Effect of Airgap Flux Regulation on Interior Permanent Magnet Synchronous Motor

E. IDOKO[1], C. O. ONAH[2], F. O. ODUMA[3], I. A. OBOT[4]
[1, 2]*Department of Electrical and Electronics Engineering, College of Engineering, Joseph, Sarwuan Tarka University Makurdi, Benue State, Nigeria.*
[3, 4]*Department of Electrical and Electronic Engineering, Faculty of Engineering Technology, Nigerian Army University Biu, Borno State, Nigeria.*

Abstract- ***Permanent magnet synchronous motors (PMSMs) as AC machines are mostly preferred to other AC machines for applications in industries and other household appliances due to their high efficiency, high power density, high torque-to-inertia ratio, high dynamic response, simpler structure, better heat radiation capacity etc. In this study, an algorithm was developed to control the speed and torque of an interior permanent magnet synchronous motor (IPMSM) by regulating the airgap flux. A salient pole interior permanent magnet synchronous motor (IPMSM) drive powered by a Vdc source and incorporating a three-phase inverter (VSI) controlled by PWM, an electrical motor, a vector controller and a speed controller was modelled using MATLAB/Simulink 2021a version. The airgap flux was adjusted at an interval of 0.0005 Wb to assess the machine's performance such as speed, torque and mechanical power from the simulated results obtained. It was obvious from the results that the motor was improved by 64.12 % electromagnetic torque, 36.12 %, 25.9 % and 36.12 % mechanical power, efficiency and power density respectively. These features of the motor make it suitable for application in electric vehicles, home appliances, robotics and automation, medical devices, renewable energy systems, industrial drives, consumer electronics etc. Simulation results showed the efficacy of this method.***

Indexed Terms- ***Airgap Flux, Electromagnetic Torque, Mechanical Power, Power Density, Efficiency.***

I. INTRODUCTION

AC machine drives are becoming more popular; especially, the induction motor (IM) and the permanent magnet synchronous motor (PMSM). The interior permanent synchronous motor (IPMSM) is preferable because of its unique features such as high efficiency, high power density, high electromagnetic torque, dynamic response, simpler structure, better heat radiation capacity, high power factor, and wide operating speed range etc. [1]. As a result, the PMSM drives are applied in low and mid power usages [2].

Absence of mechanical components like brushes and slip rings makes the motor lighter and high power to weight ratio for which a higher efficiency and reliability are achieved [2]. Permanent magnet synchronous motors provide the highest power density in electrical machines. Permanent magnet synchronous motors (PMSMs) have been used in a wide spectrum ranging from industry to household appliances because of their advantages over their conventional counterparts. They find applications in fans, pumps, air conditioners, washing machines and electric vehicles (EVs) etc. [3].

The aim of this study is to analyze the performance of IPMSM as the airgap flux is regulated. The main objective of the study is to develop an algorithm that will access the performances of the torque, mechanical power and speed etc. of an IPMSM in order to show the effect of the airgap flux on the quantities.

II. LITERATURE REVIEW

Several authors and researchers have worked on speed and torque control of an IPMSM. The authors

employed various methods of control strategies to achieve their objectives different from the proposed methodology.

[4] proposed torque controlling strategies in hybrid electric vehicle in which the hybrid electric commercial vehicle must have a high-power density-to-weight ratio and excellent torque at extremely low speeds. The author also used the current proportional integral controller to determine the permanent magnetic flux linkage. Experiments were also used to validate other key metrics such as d-axis and q-axis inductances, stator resistance, and energy loss; the measured parameters were kept in lookup tables that span the whole operating range at various current levels. Both modelling and experimental findings validated the efficacy, torque ripple, stator and rotor fluxes, sensitivity of the vehicle parameters as well as the computational complexity of the proposed methodology.

But, [5] in their own view, presented a novel non-singular fast terminal sliding mode control (NFTSMC) based on deep weakening switching point tracking method in order to improve the control performance of IPMSM drive systems. The mathematical model of flux-weakening (FW) was established and the deep flux-weakening switching point was calculated accurately by analyzing the relationship between the torque curve and the voltage decline curve. The author designed the second-order NFTSMC for the speed loop controller to ensure convergence at the equilibrium in finite time. Simulation and experimental results showed the merits of the proposed scheme by improving steady-state accuracy, accelerating convergence etc.

[6] proposed a modified hybrid feed-forwarding/feedback flux-weakening algorithm for IPMSM using a standard T-type multi-level inverter, and hence, the voltage and current harmonics contents of the conventional two-level inverter were improved. The control algorithm utilized the optimal current profile for maximum torque per ampere (MTPA) operation and a voltage regulation feedback control for efficient flux-weakening operation. Extensive simulation scenarios were performed using the MATLAB/Simulink which validated the effectiveness of the proposed algorithm. Real-time simulations based on the d-space DS 1103 platform were conducted to confirm the system validity for real hardware implementation. The proposed IPMSM drive system proved simple structure, fast response, and low harmonic contents.

[7] presented a speed estimation scheme using the flux observer for a flux-vector-controlled (FVC) IPMSM drive. The FVC IPMSM drive was established using the current and flux of the stator, and the Hall effect current sensors were used to acquire the three-phase stator current from the IPMSM. The author developed the speed estimation scheme based on the flux observer in accordance with Lyapunov stability theory, and the observer gain matrix was designed using the artificial bee colony (ABC) algorithm. Simulation and experimental results confirmed the effectiveness of the proposed scheme.

[8] proposed to enhance the performance of DTC CSI fed IPMSM drive with online stator resistances estimation using a PI controller to limit the rate of rise of current under short-circuit conditions. The author used the MATLAB/Simulink software to investigate the performance of the stator resistance estimators and torque and flux responses of the drive. The results showed that the proposed method ensured reliability and performed well during low and high operations.
The review of the literature showed that much has not been done in the area of airgap flux regulation in order to access the machine's dynamic performance with respect to torque, mechanical power, and speed of IPMSM. This paper presents a detailed methodology of how the proposed work is achieved.

III. METHODOLOGY

An algorithm is developed to automatically adjust the airgap flux via the model equations of the motor in MATLAB 2021a environment as shown in Fig. 3 to access the machine's performance. Consequently, simulation results obtained are for speed, torque and mechanical power of a salient pole interior permanent magnet synchronous motor (IPMSM). The block and circuit diagrams of an IPMSM drive system are shown in Figures 1 and 2. The dynamic mathematical model equations of PMSM are shown to access the performance of IPMSM and a 2021a MATLAB/Simulink package is used for the

simulations to obtain results for considerations and analyses.

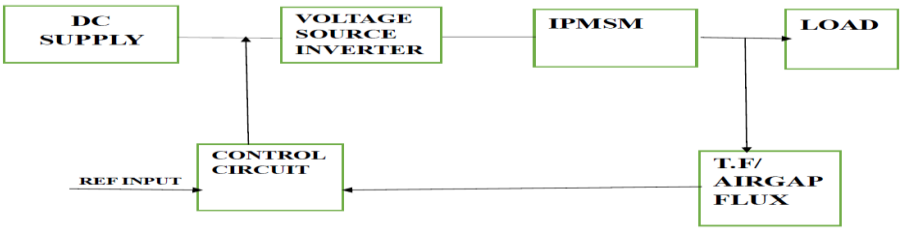


Figure 1: Block Diagram of the Interior Permanent Magnet Synchronous Motor Drive System

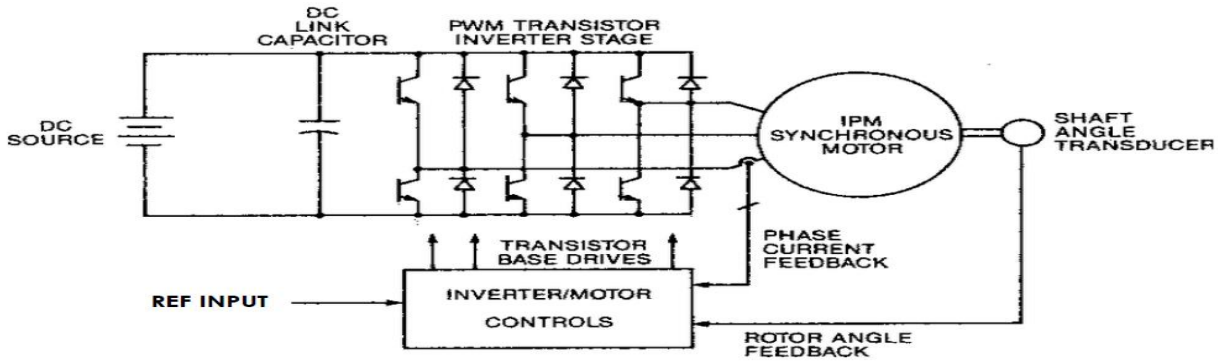


Figure 2: Circuit Diagram of the Interior Permanent Magnet Synchronous Motor Drive System

The dynamic mathematical model equations of PMSM are shown below.

$$\begin{bmatrix} V_q s \\ V_d s \end{bmatrix} = \begin{bmatrix} R_s + L_q P & \omega_r L_d \\ -\omega_r L_q & R_s + L_d P \end{bmatrix} \begin{bmatrix} i_q s \\ i_d s \end{bmatrix} + \begin{bmatrix} \omega_r Y_{af} \\ 0 \end{bmatrix} \quad (3.1)$$

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left[Y_{af} + (L_d - L_q) i_r d_r\right] i_r q_r \ (\text{Nm.}) \quad (3.2)$$

$$\omega_m = \int \left(\frac{T_e - T_l - B\omega_m}{J}\right) dt \quad (3.3)$$

$$T.F = \frac{\omega_m(s)}{V_q(s)} = \frac{K_t}{(R_s + L_q S)(J+B) + K_t P Y_{af}} \quad (3.4)$$

Where,

V_q and V_d are the quadrature and direct axes voltages respectively.
T_e is the electromagnet torque of the motor.
ω_m is the synchronous speed of the motor.
T.F is the transfer function of the motor.
R_s, B, J, K_t, Y_{af}, P, L_q, L_d, ω_r, $i_r d_r$, $i_r q_r$ are the stator resistance, coefficient of friction, moment of inertia, airgap flux, number of pole pairs, quadrature axis inductance, direct axis inductance, electrical rotor speed, direct axis current, and quadrature axis current respectively.

The Simulink model of the IPMSM drive is shown below in Figure 3.

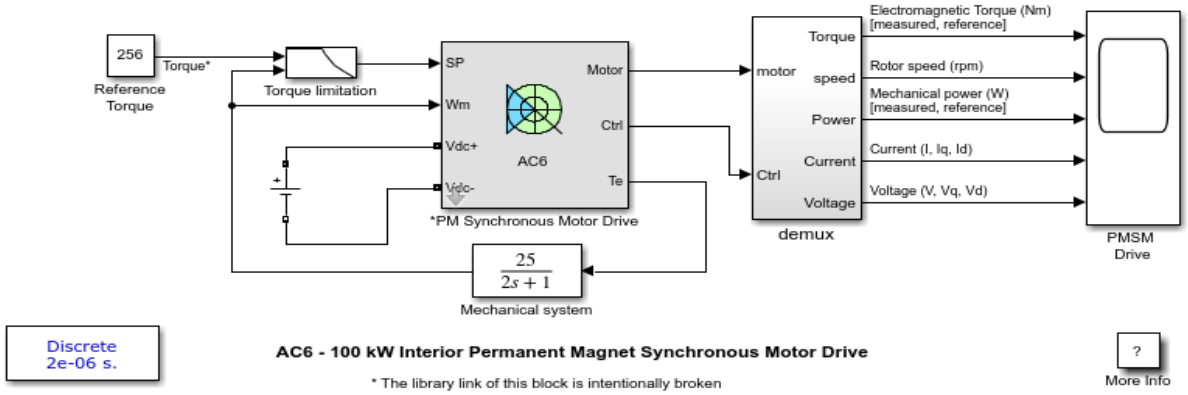


Figure 3: Simulink Model of the Interior Permanent Magnet Synchronous Motor Drive System

The salient pole IPMSM drive parameters are shown in Table 1.

Table 1: The Salient Pole IPMSM Drive Parameters and their Values.

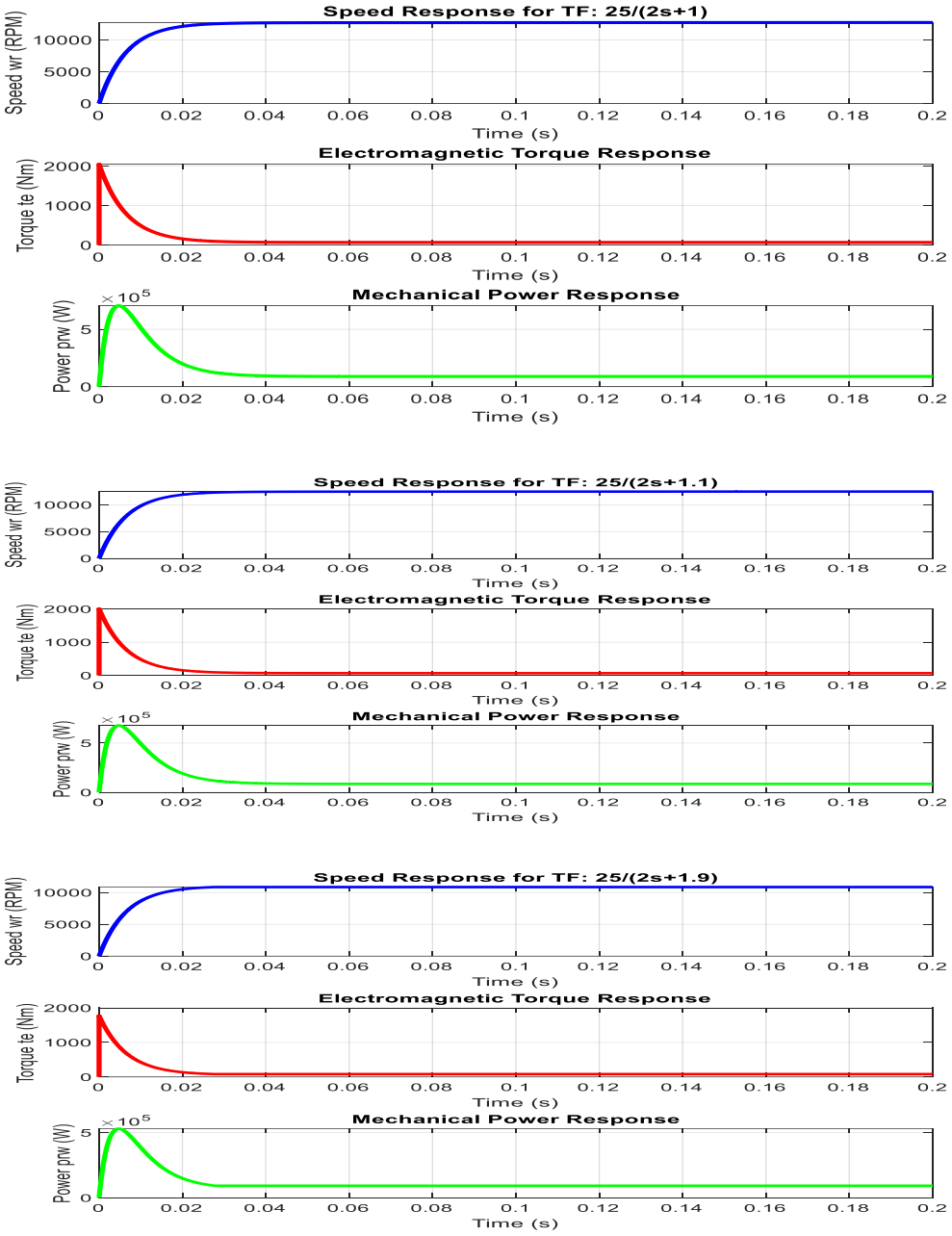
Parameter	Value
Mechanical angular speed	≈ 1308.99 rad/s
Proportional gain (K_p) and integral gain (K_i)	1.5 and 0.8
Motor's rated speed	12,500 rpm
Back emf constant (K_e)	≈ 193.91 Vs/rad
Stator resistance (R_s)	0.5 Ohms
Direct axis inductance (L_d)	0.002 H
Quadrature axis inductance (L_q)	0.0035 H
Torque constant (K_t)	25 Nm/A
Moment of inertia (J) of the motor	0.01 Kg.m^2
Coefficient of friction (B)	0.005 Nms.
Time constant	0.5 secs
Direct current supply (V_{dc})	288 V
Switching frequency	10 kHz
Efficiency	71.7 %
Airgap flux (Y_{af})	0.005 Wb
Sampling time	0.2 secs
Maximum torque	256 Nm
Air gap Length (g)	1.5 mm
Input Power	100 kW

To obtain the values of torque, speed, mechanical power, power density and efficiency, the airgap flux is adjusted from 0.005 Wb to 0.0095 Wb as seen from Figures 4 to 8.

MATLAB/Simulink and simulation results obtained in Figures 4 to 8 to show how airgap flux adjustments affect the torque, speed, efficiency, power density and mechanical power of an IPMSM at different transfer function values.

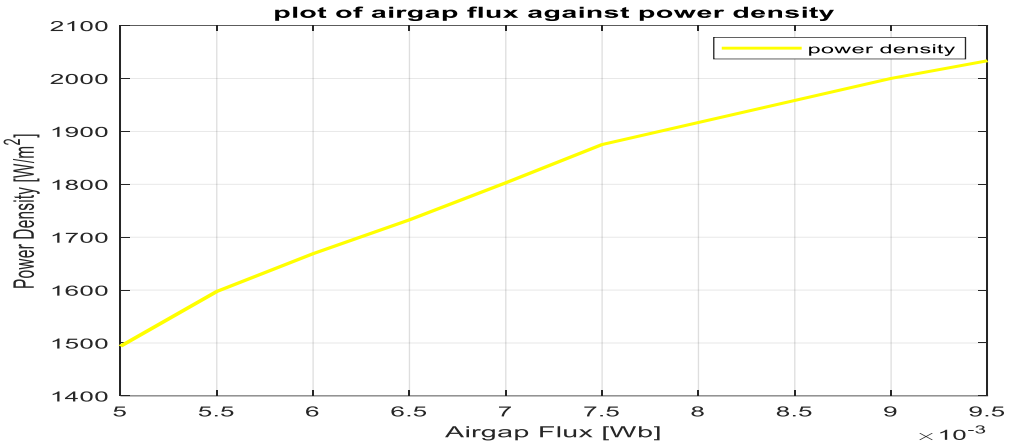
IV. RESULTS

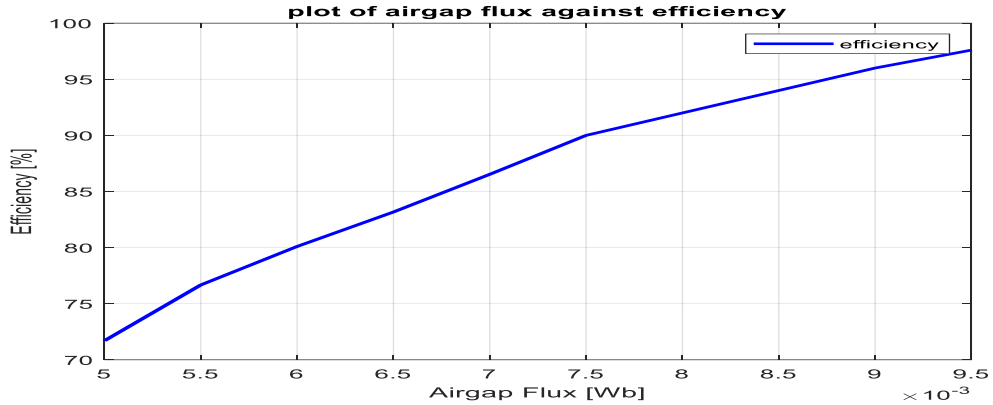
A 100 kW, 12500 rpm, salient pole interior permanent magnet synchronous motor (IPMSM) drive powered by a 288 V_{dc} source was modelled using



Figures 4 to 6: Effects of Airgap Flux Regulation on Speed, Torque, and Mechanical Power of the IPMSM Drive System.

The effects of airgap flux on power density and efficiency following the various transfer function adjustments are shown in Figures 7 to 8.





Figures 7 to 8: Effects of Airgap Flux Regulation on Power Density and Efficiency.

V. DISCUSSION

From Figures 4 to 6, it was observed that increasing the airgap flux led to an increase in the electromagnetic torque of the motor. This implies that the flux has a direct proportionality with the electromagnetic torque of the motor. For example, a base flux of 0.005 Wb led to an electromagnetic torque of 52.4 Nm. Increasing the flux to 0.0055 Wb consequently led to an electromagnetic torque of 57.5 Nm. This continued throughout the duration of the simulation with an increase of the flux to 0.0095 Wb leading to a further improvement in the electromagnetic torque to 86.0 Nm. This accounted for approximately 64.12 % improvement in the electromagnetic torque of the motor over the entire simulation process.

From Figures 4 to 6, it was observed that increasing the airgap flux allowed the motor to attain synchronous speed earlier within the same period of time. At a flux of 0.005 Wb, the synchronous speed was achieved at 13,070 RPM whereas, increasing the flux to 0.0055 Wb, the synchronous speed was achieved earlier at 12,732 RPM within the same period of time. This trend continued throughout the duration of the simulation. As long as the flux was increased, the synchronous speed would be achieved earlier than the previous flux value.

From Figures 4 to 6, it was observed that increasing the airgap flux led to an increase in the mechanical power of the motor. At a flux of 0.005 Wb, the mechanical power of the motor was 71,700 W. By increasing the flux to 0.0095 Wb, the mechanical power also increased to 97, 600 W. This trend continued throughout the duration of the simulation thereby improving the efficiency and power density of the motor. This also accounted for approximately

36.12 % improvement in the mechanical power of the motor over the simulation process.

From Figure 7, an airgap flux of 0.005 Wb resulted in a power density of 1493.75 W/m^2. Increasing the airgap flux to 0.0055 Wb resulted in a power density of 1597.29 W/m^2. This trend continued throughout the simulation process, thereby improving the power density by 36.12 %.
From Figure 8, an airgap flux of 0.005 Wb resulted in an efficiency of 71.7 %. Increasing the airgap flux to 0.0055 Wb resulted in an efficiency of 76.67 %. This trend continued throughout the simulation process, thereby improving the efficiency by 25.9 %.

CONCLUSION

In this study, a method of speed and torque control of an interior permanent magnet synchronous motor (IPMSM) has been established. The electromagnetic torque and mechanical power were improved by 64.12 % and 36.12 % respectively. By improving the electromagnetic torque and mechanical power occasioned by the increase in airgap flux, the motor's efficiency was improved by 25.9 % from 71.7 % to 97.6 %, the power density was also improved by 36.12 % from 1493.75 W/m2 to 2033.33 W/m2. Reliability and performance characteristics were also greatly improved. This makes this motor suitable for application in industries and household appliances such as: electric vehicles, industrial drives, medical devices, consumer electronics, HVAC systems, household appliances, renewable energy systems, air conditioning and refrigeration systems, and robotics and automation.

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