INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 16 No. 2 (2024) 58-65
https://publisher.uthm.edu.my/ojs/index.php/ijie

Non-Linear Modelling and Control of Permanent Magnet Synchronous Machine for Actuator Applications

Phaneendra Babu Bobba[1], Gaurang I Vakil[2]*, Himavarsha Gajala[1], B V Ravi Kumar[3]

[1] *Department of Electrical and Electronics Engineering. Gokaraju Rangaraju Institute of Engineering and Technology, Hyderabad, INDIA*
[2] *Department of Electrical and Electronics Engineering, University of Nottingham, UNITED KINGDOM*
[3] *DRDO, Research Centre Imarat, INDIA*

*Corresponding Author: gaurang.vakil@nottingham.ac.uk
DOI: https://doi.org/10.30880/ijie.2024.16.02.006

Article Info

Received: 19 September 2023
Accepted: 25 October 2023
Available online: 15 April 2024

Keywords

Permanent magnet synchronous machine (PMSM), actuators, non-linearities, iron loss, rotor position, simulink

Abstract

Permanent magnet synchronous motors grabbed the attention due to their intrinsic characteristics. Aerospace applications necessitate great dependability and while reducing weight, complication, fuel intake, working expenses, and environmental effects. All these demands can be fulfilled to some extent with the PMSM motors because of their characteristics. The mathematical modelling of an Interior permanent magnet synchronous motor (IPMSM) including nonlinearities is proposed in this paper. The conventional models neglect nonlinearities such as hysteresis and eddy current losses, parameters variation with respect to rotor angle, magnetic saturation, cross-coupling effect, armature reaction, etc. The present model considers core loss and inductance varying concerning rotor position. Usually, the core loss is taken as a constant loss, but it varies with the speed. Ignoring the above parameters may deteriorate the performance of the motor in real-time compared to linear model. To validate the efficacy of the proposed model, two models are simulated in MATLAB and the results are compared.

1. Introduction

The inclusion of permanent magnets instead of rotor windings increased the flow of magnetic flux between the rotor and stator-made PM motors in numerous manufacturing appliances [1]. Though there are different motors including induction motor, Switched Reluctance Motor, PMSM is preferred over it. Because of their inherent features such as power density, less maintenance, small size, high energy density, and employed in applications, such as actuators, robotics, metal cutting machines, precision machining, etc. [2]. A theory is analyzed about the choice of motor for aerospace application, especially for actuators. Space appliances require high-level dependability, high convenience, and high-power density while aiming to reduce weight, complexity, fuel consumption, operational costs, and eco-friendly [3]. Innovative electric-driven systems can fulfill these needs and provide significant technical and fi-nancial improvements on already existing systems. Logical approaches are embraced to assess caged induction, reluctance, and PM motor technologies and their relative merits. The investigation recommends that the three-phase Permanent Magnet motor drive may be a preferred alternative for general aerospace applications. Though Permanent magnet machines have some disadvantages like expensive, more harmonic content in torque, etc remarkable balance, can be maintained. Rather than a Brushless dc motor

Synchronous motor of the permanent magnet have fewer ripples in torque and position control through commutation is a little easy. So, PM machines also each have their pros and cons. [3].

An actuator mechanical system could not arrange the input command signal due to Coulomb friction, and this phenomenon is known as dead-zone nonlinearity. In the current scenario, more electrical actuation systems have been adopted to minimize the effects caused by mechanical systems. The actuator is schematically represented as fig.1[4]. In actuators, electrical and mechanical non-linear factors such as the dead-zone, backlash, saturation, friction, and others can degrade the dynamic performance of the actuator, resulting in substantial degradation of attitude control effect, even causing oscillations, and jeopardizing global stability. Installation and de-bugging errors, dead-zone, gear backlash, and zero position error, among other things, exist in the actuator system due to manufacturing technology restrictions. Therefore, installation and debugging errors cannot be nullified.

Basically, the d-q axis model is considered while simulating because of quick execution compared to the time-varying model. Since PMSM has a complex mathematical model motor, for better dynamic performance the vector-controlled field Oriented Control technique is used. This enables independent control of torque and flux producing current components. The old-fashioned d-q model [7] is a classical magnetic circuit model which only considers the fundamental components of flux and inductance, views motor inductance as constant, and does not take into consideration hysteresis and eddy current loss as well [8]. Because of neglecting losses, time-varying parameters, etc the developed motor may not provide precise results and deviates from the actual motor in performance. Moreover, to nullify the variations a model must be developed which incorporates both nonlinearities.

Several models have been developed considering iron loss and position varying parameters. The nonlinear models [8-12] used different techniques, tools like Finite Element Analysis, JMAG, and other estimation methods to analyze the varying parameters. The model presented in [13] included additional core resistance which can account for core loss in Surface-mounted PMSM in time-varying models. This paper proposed deals with IPM machines given the effect of iron loss on the machine electromagnetic behavior, spatial harmonics in phase voltages which cause torque ripples. As the IPM rotor is configured the existence of reluctance torque causes an increase in spatial harmonics owing to the naturally large variation in magnetic energy with rotor position [14,15]. Hence, Linear modelling approaches cannot identify the effects caused by the nonlinearities mentioned.

Table 1 *Non-linearities and their effects on actuators*

Non-linearities	Effects
Dead zone	The correction time increases as the dead zone widens, and the overshoot gradually increases. It demonstrates the influence on mistake tracking. Future increases may cause system oscillations.
Backlash	Backlash in a mechanical system makes it harder to regulate the system with great precision. It raises the error rate between the input and output systems.
Friction	Tracking mistakes, limit cycles, and other unwanted effects can all be caused by Friction.
Saturation	Proportional-derivative (PD) controllers have seen limit cycles in their presence, which could lead to a phenomenon known as integrator windup. The control signal saturates the actuator because of this effect, therefore increasing the control signal will not result in faster system response.
Iron loss	It influences the d-axis and q-axis currents resulting in a reduction of electromagnetic torque.
Inductance variation	It may cause harmonics in current and voltage waveforms and result in spatial harmonics in the system.
Magnetic saturation	The d-axis inductance of PMSM is affected by d-axis magnetic saturation. Inductance along the q-axis of the L_d The magnetic saturation of the q-axis alters L_q. Meanwhile, as the q-axis current rises, the saturation of PMSM rises, resulting in a decrease in d-axis inductance; at the same time, the d-axis current affects the q-axis inductance, resulting in the so-called cross saturation effect. As a result, the motor inductance exhibits non-linear behavior.

2. Linear Mathematical Model of PMSM

The mathematical model of permanent magnet synchronous motor is usually composed of voltage equation (1), stator flux equation (2), electromagnetic torque equation (3), and mechanical equation of motion (4). The equations can be expressed in the d-q coordinate systems as in [3,4]. The block diagram of the system is shown in fig (1). Voltage equation is:

$$V_d = R_s i_d + \frac{d\Psi_d}{dt} - \omega_e \Psi_q \tag{1}$$

$$V_q = R_s i_q + \frac{d\Psi_q}{dt} + \omega_e \Psi_d \quad (2)$$

Stator equation:

$$\Psi_d = L_d i_d + \Psi_f \quad (3)$$

$$\Psi_q = L_q i_q \quad (4)$$

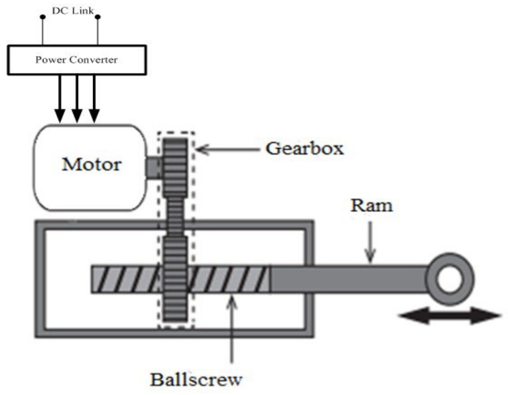

Fig. 1 *Schematic diagram of an electromechanical actuator*

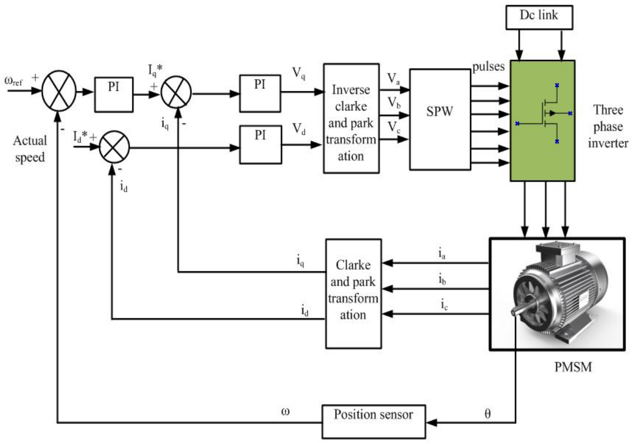

Fig. 2 *Block diagram of conventional IPM machine model*

The electromagnetic torque equation is:

$$T_e = \frac{3}{2} p[\Psi_f i_q + (L_d - L_q) i_d i_q] \quad (5)$$

The mechanical torque equation is:

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \quad (6)$$

$$\omega_m = \omega_e \frac{2}{p} \quad (7)$$

From the above equations (1-7), it implies the parameters of the motor are constant excluding core loss, armature reaction, saturation, cross-coupling effect, variable inductance, etc. This reduces the accuracy of the motor's static and dynamic performance [8]. So, there is a need to remodeling the PMSM model as of real motor's characteristic.

3. Proposed Model of PMSM

In this section, the modeling of PMSM is presented by considering hysteresis and eddy current losses, inductance variation concerning rotor position.

3.1 Mathematical Modelling Including Hysteresis and Eddy Current Losses

To sort out the difficulties of the typical model as reviewed in section 2, a machine model is employed with the following equations (8-10)

$$V_d = R_s i_{da} + \frac{d\Psi_d}{dt} + \omega_e \Psi_q \quad (8)$$

$$V_q = R_s i_{qa} + \frac{d\Psi_d}{dt} + \omega_e \Psi_d \quad (9)$$

$$T_e = \frac{3}{2} p[\Psi_f i_{qa} + (L_d - L_q) i_{da} i_{qa} \quad (10)$$

where i_{da}, i_{qa} are the currents after incurring losses. Iron loss in electrical machines impacts phase currents at a given supply voltage by increasing or decreasing active power depending on whether they operate as a motor or generator. The iron loss model given in [16, 17] is used to study the core loss influence on the machine electromagnetic behavior at different load circumstances in a computationally effective way which can be described by

$$P_{Fe\_oc} = c_h \frac{g}{2\pi} + c_e\left(\frac{g}{2\pi}\right)^2 + c_x\left(\frac{g}{2\pi}\right)^{1.5} \quad (11)$$

$$g = \frac{V_m}{\Psi_f} \quad (12)$$

$$P_{Fe\_sc} = d_h \frac{k}{2\pi} + d_e\left(\frac{k}{2\pi}\right)^2 + d_x\left(\frac{k}{2\pi}\right)^{1.5} \quad (13)$$

$$k = \frac{V_{da}}{\Psi_f} \quad (14)$$

where, the iron loss coefficients (c_h, c_e, c_x) as well as (d_h, d_e, d_x) are taken from [16]. The core loss of the machine at a particular operation can be computed by P_{Fe_oc} and P_{Fe_sc}. P_{Fe_oc} is the open circuit iron loss and $PFe_{\_sc}$ is the short circuit iron loss (11-14). The voltage magnitude V_m and the voltage due to armature reaction of the d-axis current V_{da} can be calculated by (15-16).

$$V_m = \sqrt{\omega_e^2 \Psi_d^2 + \omega_e^2 \Psi_q^2} \quad (15)$$

$$V_{da} = -\omega_e \Psi_d + \omega_e \Psi_f \quad (16)$$

The iron losses P_{Fe_d} and P_{Fe_q} taken from [9] are further divided into q axis and d axis loss components as follows and calculated using the equations (17-18):

$$P_{Fe\_d} = \frac{\Psi_q^2}{\Psi_d^2 + \Psi_q^2} P_{Fe\_oc} + P_{Fe\_sc} \quad (17)$$

$$P_{Fe\_q} = \frac{\Psi_d^2}{\Psi_d^2 + \Psi_q^2} P_{Fe\_oc} \quad (18)$$

In motoring mode, the machines absorb power from the electrical source, however, in generator mode, it reduces electrical output power. The loss caused due to the inclusion of iron loss is expressed in terms of induced voltages as given in [9]:

$$i_{da} = i_d \pm \frac{P_{Fe\_d}}{V_d - R_s i_d} \quad (19)$$

$$i_{qa} = i_q \pm \frac{P_{Fe\_q}}{V_q - R_s i_q} \quad (20)$$

Whereas ida and iqa [9] are the currents of the d-axis and q-axis as shown in (19-20).

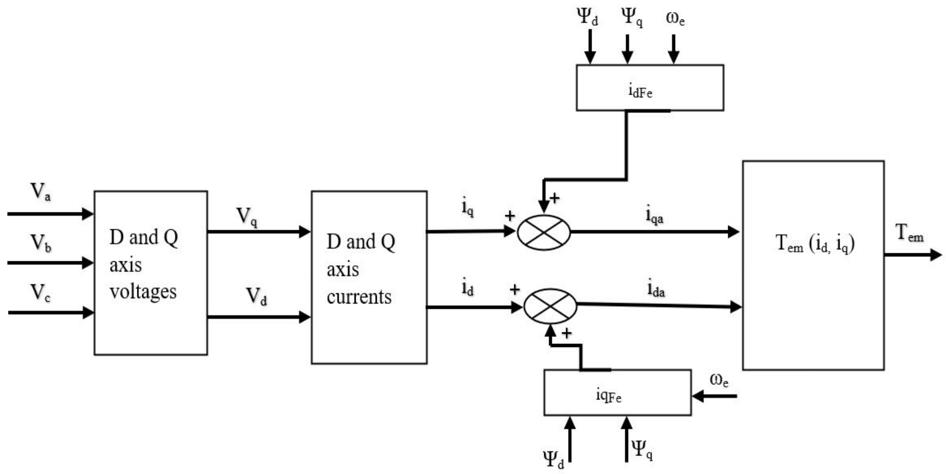

Fig. 3 *Proposed IPM machine schematic with iron loss effect*

3.2 The Effect of Iron Loss on PMSM Motor

From the model in Fig. 2, the impact of considering hysteresis and eddy current losses on IPM machines' electromagnetic behavior can be studied. A notable difference is observed in the amplitude of the d axis and q axis current with the inclusion of losses. In the constant torque region with the current limit, the amplitudes of both d and q-axis currents, i_{da}, and i_{qa}, associated with electromechanical conversion are slightly reduced [9]. As a result, the output power of the motor is also reduced.

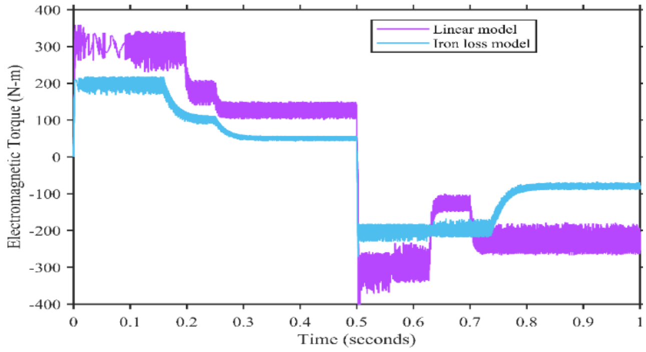

Fig. 4 *Comparison of electromagnetic torque with and without iron loss*

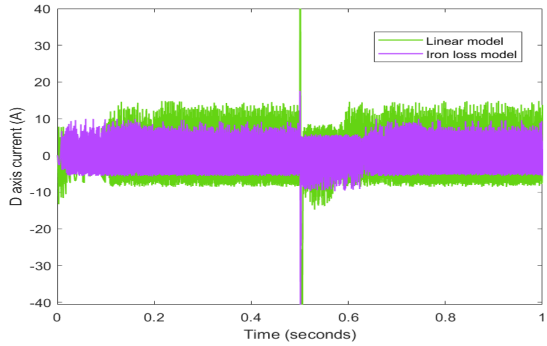

Fig. 5 *Comparison of d axis current with and without iron loss*

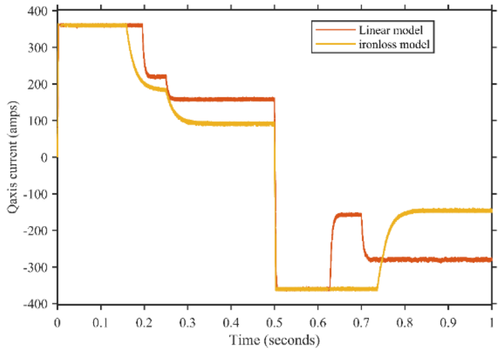

Fig. 6 *Comparison of q axis current with and without iron loss*

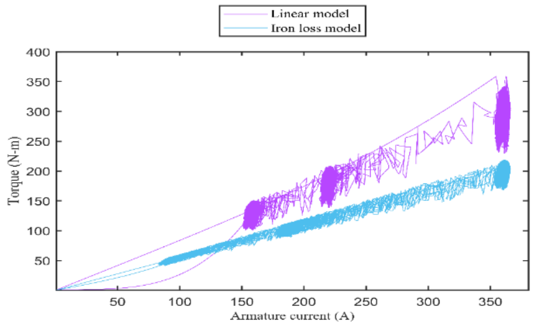

Fig. 7 *Comparison of Torque versus armature current with and without loss*

3.3 PMSM Modelling with Inductance Function of Rotor Angle

The PMSM is modelled with inductance variation using the following equations (21-28):

$$\Psi_d = L_{dd} i_d + L_{dq} i_q + \Psi_f \cos\theta \quad (21)$$

$$\Psi_q = L_{qq} i_q + L_{dq} i_d + \Psi_f \sin\theta \quad (22)$$

$$L_{dd} = L_1 - L_2 \cos\theta \quad (23)$$

$$L_{qq} = L_1 + L_2 \cos(2\theta) \quad (24$$

$$L_{qd} = -L_1 \sin\theta \quad (25)$$

$$L_1 = \frac{1}{2}(L_q + L_d) \quad (26)$$

$$L_2 = \frac{1}{2}(L_q - L_d) \quad (27)$$

$$T_e = \frac{3}{2} p[(L_{dd} - L_{qq}) i_d i_q + (\Psi_{dpm} i_q - \Psi_{qpm} i_d) + (L_{dq} i_q^2 - L_{dq} i_d^2)] \quad (28)$$

where L_{dd} is self-inductance of d-axis, L_{qq} is self-inductance of q-axis, L_{qd} is mutual inductance of stator, i_d and i_q are the d-axis and q-axis current. Generally, flux, torque, inductance, permanent magnet flux, etc parameters are taken as constant but they are dependent on rotor position θ as shown in figures below and above equations (21-28) taken from [21]. The spatial harmonics are neglected in the traditional model as parameters are considered independent of rotor angle. The distortions in voltage, ripples in torque are caused due to spatial harmonics. Ignoring the rotor dependency, makes the model deviate from the actual performance of the machine. From figures (9), (10), (11), it is evident that flux, inductance, and torque vary with rotor position. As from the fig.11, torque is constant in linear models whereas it varies with the rotor in real-time.

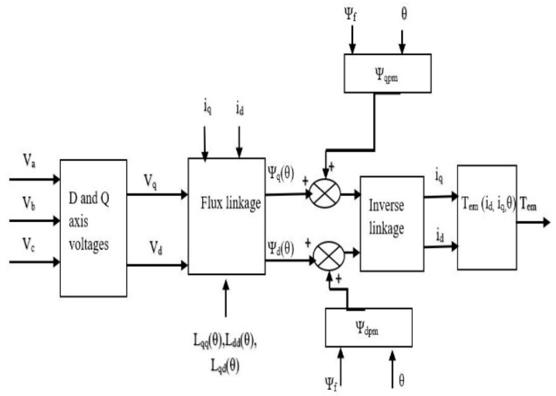

Fig. 8 *Proposed schematic diagram of IPMSM with inductance function of rotor position.*

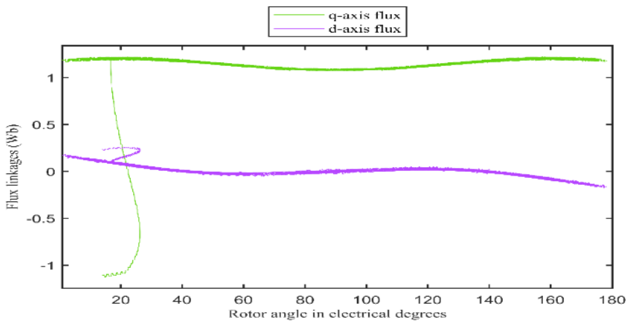

Fig.9 *Flux linkages variation with rotor position in electrical degrees*

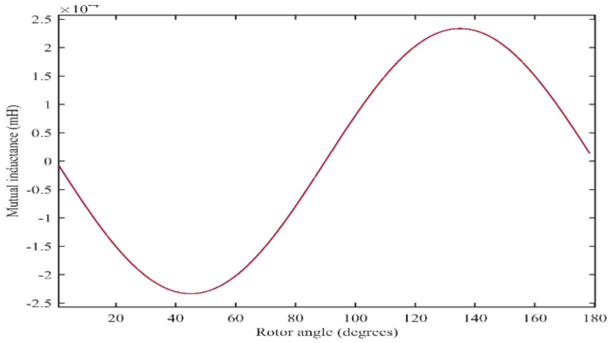

Fig. 9 *Mutual inductance variation with rotor position angle in electrical degrees*

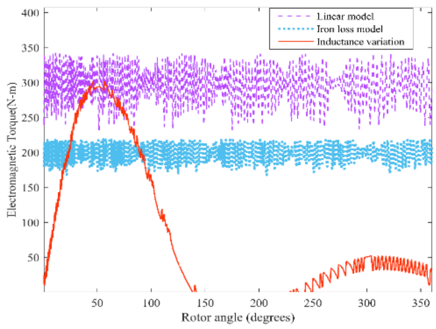

Fig. 10 *Comparison of electromagnetic torque for rotor position*

Table 2 *Specifications of motor*

S.no	Parameters	Unit	Value
1.	Poles	--	4
2.	Rated speed	rpm	1500
3.	Rated torque	N.m	400
4.	Dc link voltage	V	550
5.	Moment of Inertia	$Kg.m^2$	0.09
6.	Friction coefficient	Nm-s	0.002
7.	Flux linkage	V.s	0.185
8.	Resistance	Ω	6.5e-3
9.	D-axis Inductance	mH	1.597e-3
10.	Q-axis Inductance	mH	2.057e-3

4. Simulation Results

An Interior Permanent Magnet Synchronous Machine is modelled by field-oriented control technique as shown in fig. 2 with parameters in Table 2 As it is advantageous compared to dynamic modelling. From fig (5-15) comparative analysis is done on the performance of motor with and without nonlinearities. The motor is operated forward and reverse direction with 0.5s step time. In fig (6) it is evident that when the iron loss is considered, the magnitude of currents, is decreased and power output is reduced. As a result, the electromagnetic torque will be reduced slightly. When variation of parameters according to rotor angle is considered, there are oscillations and harmonic content exhibited in torque, current, etc. From fig (9-11) the flux, stator current, torque, and inductance are a function of rotor position. If various non-linearities are taken into consideration, we may see the change in parameters from the above figures (12), (13), (14). The traditional mode, however, shows no distortion in the expected voltages, currents, or flux connections. Position-dependent d- and q-axis flux connections harmonics are visible in torque and current waveforms, unlike the typical conventional model that ignores spatial harmonics. Ignoring the iron loss effect in the simulation cannot accurately replicate real-world machine behavior, especially at high speeds where the iron loss influence is substantial and important.

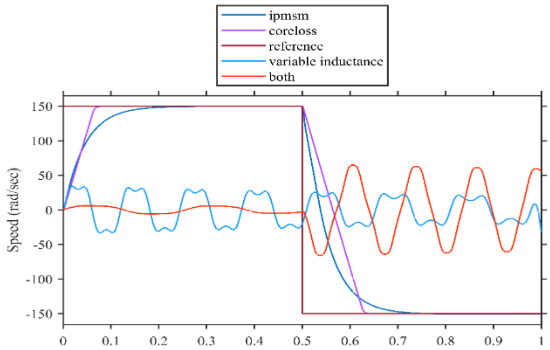

Fig. 11 *Comparison of the speed of the motor with the conventional and proposed model*

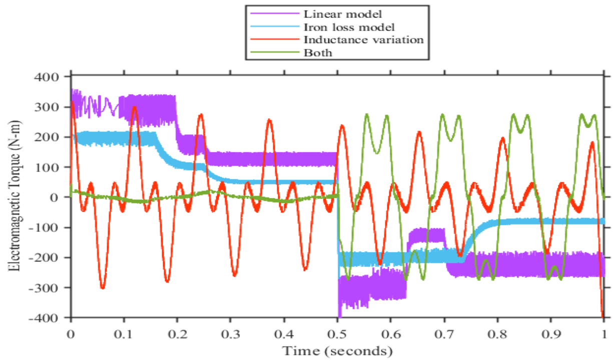

Fig. 12 *Comparison of electromagnetic torque with the conventional and proposed model*

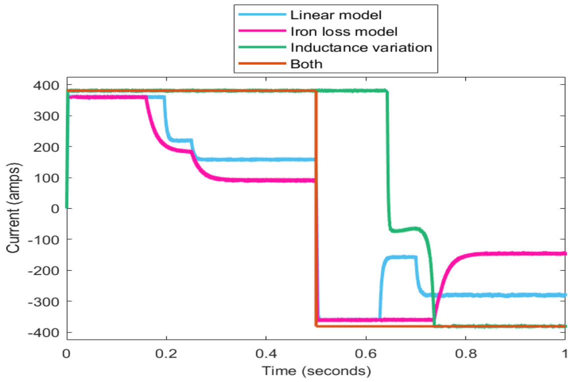

Fig. 13 *Comparison of armature current with the conventional and proposed model*

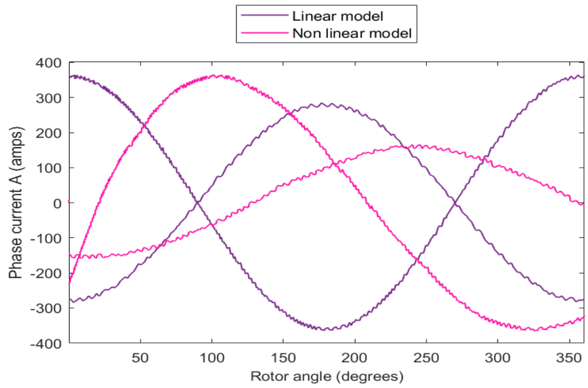

Fig. 15 *Comparison of phase current with the conventional and proposed model*

5. Conclusion

In aerospace applications as guided missiles need extremely accurate control systems. This is because the missile must reach the target without fail. So, in Electromechanical actuators, motor control plays a vital role. The inclusion of non-linearities is complex than the simplified model but it yields better performance The proposed mathematical model includes iron loss and varying inductance impact on the machine. To build the best control technique for precise controls, it is critical to reflect these negative impacts in drive system simulations. The results of the developed and simplified model are compared and presented. This model is more accurate when compared with the conventional model. The efficacy of the proposed model is done through a comparison of models. The simulation of the motor close to the real motor provides satisfaction to the user. It does not give false assurance about the performance of the motor.

Acknowledgement

The authors fully acknowledged the Institute of Engineering and Technology, University of Nottingham and Research Centre Imarat for supporting this work.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

References

[1] A. Aishwarya, R. Walambe, R. Kirti and K. Jaywant: Simulation of Permanent Magnet Synchronous Motor using MATLAB-Simulink. Annual IEEE India Conference (INDICON 2014).
[2] P. Ramesh and R. Prathyusha: Field Oriented Control of Permanent Magnet Synchronous Motor. International Journal of Computer Science and Mobile Computing, Vol.3 (2014).
[3] I. Chakraborty, D.N. Mavis, M. Emeneth and S. Alexander: A methodology for vehicle and mission level comparison of More Electric Aircraft subsystem solution: Application to the flight control actuation system. Journal of Aerospace Engineering.0(0), 1-15(2014).
[4] C. Wenping, B. C. Mecrow, J. A. Glynn, W. B John, and David J. A. David: Overview of Electric Motor Technologies Used for More Electric Aircraft. (IEEE Trans Ind., Electron., Vol. 59 2012).
[5] P. Pillay, R. Krishnan: Modelling of Permanent Magnet Motor Drives. (IEEE Trans., Ind. Electron.,1988).
[6] A. Mary Suja, R.S. Praveen Raj: Field Oriented Control of PMSM with Carrier Based Space Vector Pulse Width Modulation Technique. International Journal of Engineering Research & Technology, Vol. 4 (2015).
[7] A. Zaher: Nonlinear Computer-Based Modelling and Simulation of PMSMs. Second UKSIM European Symposium on Computer Modelling and Simulation (2008).
[8] L. Guangzhoa, Z. Rong, C. Zhen, T. Wencong, Z. Sha, K. Ralph: A Novel Nonlinear Modelling Method for Permanent Magnet Synchronous Motors. (IEEE Trans., Ind. Electron., Vol.63,2016).
[9] C. Xiao, W. Jiabin, S. Bhaskar, L. Panagiotis, and S. Tianfu: A High-Fidelity, Computationally Efficient Model for Interior Permanent Magnet Machines Considering the Magnetic Saturation, Spatial Harmonics and Iron Loss Effect. (IEEE Trans., Ind. Electron.,2009).
[10] T. Suresh Kumar, D. G Padhan, et al: Experimental Verification of Closed Loop Speed Control of PMSM using DSP 2407.International Conference on Control, Power, Communication and Computing Technologies (2018).
[11] M. Hrishikesh, A. Aishwarya, P. Swapnil and J. Vrunda: Vector Control of PMSM Using TI's Launchpad F28069 and MATLAB Embedded Coder with Incremental Build Approach.7th International Conference on Power Systems (2017).
[12] K. Alicemary, B. Arundhati, M. Padma: Modelling, Simulation and Nonlinear Control of Permanent Magnet Linear Synchronous Motor. International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, Vol. 1, pp.555-562 (2012).
[13] Ying Y, Jianguo Z and Youguang G: A Permanent Magnet Synchronous Motor Model with Core Loss: Journal of the Japan Society of Applied Electromagnetics and Mechanics Vol.l5, Supplement (2007).
[14] L. Parsa and H. Lei: Interior Permanent Magnet Motors with Reduced Torque Pulsation. (IEEE Trans. Ind. Electron., vol. 55, pp. 602-609,2008).
[15] X. Chen, J. Wang, P. Lazari, and L. Chen, Permanent Magnet Assisted Synchronous Reluctance Machine with fractional-slot winding configurations. (IEEE IEMDC 2013).
[16] P. H. Mellor, R. Wrobel, and D. Holliday: A computationally efficient iron loss model for brushless AC machines that caters for rated flux and field weakened operation. (IEEE IEMDC 2009).
[17] J. Goss, P. H. Mellor, R. Wrobel, D. A. Staton and M. Popescu: The design of AC permanent magnet motors for electric vehicles: A computationally efficient model of the operational envelope. (IET PEMD 2012).
[18] A. H. Wijenayake and P. B. Schmidt: Modelling and analysis of permanent magnet synchronous motor by taking saturation and core loss into account. Proceedings of International Conference on Power Electronics and Drive Systems (1997).
[19] K. Omer Cihan and O. Salih Baris: MATLAB Function Based Approach to FOC of PMSM Drive. IEEE European Modelling Symposium (2015).
[20] Z. Zaimin, Z. Shuihua, H. Chengyu, Y. Junming: Current harmonic selection for torque ripple suppression based on analytical torque model of PMSMs. Journal of Power Electronics (2020).
[21] R. Krishnan: Permanent Magnet Synchronous and Brushless DC Motor Drives.1st edition. CRC press, Boca Raton, Florida (2010).
[22] C. Roopa and Dr. S. Sujitha: The Implementation of Field Oriented Control for PMSM Drive Based on TMS320F28035 DSP Controller. International Journal of Applied Engineering Research, Vol.13, pp.4403-4408 (2018).