**Rotor Eddy Loss in High Speed Permanent Magnet Synchronous Generators**

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*Abstract*-- Analytical and transient finite element analysis (FEA) methods are used to calculate on-load rotor eddy current power loss in permanent magnet (PM) machine taking into account the effect of the reaction of eddy current. The effect of phase advance angle between the back EMF and the phase current on rotor eddy current power loss is investigated. Both magnet flux tooth ripple and MMF harmonics are considered in the analytical calculation of rotor loss; the harmonic due to magnet flux tooth ripple and armature reaction flux are added vectorially. Good agreement between analytical and FEA results is observed when the stator laminations are assumed to have a linear BH curve. But a significant discrepancy is observed between the analytical and FEA solutions when a non-linear BH curve is used.

*Index Terms*-- Permanent Magnet (PM) machine, Rotor Eddy Current Power Loss, phase advance.

# Introduction

Accurate calculation of rotor eddy current losses in high-speed PM synchronous machines can be critical, as these machines are highly stressed mechanically and thermally and a relatively small change in rotor loss of say 100 W in a 100 kW machine can make a difference when determining the feasibility or otherwise of a design variant.

Finite element analysis (FEA) software packages capable of solving transient models including rotation and external circuits are now widely available. With such advanced computational tools, it is now possible to accurately calculate rotor losses taking into account realistic features such as saturation, magnet segmentation and end effects (if a 3D solver is used). However, these solvers require very fine mesh and time step to get good accuracy, which means simulations can take a long time [[1](#_ENREF_1)].

Using analytical methods yields quicker results and they are therefore commonly used in the early design stages. These methods also help provide an insight into the sources of rotor losses. Most of the analytical techniques used to calculate rotor losses follow similar steps, i.e., 1) Estimate asynchronous flux harmonics in the rotor frame either analytically [[2](#_ENREF_2)], [[3](#_ENREF_3)], [[4](#_ENREF_4)] or from magnetostatic solutions [[5](#_ENREF_5)]; 2) use a multilayer rectilinear [[6](#_ENREF_6)], [[7](#_ENREF_7)], [[8](#_ENREF_8)], [[9](#_ENREF_9)], or cylindrical [[10](#_ENREF_10)] model of the machine to calculate eddy current losses due to each asynchronous flux harmonic. A current sheet on the surface of a slotless stator is used to represent each travelling harmonic and rotor losses are calculated by solving the diffusion equation. In many machines, these losses are assumed to be resistance limited, in which case the techniques developed in [[11](#_ENREF_11)], [[12](#_ENREF_12)], [[13](#_ENREF_13)] would give reasonably accurate results for machines with segmented insulated magnets. However, in high-speed machines with solid steel rotors, where the magnets’ widths are significantly larger than the wavelength of the main harmonics, the eddy currents are typically inductance limited, especially in the rotor steel [[4](#_ENREF_4)]. Therefore in these cases, the reaction of the eddy currents needs to be taken into account [[5](#_ENREF_5)], [[10](#_ENREF_10)],[[14](#_ENREF_14)].

In some machines magnet flux tooth ripple loss, losses caused by harmonics produced due to the modulation of the magnet’s flux by the stator teeth, are very small and they can be neglected [[4](#_ENREF_4)], [[15](#_ENREF_15)], [[16](#_ENREF_16)]. But in some high-speed machines, this loss can be significant. Several authors [[17](#_ENREF_17)], [[2](#_ENREF_2)], [[10](#_ENREF_10)], [[18](#_ENREF_18)], [[19](#_ENREF_19)], simply add both magnet flux tooth ripple harmonic losses and stator armature reaction flux harmonic losses, which is not correct. As the authors have shown in a previous paper [[5](#_ENREF_5)], the losses depend on the angle between the stator mmf and rotor fluxes, i.e., the angle between the phase current and emf. The magnet flux tooth ripple and armature reaction flux harmonics of the same order interact to increase or decrease depending on this angle. The correct procedure is therefore to calculate the resultant harmonics, by adding the magnet flux tooth ripple and armature reaction flux harmonics of the same order vectorially, and then calculate the losses caused by the resultant harmonics [[20](#_ENREF_20)].

This paper presents an analytical method for calculating rotor eddy current power loss in a high-speed PM machine taking into account effect of the reaction of eddy current. Both magnet flux tooth ripple and armature reaction flux harmonics are taken into account: the vector sum of the same time and space order harmonics is calculated. A comparison between rotor eddy current power losses calculated using superposition (direct addition of magnet flux tooth ripple and armature reaction harmonic) and vector addition is presented for various current advance angles. The results are validated using FEA for a particular machine.

# Machine under study

Fig. 1 shows a quarter radial cross-section of the 4 pole, 90,000 rpm permanent magnet synchronous generator (PMSG) under study. The surface mounted permanent magnets are arc-shaped and parallel magnetized. The rotor is made of solid steel for essential strength. A non-conducting sleeve with magnetic properties assumed to be similar to that of air is used to hold the magnets. The generator dimensions and properties of materials are shown in Table I.

TABLE I

Parameters of the PM machine under study.

|  |  |
| --- | --- |
| Parameters | 3-phase PMSG |
| Number of poles, 2*p* | 4  |
| Number of slots, *Qs* | 12 |
| Number of winding layers | 2 |
| Number of turns per coil, *Nc* | 2 |
| Number of parallel paths | 1 |
| Coil pitch to pole pitch ratio | 2/3 |
| pole-arc to pole-pitch ratio, *αp*  | 1 |
| Core length, *L* | 125 mm |
| Stator outer radius, *R*4  | 53.5 mm |
| Stator bore radius, *R*3  | 31 mm |
| Magnet outer radius, *R*2 | 27.1 mm |
| Rotor hub radius, *R*1 | 21.6 mm |
| Magnet thickness, *hm* | 5.5 mm |
| Stator back of core, *Rbc*  | 13.5 mm |
| Sleeve thickness, *tsleeve* | 2 mm |
| Tooth pitch, *t* | 8 mm  |
| Airgap, *g* | 1.9 mm |
| Tooth width,*w* | 3.25 mm |
| Slot opening, *b*0 | 4 mm |
| Tooth tip thickness, *ttip* | 1 mm |
| Rotor hub linear, *μr* | 750 |
| Rotor hub conductivity, *r*  | 6.7 × 106 S/m |
| Magnet conductivity,*m*  | 0.77 × 106 S/m |
| Magnet material | NdFeB |
| Magnet Remanence, *Br* | 1.12 |
| Magnet Coercivity, *Hc* | 781 kA/m  |



C`

C`

Yoke

B

B

C

B

A`

Tooth





B

A`

A`



C`

A

Sleeve

Magnet

Rotor

Air-Gap



Fig. 1. Quarter model of permanent magnet generator under study

# Travelling Flux Harmonics

In this section magnet flux tooth ripple harmonics in the airgap flux density are calculated using the methods in [[21](#_ENREF_21)], [[22](#_ENREF_22)] transformed into the rotor reference frame. The armature reaction (winding mmf) flux harmonics are calculated using the winding factors derived in [[23](#_ENREF_23)], [[24](#_ENREF_24)]. Each travelling harmonic, in the rotor frame, is represented by a current sheet on the surface of a slotless stator for the purpose of calculation of rotor eddy current power loss, as shown in Fig. 2 (see section IV for details).

1

1

,

**

**

Hub

2

,

2

**

**

Magnet

3

,

3

**

**

Airgap

4

4

,

**

**

Stator

Current sheet

Region (1)

Region (2)

Region (3)

Region (4)

Fig. 2. Cylindrical slotless model of a PM machine in which each flux harmonic is represented as an equivalent current sheet

1. *Armature Reaction Flux Harmonics*

In a machine that has a symmetrical three phase stator winding with *p* pole pairs, and the rotor moving synchronously with the stator fundamental rotating field, the MMF acting across the airgap at any point is equal to the total number of airgap conductors between that point and the nearest peak of the current density wave [[24](#_ENREF_24)]. The amplitude of the armature reaction flux harmonics with space order *q* and time order *k*, can be estimated using:

 (1)

where, is the number of turns per phase, is the peak amplitude of harmonic current and is the winding distribution factor [[23](#_ENREF_23)]. The relation between the amplitudes of the armature reaction flux harmonicsand its equivalent current sheet at the stator bore is given by:

 (2)

The equivalent current sheet for the armature reaction flux harmonic of an arbitrary space order *q* and time order *k* has the following distribution:

 (3)

where,is the line density of current in A/m, is the angular frequency equal to, *f* the fundamental frequency.

The airgap flux density due to the current sheet, in the absence of eddy currents, can be calculated using the Laplace equation as:

 (4)

Using the method of separation of variables, the general solution of (4) is given by:

 (5)

Substituting (5) in (4), it can be shown that:

 (6)

where,andare constants, to be determined using following two boundary conditions as:

  (7)

 (8)

For the permanent magnet machines the airgap flux density  and  in the airgap are coupled by:

 (9)

Therefore in terms of vector potential the tangential component of field quantities and can be derived as:

 (10)

  (11)

Similarly, the radial component of field quantitiesandare given by:

  (12)

  (13)

Hence by applying the boundary conditions in (7) and (8), the value of and in (6) can be derived as:

 (14)

 (15)

The final field solution can be obtained by substituting (14) and (15) into (6). From (6) the value of is substituted in (5). The value of vector potential from (5) is used in (10), (12) to calculate the tangential and radial airgap flux density as:

 (16)

 (17)

1. *Magnet flux Tooth Ripple Harmonics*

The approach used to calculate magnet flux tooth ripple harmonics is based on multiplying the flux density of a slotless machine, with a slotting permeance function.

 *B.1 Slotless Machine Airgap Flux*

The analytical field solution in the airgap of a slotless PM machine with an internal rotor, having parallel magnetized magnets has been presented in [[22](#_ENREF_22)]. Theand, viz. radial and tangential components of airgap flux distribution produced by the magnet flux only in a slotless PM machine are given by:

##  (18)

 (19)

where,,andfor an internal rotor machine with, can be written as:

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****

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The magnetization vector is given by:

 (20)

For parallel magnetized magnets,

 , 

For 

 , 

 

where *n, p*,,are defined as: an odd integer ; rotor pole pairs; angular position; permanent magnet remanent flux density; relative recoil permeability and pole-arc to pole-pitch ratio of the magnet, respectively.

*B.2 Permeance Function*

To cater for the effect of slotting in a PM machine, the method developed by Žarko *et al.*[[21](#_ENREF_21)], is used to calculate complex permeance function, with both realand imaginaryparts, as

 (21)

The function in [21] is then multiplied with the radial  and tangential component  of the slotless machine airgap flux density to give the radial and tangential air gap flux density components in the slotted PM machine:

 (22)  (23)

The permeance function is calculated using four conformal transformations between the planes to transform the slotted stator geometry into a simple slotless geometry. The airgap flux density is calculated in a plane having slotless machine geometry using the method in [[22](#_ENREF_22)]. The solution is then transformed back to the original plane having slotted stator to calculate the effect of slotting on airgap flux density. The component of complex relative permeance function, in the rotor frame, can be shown to be given by:



 (24)

In (24), ,, andare Fourier series coefficients and are calculated from the waveforms, shown in Fig. 3, of the real and imaginarycomponent of complex relative function using discrete Fourier transform. These waveforms are calculated from analytical solution presented in [[21](#_ENREF_21)]





(a)

(b)

Fig. 3. Complex relative air-gap permeance per one slot pitch on the surface of the magnet of the machine under study (a) Real component (b) Imaginary component.

1. *Resultant Airgap Flux Harmonics*

The magnet flux tooth ripple and armature reaction flux density harmonics of the same order can be added vectorially to obtain the resultant harmonics. To specify the correct phase angle between the two flux harmonics, the relationship between the phase angle, load angle, and the angle  between stator current *I* and the stator emf *E* induced by rotor fundamental field can be determined using Fig. 4. The resistance of the winding is assumed to be negligible in this phasor diagram.



Fig. 4 Phasor diagram of synchronous generator with inductive load

For each harmonic with a phase angle , the angle is between the magnet flux tooth ripple harmonic component and the stator mmf harmonic component, which combine vectorially to produce the resultant harmonic. The result of the calculation is shown in Table II. From the Table II, it is clear that all harmonics present a relation of either  or .

The anglebetween the rotor and the stator magnetic field axes is always 90-degrees for the fundamental and other harmonics as shown in Table II.

TABLE II

Angle in degrees between rotor and stator fields for different harmonics and phase angles in PM synchronous generator

|  |  |  |
| --- | --- | --- |
| TimeOrder *k* | SpaceHarmonic *q* |  |
| -90(90) | -60(-54) | -30(-21) | 0(10) | 30(38) | 60(65) | 90(90) |
|  |  |  |
| 6 | 5 | 180 | 150 | 120 | 90 | 60 | 30 | 0 |
| 7 | 0 | 30 | 60 | 90 | 120 | 150 | 180 |
| 12 | 11 | 180 | 150 | 120 | 90 | 60 | 30 | 0 |
| 13 | 0 | 30 | 60 | 90 | 120 | 150 | 180 |
| 18 | 17 | 180 | 150 | 120 | 90 | 60 | 30 | 0 |
| 19 | 0 | 30 | 60 | 90 | 120 | 150 | 180 |

The vector addition of equation (16) and (22) can be performed as:

 (25)

Equation (25) can be further simplified as:

 (26)

From (26), it can be observed that if the load angle between back EMF *E* and current *I* is 0 degrees and the angleis at 90 degrees then superposition, viz. direct addition of tooth ripple and stator MMF harmonics can be performed for which (26) becomes:

 (27)

For all other values of superposition can’t be employed, as the amplitude of harmonics will increase or decrease depending on the angle.

# Eddy Current Power Loss

1. *Rotor Eddy Current Power Loss Calculation using FEA*

The 2D Maxwell FEA software was used to calculate transient rotor eddy current power loss in PM machine with ring magnets, in order to validate the analytical results. Due to magnetic symmetry it is sufficient to model a quarter portion of the PM machine, covering a full pole pitch, as shown in Fig. 1. The boundary conditions along the *x* and *y* axis in Fig. 1 are defined to have negative symmetry.

1. *Analytical Rotor Eddy Current Power Loss Calculation*

Rotor eddy current power loss due to rotating flux harmonics in time and space is calculated analytically using a current sheet method as shown in Fig. 2. The ring magnet is assumed to be a conducting region with zero magnetization. End effects, which tend to reduce the losses, are neglected.

The current sheet density of a harmonic of space order *q* and time order *k* can be written as [[25](#_ENREF_25)]:

 (28)

The relationship between the current sheet density and the magnetostatic normal flux density is determined by solving the Laplace equation of the model in Fig. 2 with conductivities set to zero as discussed in the previous section. The amplitude of the current sheet,, is set such that it produces the corresponding normal flux density on the surface of the magnet as determined by (26).

The Laplacian of the vector potential *A,* assuming no variation in the *z* direction can be written as:

 (29)

In the air-gap:  (30)

In the magnets and steel:  (31)

whereandare the permeability and conductivity of the material. Using the separation of variables method yields the following solution:

 (32)

 Substituting (32) in (31), it can be shown that:

 (33)

where,andare the modified Bessel functions of the first and second kinds of order *q.* The radial and tangential components of the flux density in different regions, in terms of vector potential are given by:

 (34)

 (35)

Equations (34) and (35) are solved to obtain the field solution in each region of the PM machine and constantsandare determined by applying the boundary conditions. The boundary conditions assume that the radial flux componentis continuous at all interfaces between regions and the tangential componentis continuous at  and . The only difference will be at the stator bore  where there is a discontinuity in the tangential field intensity by the amount of current sheet density.

  (36a)

   (36b)

  (36c)



 (36d)

Rotor eddy current power loss can be calculated in each region using the Poynting vector. For a sinusoidal electromagnetic field at steady state, the average power transmitted through a surface is calculated using the Poynting vector as:

 (37)

Since we know the solution of Vector potential *A* from (29), the amplitudes of phasors of *E* and *H* can be obtained from the following equations:

  (38)

 (39)

Integrating (37) over the magnet surface, the total power transmitted from the airgap to the magnet region, designated byand power transmitted to the hub bycan be calculated in terms of field quantities as:

  (40)

  (41)

where and are the surface areas over the magnet and hub surfaces, respectively. The power loss in the magnet region  and the power loss in the hub region bythen can be calculated as:

 (42)

 (43)

# Travelling Flux Harmonics

For the PMSG shown in Fig.1, a comparison between airgap flux density calculated on the surface of the magnet using FEA static linear method and the analytical method in[[21](#_ENREF_21)] is presented in Fig. 5.



*CR*

FEA

FEA

*CR*

Fig. 5 Magnetic flux density on the surface of PM in PM machine taking into account slotting

The magnet flux tooth ripple harmonics along with their corresponding eddy current power loss is shown in Table III. An empty cell in Table III below indicates that power loss < 0.5 W; a negative sign represents backward rotating harmonics; and the fundamental frequency is *f1 =* 3000 Hz. Rotor losses calculated using FEA (BH curve of the stator laminations is assumed to be linear, with a relative permeability of 5000) are also included in Table III. The FEA results are significantly higher than the analytical results, which is partly due to the limitations of the analytical model used to calculate the harmonics arising from the assumptions it makes (infinite permeability, infinitely deep slots, non-parallel teeth). The discrepancy may also be due to FEA numerical errors.

TABLE III

Magnet flux tooth ripple harmonics amplitudes with corresponding power loss shown in brackets

|  |  |
| --- | --- |
| Space order *q* | Time order *k* |
|  | 6 | 12 | 18 |
| 5 | 0.0041-(14) |  |  |
| 7 | 0.0072-(18) |  |  |
| 11 |  | 0.0017-(1.1) |  |
| 13 |  | 0.0022-(1.1) |  |
| 17 |  |  |  |
| 19 |  |  |  |
| Power loss (Analytical) 34 WPower loss (FEA Linear) 43 W |

The main armature reaction harmonics calculated using (16) are shown in Table IV. The losses caused by these harmonics, in the absence of magnet flux, are included between brackets. The losses were also calculated using transient rotating mesh FEA with stator core material is assumed to be linear), magnets replaced with a demagnetized conducting region that has a relative permeability equals to the recoil permeability of the magnet material. The FEA value is significantly lower than the analytical one, which could be due to numerical FEA errors as well as the simplifying assumptions made in the analytical solution.

TABLE IV

Armature reaction flux density harmonic amplitudes at 0 degree load angle, with corresponding power loss shown in brackets

|  |  |
| --- | --- |
| Space order *q* | Time order *k* |
|  | 6 | 12 | 18 |
| 5 | 0.0114-(122) |  |  |
| 7 | 0.0066-(15) |  |  |
| 11 |  | 0.0022-(2) |  |
| 13 |  |  |  |
| 17 |  |  |  |
| 19 |  |  |  |
| Power loss (Analytical)  139 WPower loss (FEA linear)  130 W |

The results of the vector addition of the magnet flux tooth ripple and armature reaction flux harmonic of same order using equation (26) are shown in Table V. Corresponding rotor loss of each harmonic is shown between brackets. The results in Table V suggest a very good agreement between FEA and analytical calculations. But this hides their disagreement on calculating the individual components of loss as discussed earlier in relation to the results in Tables III and IV.

TABLE V

Resultant harmonic flux density amplitudes with corresponding power loss shown in brackets. The phase advance angle is 0 degrees.

|  |  |
| --- | --- |
| Space order *q* | Time order *k* |
|  | 6 | 12 | 18 |
| 5 | 0.0125-(129) |  |  |
| 7 | 0.009-(28) |  |  |
| 11 |  | 0.0025-(2) |  |
| 13 |  | 0.0027-(2) |  |
| 17 |  |  |  |
| 19 |  |  |  |
| Power loss (Analytical)  161 WPower loss (FEA linear )  162 WPower loss (FE non-linear)  180 W |

## Effect of phase advance angle

The rotor power loss presented in Table V is performed when between back EMF *E* and current *I* is zero degrees, and therefore angleis 90 degrees. A study is performed to calculate the effect of different current advance angle on rotor eddy current power loss. The results are presented in Fig. 6.



Fig. 6 Effect of current advance angle on rotor eddy current power loss

Fig. 6 shows that the rotor eddy current power loss increases as current advance angle varies from inductive to capacitive load in case of a generator. One may be tempted to explain this to be due to the armature reaction changing the fundamental flux component [5]. But this would be an oversimplification. It is in fact the way the significant harmonics combine with each other, strengthening or weakening each other depending on their relative phase angle.

While good agreement is observed between the analytical and linear FEA solutions, there are significant differences between the analytical and non-linear FEA calculations. This is largely due to the saturation of the tooth tip, which virtually increases the slot opening thus increasing the amplitude of the harmonics.

In Fig. 6, we also present the results of simply adding the magnet flux tooth ripple losses and the armature reaction losses, i.e. applying superposition. As can be seen, the losses are significantly overestimated when the load is inductive and underestimated when it is capacitive. The superposition of losses or (amplitude of harmonics) is correct only when the phase advance angle is zero.

# Conclusion

The paper calculated and compared rotor eddy current power loss in a PM machine using analytical method and FEA, taking into account effect of reaction eddy current field.

It has been shown that tooth ripple loss can be significant in PM machine and if ignored may lead to inaccurate rotor power loss calculation. In the context of adding tooth ripple and armature reaction flux harmonics it has been shown that, in comparison to superposition, vector addition of the two field harmonics results in accurate power loss calculation. It has been shown that superposition can only be employed when the angle between back EMF *E* and current *I* is zero degrees.

Saturation of the tooth tip can have a significant effect on rotor losses.

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