EFFECT OF SALIENCY AND CORE LOSSES ON THE DYNAMIC BEHAVIOR OF PERMANENT MAGNET SYNCHRONOUS MOTOR

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ABSTRACT

This paper presents the effect of saliency and core losses on the dynamic behavior of permanent magnet synchronous motor. The objective was realized with the aid of Matlab/Simulink. The two motors (Interior and Surface-Mounted Permanent Magnet Synchronous Motor) used in this work are of specifications 3-phase, 2 KW, 50 Hz, 4 poles, 240 V each. The transient and steady state responses of the motors were obtained, which revealed that when core loss is introduced to the motor, it decreases the magnitude of the ripple of electromagnetic torque and output power but affects the speed of the motor as it takes more time to attain steady state. The effect of saliency caused by reluctance torque showed that the load angle during the rated operation increases, and so the pull-out torque is obtained at the power angle greater than 90°. The maximum fundamental and electromagnetic torque is achieved at saliency ratio of 0.5. The results obtained in this work as compared to other literatures show improved design of Interior and Surface-Mounted Permanent Magnet Synchronous Motor with clear understanding of the parameters required of a particular motor for best operating performance.

Keywords: Core Loss; Interior Permanent Magnet Synchronous Motor (IPMSM); Permanent Magnet (PM); Saliency; Surface-Mounted Permanent Magnet Synchronous Motor (SPMSM).

1 INTRODUCTION

Permanent magnet synchronous motor (PMSM) is a type of alternating current synchronous motor with a sinusoidal back EMF waveform and whose field excitation is produced by permanent magnets. It uses permanent magnets embedded in the steel rotor to produce a constant magnetic field. The stator carries windings connected to an ac supply to produce a rotating magnetic field. At synchronous speed the rotor poles are lock to the rotating magnetic field and they are directly opposite to the stator poles and their axes coincide if on no-load, while at load the rotor poles lag behind the stator poles, but the rotor continues to turn at synchronous speed (Siva et al., 2013; Mishra et al., 2014). The choice of PMSM is influenced by features such as the motor’s high speed performance and adjustable speed operation which distinguished them from other ac machines, lower weight, smaller size, high efficiency, elimination of copper loss in the rotor, removal of slip rings, and high reliability (Consoli et al., 1990; Chee-Mun, 1998; Ogbonnaya and Ogbuka, 2015; Ritu et al., 2017).

Due to high torque density, high efficiency, high reliability and mass saving, permanent magnet synchronous motors have become better options for electric vehicles drive systems (EVs). In particular, as a representative of conventional permanent motor, Surface-Mounted Permanent Magnet Synchronous Motor (SPMSM) is widely used because of its simple construction and short end connections. However, this type of motor exhibits no magnetic saliency since d-axis and q-axis inductances are equal, which implies that no reluctance torque can be used. As a result, the overload capacity and speed regulation capability are relatively restricted in multi-driving cycles of EVs (Aye and Aung, 2001; Wenye et al., 2018). The proper knowledge of permanent magnetic materials and its properties is required for the selection of the materials and for understanding permanent magnet (PM) motors since
it directly affects the performance of the motor. Hardened steel was the earliest manufactured magnetic material. Steel magnets hold low energy and they can be easily magnetized but they are also prone to demagnetization. Other magnetic materials have been recently developed such as Aluminum Nickel and Cobalt alloys (ALNICO), Ferrite, Samarium Cobalt (SmCo) and Neodymium Iron-Boron (NdFeB). SmCo PMs can hold higher flux density but their cost is relatively high. NdFeB PMs are widely used in motor manufacturing nowadays (Enrique, 2006). It has been shown that NdFeB magnets have similar merits as Ferrite and Samarium-Cobalt but have lower cost. High air gap flux density of 0.8-1.0 Tesla can be produced with relatively small volume of these magnets. Furthermore, PMSMs using NdFeB are well suited for high performance and variable speed drives because of their high peak torque capability and their linear relationship between torque and stator current. Some potential limitations of NdFeB material in comparison with other high energy magnets are its relatively low temperature limit and vulnerable to corrosion (Liu, 2005). The magnets can be placed internally inside the rotor for high speed operations or mounted on the surface of the rotor for medium speed operations as in Figures 1 and 2 respectively (Remitha and Anna, 2013).

The configuration of Figure 1 is used in low speed as well as high speed applications up to 5000 rpm. There is inductance variation for this type of rotor because the permanent magnet part is equivalent to air in the magnetic circuit calculation. These motors are considered to have saliency with $q$-axis inductance greater than the $d$-axis inductance ($L_q > L_d$) (Bose, 2002; Enrique, 2006).

Figure 1: Interior Permanent Magnet.

The configuration of Figure 2 is used for low speed applications of about 3000 rpm and below because of the limitation that magnets will fly apart during high-speed operations. The effective air gap of the $d$-axis equals that of the $q$-axis and the motors are considered to have small or no saliency, thus having practically equal inductances in both axes ($L_d = L_q$) and torque is produced by the interaction between the stator currents and the magnets only (Krishnan, 2001; Alexander, 2006; Shady, 2016).

Figure 2: Surface-Mounted Permanent Magnet.

Enrique (2006) carried out detailed modeling of permanent magnet synchronous motor drive system using Simulink. The Simulation results were given for two speeds of operation, one below rated and another above rated speed. In his PMSM drive system modeling he failed to mention how stator core resistance and damper winding affects the performance of the motor. Remitha and Anna (2013) presented Matlab/Simulink Model of Field Oriented Control of Permanent Magnet Synchronous Motor Drive using Space Vectors. From their analysis of transient and steady state values of current, speed and torque curves, the three phase currents showed less distortion and torque curves have very little ripples. However, since core resistance affects the ripples of the output parameters of the motor, this has to be considered for better analysis of the transient values of speed and torque. Siva et al. (2013) presented Mathematical Modeling and Simulation of Permanent magnet Synchronous Motor using Simulink. In their work, they suggested that the conventional electromagnetic field poles in the rotor are replaced by the PM poles and by doing so the slip rings and brush assembly are dispensed. However core loss effect which directly affect the level of ripple and time at which steady state value is attained were not considered. Ogbonnaya and Ogbuka (2015) analyzed Startup Performance of Grid-Connected Permanent magnet
Synchronous Motor using Matlab/Simulink. Their work focused on the Start-up Performance of Grid-connected PMSM, thus, core loss and saliency effect to determine operating load angle and maximum torque were not considered. Chen et al. (2016) presented Effect of Salient Pole on Permanent Magnet Synchronous Motors Direct Torque Control. From his result, during motor operation the salient pole effect produces reluctance torque which offset a portion of the electromagnetic torque, weakening the permanent magnet synchronous motor's torque output capacity. However they failed to show the angle for motor operation due to saliency and its ratio for maximum torque.

In Parvathi and Nisha (2016), Interior Permanent Magnet Synchronous Motor Drive System was modeled using Transient Simulation Technique. In their transient analysis of speed, the effect of core loss was not taken into consideration which directly affects the transient of the motor speed. Ritu et al. (2017) modeled Surface-Mounted Permanent Synchronous Motor for Servo Motor Application. Their paper concentrated on the dynamic modeling and the transient analysis of the PMSM using Matlab. However, stator core resistance was not used in their modeling hence effect of core loss was not considered, but the core resistance has appreciable effect on the transient of the output parameters of the motor. Sakunthalan et al. (2017) presented a simulation platform for Permanent Magnet Synchronous Motor Drives using Simulink. In their model equations core resistance were not included and torque expression in terms of back Emf and stator phase voltage for saliency analysis were not shown hence the need to add core resistance in the modeling for clear observation of the ripple during transient as it affects the performance of the motor.

In Wenye et al. (2018), three interior permanent magnet (IPM) synchronous machines respectively having a large saliency, a low saliency and an inverse saliency were analyzed. From their result, the inverse saliency ratio machine shows a larger high efficiency region and extends the high efficiency region to a wider speed-and-torque range due to its unique characteristic of $L_q < L_d$, hence with the different saliency analyzed, they fail to show at what saliency the machine attain its maximum torque and the angle of occurrence for pull-out torque. Meiling and Shengxian (2019) presented On-Speed Control of a Permanent Magnet Synchronous Motor with Current Predictive Compensation. In their model analysis, stator core resistance was not considered which means the effect of core loss to determine the magnitude of ripples associated with speed during transient were not analyzed.

This paper analyses the effect of saliency and core losses in the dynamic behavior of permanent magnet synchronous motor. From the reviewed literatures, it is seen that core loss effect was lacking in their analysis. As a result, core resistance which causes core loss is introduced in the modeling of the PMSM and a comparative analysis of the effects of core loss considerations is done to determine the motor’s best operating performance and magnitude of ripples associated with speed, torque, and output power of the motor during transient. Again, the effect of saliency, to determine the motor’s preferred load angle and maximum operating torque was not mentioned. This paper also seeks to determine the effect of saliency ratio, at which fundamental and electromagnetic torque are maximum and at what power angle will pull-out torque be obtained.

### 2. METHOD OF ANALYSIS

The dynamic model of permanent magnet synchronous motor is derived using a two-phase motor in direct and quadrature axes. The $d$-$q$ model has been developed on rotor reference frame as shown in Figure 3. At any time $t$, the rotating rotor $d$-axis makes an angle $\theta_r$ with the fixed stator phase axis and the rotating stator MMF makes an angle $\alpha$ with the rotor $d$-axis. Stator MMF rotates at the same speed as that of the rotor (Enrique, 2006).
The model of PMSM is developed on rotor reference frame using the following assumptions:

i. Saturation is neglected.

ii. The induced EMF is sinusoidal.

iii. Eddy currents and hysteresis losses are negligible.

iv. There are no field current dynamics.

2.1 Electrical Model of PMSM

The equivalent circuit of PMSM is shown in Figure 4, while Equations 1 to 8 are the voltage, current and flux linkage of the motor (El Shewy et al., 2008).

Voltage equations are given by:

\[ V_q = R_s i_q + \left( \frac{R_s + R_c}{R_c} \right) \rho(\lambda_q) + \left( \frac{R_s + R_c}{R_c} \right) \omega_r \lambda_d \] \hspace{1cm} (1)

\[ V_d = R_s i_d + \left( \frac{R_s + R_c}{R_c} \right) \rho(\lambda_d) - \left( \frac{R_s + R_c}{R_c} \right) \omega_r \lambda_q \] \hspace{1cm} (2)

Flux Linkages are given by:

\[ \lambda_q = L_q i_q \] \hspace{1cm} (3)

\[ \lambda_d = L_d i_d + \lambda_m \] \hspace{1cm} (4)

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Substituting Equations 3 and 4 in Equations 1 and 2,

\[
V_q = R_s i_q + \left(\frac{R_s + R_c}{R_c}\right)\rho(L_{q1}i_q) + \left(\frac{R_s + R_c}{R_c}\right)\omega_r (L_{d1}i_d + \lambda_m) \quad \ldots (5)
\]

\[
\frac{di_q}{dt} = \frac{-R_s R_c}{L_q(R_s + R_c)} i_q - \frac{\omega_r L_{d1}i_d}{L_q} + \frac{V_q R_c}{L_q} \left(\frac{R_s + R_c}{R_c}\right) \omega_r L_{q1}i_q \quad \ldots (6)
\]

\[
V_d = R_s i_d + \left(\frac{R_s + R_c}{R_c}\right)\rho(L_{d1}i_d + \lambda_m) - \frac{(R_s + R_c)}{R_c} \omega_r L_{q1}i_q \quad \ldots (7)
\]

\[
\frac{di_d}{dt} = \frac{-\omega_r L_q}{L_d} i_q - \frac{R_s R_c}{L_d(R_s + R_c)} i_d - \frac{V_d R_c}{L_d} \left(\frac{R_s + R_c}{R_c}\right) \omega_r L_{q1}i_q \quad \ldots (8)
\]

where:

- \(\rho\): Operator \(\frac{d}{dt}\)
- \(\rho(\lambda_m) = 0\)
- \(V_q\) and \(V_d\): q- and d-axis voltages
- \(i_q\) and \(i_d\): q- and d-axis currents
- \(L_q\) and \(L_d\): q- and d-axis inductances
- \(\lambda_q\) and \(\lambda_d\): q- and d-axis flux linkages
- \(R_s\): Stator resistance
- \(R_c\): Core resistance
- \(\omega_r\): Electrical speed of the rotor
- \(\lambda_m\): Rotor flux linkage.

### 2.2 Mechanical Model of PMSM

Equations 9 to 22 represent the mechanical equations of the motor which include torque, power and rotor speed.

Electromagnetic torque of the motor in terms of \(d\)- and \(q\)-axis linkages, rotor flux linkage, and \(d\)- and \(q\)-axis inductances as stated in (El Shahat and El Shewy, 2010) is given as:

\[
T_e = \frac{3P}{4}\left(\lambda_m i_q\right) \quad \ldots (11)
\]

and Reluctance Torque is given by:

\[
T_{rel} = \frac{3P}{4}\left(L_d - L_q\right)i_q i_d \quad \ldots (12)
\]

Electromagnetic torque of the motor in terms of back-EMF induced by the magnets \(E_{pm}\), the stator phase voltage \(V_s\), and the \(d\)- and \(q\)-axis inductances as stated in (Jussi, 2006) is given as:

\[
T_e = \frac{m}{2\pi n_s}\left[\frac{E_{pm} V_s}{\omega_r L_d} \sin(\delta_a) + \frac{V_s^2}{2} \left(\frac{1}{\omega_r L_q} - \frac{1}{\omega_r L_d}\right) \sin(2\delta_a)\right] \quad \ldots (13)
\]

where Fundamental Torque is given as:

\[
T_{fun} = \frac{m}{2\pi n_s}\left[\frac{E_{pm} V_s}{\omega_r L_d} \sin(\delta_a)\right] \quad \ldots (14)
\]

and Reluctance Torque is given as:

\[
T_{rel} = \frac{m}{2\pi n_s}\left[\frac{V_s^2}{2} \left(\frac{1}{\omega_r L_q} - \frac{1}{\omega_r L_d}\right) \sin(2\delta_a)\right] \quad \ldots (15)
\]

The Electromechanical power is given as:

\[
P_{em} = \omega_r T_e = \frac{3}{2} \omega_r \left(\lambda_d i_q - \lambda_q i_d\right) \quad \ldots (16)
\]

\[
\omega_r = \frac{\omega_{rm}}{P} \quad \ldots (17)
\]

where:

- \(\omega_{rm}\): Mechanical speed of the rotor
- \(P\): Number of poles
- \(n_s = \frac{120f}{P}\): Synchronous speed
- \(\delta_a\): The load angle measured between the phasors
- \(V_s\): Stator voltage
- \(E_{pm}\): PMSM no load voltage.

The general mechanical equation for the motor is:

\[
T_e = T_l + T_d + B\omega_r + J\rho \omega_{rm} \quad \ldots (18)
\]

Solving for the rotor mechanical speed from Equation 18, assuming the dry friction is equals zero gives

\[
\frac{d\omega_r}{dt} = -\frac{B}{J} \omega_r + \frac{1}{J}(T_e - T_l) \quad \ldots (19)
\]

also,

\[
\frac{d\theta_r}{dt} = \omega_r \quad \ldots (20)
\]

\[
\theta_r = \frac{P}{2} \theta_{rm} \quad \ldots (21)
\]
The mechanical speed \( N \) (that is synchronous speed) in terms of revolutions per minute (rpm) can be stated as
\[
N = \frac{60}{\pi} \omega_{\text{rm}} = \frac{30}{\pi} \omega_{\text{rm}} \quad \ldots \quad (22)
\]
where:
\( B \): Viscous frictions coefficient
\( J \): Inertia of the shaft and the load system

The three phase stator voltages are related to \( d \)- and \( q \)-axis reference frame as follows:
\[
\begin{bmatrix}
V_d \\
V_q \\
V_a \\
V_b \\
V_c
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
\cos \theta & \cos(\theta - 120^\circ) & \cos(\theta + 120^\circ) \\
\sin \theta & \sin(\theta - 120^\circ) & \sin(\theta + 120^\circ)
\end{bmatrix} \begin{bmatrix}
V_d \\
V_q \\
V_a \\
V_b \\
V_c
\end{bmatrix} \quad \ldots \quad (24)
\]
\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} = \begin{bmatrix}
\cos \theta & \sin \theta \\
\cos(\theta - 120^\circ) & \sin(\theta - 120^\circ) \\
\cos(\theta + 120^\circ) & \sin(\theta + 120^\circ)
\end{bmatrix} \begin{bmatrix}
V_q \\
V_d
\end{bmatrix} \quad \ldots \quad (25)
\]

3 RESULTS AND DISCUSSION

This section introduces some simulation performances of the motor by using MATLAB m-file to observe the various characteristics with time. Also, this section shows the comparison with and without considering core loss and saliency ratio against load angle. The analysis is validated by using the machine data as shown in Table 1 and Table 2. The machines’ parameters are obtained by carrying out the Finite Element Analysis, FEA on the test motors using Maxwell2D/RMxpert (Maxwell 2D/RMxpert FEA-Simulation Program, 2010).

| Table 1: Motor parameters for Interior Permanent Magnet Synchronous Motor (IPMSM) |
|---------------------------------|----------|
| Motor Parameter                | Value    |
| Rated power, P                 | 2 kW     |
| Rated voltage, V               | 240 V    |
| Rated speed, \( \omega \)      | 1500 rpm |
| \( q \)-axis inductance, \( L_q \) | 11.8 mH  |
| \( d \)-axis inductance, \( L_d \) | 4.6 mH   |
| Rotor flux linkage, \( \lambda_{af} \) | 1.14 mWb |
| Number of poles, P             | 4        |
| Stator resistance, \( R_s \)   | 0.86 \( \Omega \) |
| Stator core resistance, \( R_c \) | 18 \( \Omega \) |
| Inertia coefficient, \( J \)   | 0.00021 kg/m\(^2\) |
| Load torque, \( T_l \)         | 12 Nm    |
| Dry friction, \( T_d \)        | 0 Nm     |
| Frequency, \( f \)             | 50 Hz    |
| Viscous friction coefficient, \( B \) | 0.015 Nms |

| Table 2: Motor parameters for Surface-Mounted Permanent Magnet Synchronous Motor (SPMSM) |
|---------------------------------|----------|
| Motor Parameter                | Value    |
| Rated power, P                 | 2 kW     |
| Rated voltage, V               | 240 V    |
| Rated speed, \( \omega \)      | 1500 rpm |
| \( q \)-axis inductance, \( L_q \) | 0.0171 H |
| \( d \)-axis inductance, \( L_d \) | 0.0171 H |
| Rotor flux linkage, \( \lambda_{af} \) | 0.321 Wb |
| Number of poles, P             | 4        |
| Stator resistance, \( R_s \)   | 5.29 \( \Omega \) |
| Stator core resistance, \( R_c \) | 18 \( \Omega \) |
| Inertia coefficient, \( J \)   | 0.00021 kg/m\(^2\) |
| Load torque, \( T_l \)         | 12 Nm    |
| Dry friction, \( T_d \)        | 0 Nm     |
| Frequency, \( f \)             | 50 Hz    |

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Viscous friction coefficient, \( B = 0.015 \text{ Nm}s \)

In Figures 5 and 6, it is seen that introduction of core loss in the motor introduces lower ripples but takes more time for the transient to settle. In Figure 5, the speed attained its steady state value of 1500 rpm at 0.06 seconds when core loss is not considered and at 0.12 seconds when core loss is considered whereas in Figure 6, it attained its steady state value at 0.05 seconds in both cases.

In Figures 7 and 8, it is seen that the effect of core resistance does not affect electromagnetic torque directly and also affirm torque non-linearity caused by ignoring core loss.

In Figures 9 and 10, it is seen that the effect of core resistance does not affect electromechanical power directly since it is the product of electromagnetic torque and electrical rotor speed. The only effect of the introduction of the core resistance is the reduction of magnitude of the ripple during transient by 6 kW that is, from 56 kW to 50 kW for IPMSM and from 19 kW to 13 kW for SPMSM.
From Figure 11-13, the variation of $d$-axis inductance with respect to $q$-axis inductance (saliency ratio) changes the angle at which the maximum torque occurs. The reluctance torque due to the effect of saliency shows that the load angle during the rated operation increases, and so the pull-out torque is obtained at a power angle greater than $90^\circ$. The reluctance torque greatly affect the electromagnetic torque as it increases it in the region of $90^\circ$ to $180^\circ$ load angle and decreases the electromagnetic torque when the load angle lie between $0^\circ$ to $90^\circ$. Therefore, an operation in the first $90^\circ$ is not attempted in these motors and the preferred load angle is between $90^\circ$ and $180^\circ$. At the point when $L_d$ equals $L_q$, the motor becomes SPMSM and the value of reluctance torque equals $0 \, \text{Nm}$ as can be seen in Figure 12.

**Figure 11:** Graph of Fundamental torque against load angle at different saliency ratios for IPMSM.

**Figure 12:** Graph of Reluctance torque against load angle at different saliency ratios for IPMSM.

**Figure 13:** Graph of Electromagnetic torque against load angle at different saliency ratios for IPMSM.

### 4. CONCLUSION

In this paper, simulation based mathematical model of dynamic behavior of permanent magnet synchronous motor considering core losses and saliency ratio is implemented using Matlab m-file. The simulation results show that the speed, torque and output power of the motor remain constant irrespective of introduction of core loss but decreases the magnitude of the ripple during transient. Therefore core resistance should be used in the design of PMSM. The effect
of saliency caused by reluctance torque shows that the load angle during the rated operation increases, and pull-out torque is obtained at the power angle greater than 90°. This implies that in the design of IPMSM, the load angle should be between 90° and 180°, and the value of $d$-axis inductance with respect to $q$-axis inductance (saliency ratio) should be 0.5 since maximum torque occurs at this point.

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