f_s(\alpha,\omega,t)=\sum_{\substack{h=2,5,8,\ldots\geq(h+1)\\ h=1,4,7,\ldots\geq(h-1)}} f_{s,h}\cos(h\alpha+(h\pm1)\,\omega_c t\pm\gamma_d) \tag{5}$$

α is the space angle in the frame of rotor which is calculated from the d-axis. Where ω_e is the angular speed in the unit of elec.rad/sec and $\omega_e t$ is the instant position of rotor. It is noticeable that this equation has been obtained from reference 9 indirectly, because in this reference, this equation has been determined from the stator reference frame .In order to transfer this frame to the rotor reference frame the term of (h±1) has also been added. γ_d is the phase of the current stator in relation to d-axis. $f_{s,h}$ also represents the harmonic order of MMF in the stator. It is blatant that the harmonics of the 3^{rd}-multiple are not present in the equation of 5.

Furthermore, if the whole current of stator is put in d-axis ,in order to neutralize the flux of the permanent magnet, then the losses will be almost representative of the winding losses. In the ideal condition, $\gamma_d=\pi$ (the opposite direction of d-axis) will be obtained. Hence, the equation of 5 will be shortened in the form of equation 6:

$$f_s(\alpha,\omega,t)= f_{s,1}\cos(\alpha)+ \sum_{\substack{h=2,5,8,\ldots\geq(h+1)\\ h=1,4,7,\ldots\geq(h-1)}} f_{s,h}\cos(h\alpha+(h\pm1)\,\omega_c t) \tag{6}$$

The MMF (Magneto motive force) produced by the winding and the harmonic distribution of the winding for the first phase are also obtained by Maxwell Software which are shown in figure 2. In this figure, the MMF of the winding is drawn based on the mechanical harmonics. Hence, the 4th harmonic is equal to the 1st electrical harmonic.

The MMF of the stator can be used as the sum of the amper turns of stator which are calculated in the frame of the rotor. As a result, the value of space differential (df_s) of the MMF of the stator similar to the amper turns in the internal space of stator is calculated with this equation below:

$$\frac{df_s(\alpha,\omega,t)}{d\alpha}= f_{s,1}\sin(\alpha)+ \sum_{\substack{h=2,5,8,\ldots\geq(h+1)\\ h=1,4,7,\ldots\geq(h-1)}} f_{s,h}\,h\sin(h\alpha+(h\pm1)\,\omega_c t) \tag{7}$$

Some points must be added too:[9]

1-The harmonic differential of MMF($h_{s,h}$) must be multiplied with its own harmonic.

2-Obviously, the effects of some harmonics are multiplied with the coefficient of h, in order to make the amplitude of these harmonics equal with the major components.

3-The order of harmonics of slot stators is obtained in this way:

$$h= k.n_s\pm1 \tag{8}$$

Where k is equal to all the natural numbers and n s represents the numbers of stator slots over the couple pole which is $n_s = 9$ for this motor. The slot pitch of stator α_s is related to n_s according to the equation below:

$$\alpha_s\equiv2\pi/n_s \tag{9}$$

By considering equation 7, it is resulted that the orders of slot stator harmonics are k.n s ±1, but the time harmonics are k.n s.

IV. CALCULATION OF FLUX DENSITY IN THE YOKE OF ROTOR

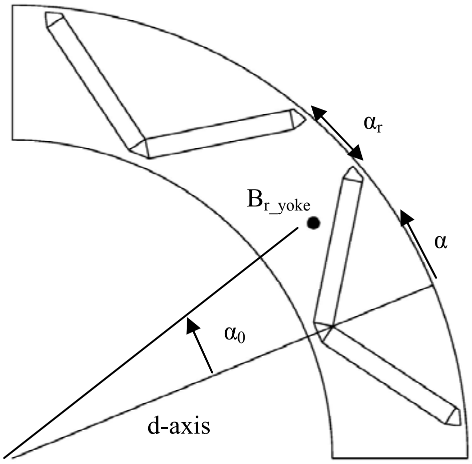

Fig 3 The Yoke of Rotor

In this section, the flux density is calculated in the point which is shown in figure 3.It is obvious that this point is put in the yoke of rotor in the phase of a 0 on the d-axis. Hence equation 10 can be calculated in this way:

$$B_{r-yoke}\Big|_{\alpha=\alpha_0} \sim \frac{1}{\alpha_r}\int_{\alpha_0-\alpha_r/2}^{\alpha_0+\alpha_r/2} f_s(\alpha,w,t)\,d\alpha \qquad (10)$$

Similar to the stator, the pitch of rotor n r can be shown in equation

$$n_r \equiv 2\pi/\alpha_r \qquad (11)$$

By replacing equation 4-6 in equation 4-10 , the time changing of flux density B r_yoke is obtained and by considering this fact that the low orders of harmonic components of slot stator have the most effect, this approximate equation can be obtained below:

$$\frac{\partial B_{r-yoke}}{\partial(\omega_e t)}\Big|_{\alpha=\alpha_0} \sim \sum_{h=n_s}(n_s) f_{s,h}\frac{[\cos(h\alpha+(h\pm1)w_c t]_{\alpha_0-\alpha_r/2}^{\alpha_0+\alpha_r/2}}{h\alpha_r} \qquad (12)$$

By considering this fact that the low orders of harmonic components of slot stator have the most effect, this approximate equation can be obtained below:

$$\frac{\partial B_{r-yoke}}{\partial(\omega_e t)}\Big|_{\alpha=\alpha_0} \sim \sum_{h=n_s}(n_s) f_{s,h}\frac{[\cos(h\alpha+(h\pm1)\omega_c t]_{\alpha_0-\frac{\alpha_r}{2}}^{\alpha_0+\frac{\alpha_r}{2}}}{h\alpha_r} \qquad (13)$$

This equation can be obtained based on the previous researches.[9]

$$|n_s f_{s,h}|_{h=n_s\pm1} \cong |f_{s,1}| \qquad (14)$$

The equation (15) can also be obtained by using equations 13 and 14:

$$\left|\frac{\partial B_{r-yoke}}{\partial \omega_e t}\right|_{\alpha=\alpha_0} \propto \sum_{h=n_s\pm1}\left|\frac{f_{s,1}}{h\alpha_r}\right| \propto \left|f_{s,1}\frac{\alpha_s}{\alpha_r}\right| \propto \left|f_{s,1}\right| \qquad (15)$$

Finally, by considering equation 4, the density of eddy current losses can be related to the mean square of time changing of B r_yoke and therefore equation 16 can be resulted:

$$P_{eddy}\left(B_{ry}\big|_{\alpha=\alpha_0}\right) \propto \left|\frac{\partial B_{r\_yoke}}{\partial \omega_e t}\right|^2_{\alpha=\alpha_0} \propto \left|f_{s,1}\frac{\alpha_s}{\alpha_r}\right|^2 \propto \left|f_{s,1}\frac{n_r}{n_s}\right|^2 \qquad (16)$$

Equation 16 reveals how 3 main parameters have the most influence on the core of the IPM motor which are explained below:

1-The amplitude of the major component of MMF in stator ($f_{s,1}$)

2-The pitch of slot stator (α_s)

3-The pitch of rotor (α_r)

V. CONCLUSION

To sum up, by increasing the speed of the motor, the value of the eddy current losses becomes higher than the hysteresis losses. Hence, the analysis of the eddy current losses was considered. Due to this fact that the eddy current losses are proportional to the mean square of the time changing of the flux density, the equation of the eddy current was obtained. Finally, by gaining different equations, the equation 16 is

ISBN: 978-988-19252-4-4
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

achieved which shows how 3 main parameters have the most influence on the core of the IPM motor.

It is suggested to continue the expansion of the rotor losses equations by considering the effects of the harmonics generated by the windings and by analyzing the time harmonics and the slotting effect.

REFERENCES

[1] Zhu, Z.Q.; Ng, K.; Schofield, N.; Howe, D.; Improved analytical modeling rotor eddy current loss in brushless machines equipped with surface- mounted permanent magnets, Dept. of Electronic & ElectricalEng., Univ. of Sheffield, UK (IEEE Publication)

[2] Shah, M.R.; Sang Bin Lee; Rapid analytical optimization of eddy current shield thickness for associated loss minimization in electrical machines, Electrical. Machines & Drives Lab., GE Global Res. Center, Niskayuna, NY, USA (IEEE Publication)

[3] Han, S.-H.; Jahns, T.M.; Zhu, Z.Q.; Analysis of Rotor Core Eddy-Current Losses in Interior Permanent Magnet Synchronous Machines (IEEE Publication)

[4] Atallah, K.; Howe, D.; Mellor, P.H.; Stone, D.A.; Rotor loss in permanent-magnet brushless machines Dept. of Electron. & Electr. Eng., Sheffield Univ., UK (IEEE Publication)

[5] Fang Deng; Delphi Energy & Eng. Manage. Syst., Gen. Motors Corp., Flint, Commutation-caused eddy-current losses in permanent magnet brushless DC motors (IEEE Publication)

[6] Yamazaki, K.; Abe, A.; Loss analysis of Interior permanent magnet motors considering carrier harmonics and magnet eddy currents using 3-D FEM (IEEE Publication)

[7] Lavers, J.; Biringer, P.; Hollitscher, H.; A simple method of estimating the minor loop hysteresis loss in thin laminations (IEEE Publication).

[8] Brockmeyer, A.; Experimental evaluation of the influence of DC premagnetization the properties of power electronic ferrites (IEEE Publication)

[9] Thomas, S.-H.; Jahns, T.M.; Soong, W.L.; Torque ripple reduction in interior permanent magnet synchronous machines using the principle of mutual harmonics exclusion (IEEE Publication).

ISBN: 978-988-19252-4-4
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)