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Steady-state Model of a Line-start Interior Permanent Magnet Synchronous Motor with Capacitance Injection

Onah. C. O.[1], Obe. E. S.[2], Idoko. E.[3]
[1]*Lecturer, Department of Electrical and Electronics Engineering, University of Agriculture, Makurdi, Nigeria*
[2]*Professor, Department of Electrical and Electronics Engineering, University of Nigeria, Nsukka*
[3]*Lecturer, Department of Electrical and Electronics Engineering, University of Agriculture, Makurdi, Nigeria*

Abstract: *For better understanding of the operational characteristics of a dual stator winding interior permanent magnet synchronous motor, the steady-state performance analysis is required. Therefore, this paper primarily set forth to address the steady-state model and performance analysis of a line-start permanent magnet synchronous motor with capacitance injection for the enhancement of power factor and torque. The proposed machine has two sets of three-phase stator windings with one directly connected to the mains supply and the other connected to a balanced set of capacitors for leading current injection. The steady-state equations are derived using d-q model and the impact of capacitance on the various operational parameters investigated. Also, an equivalent circuit is deduced from the steady-state equations. Current in both the main and auxiliary windings contributes positively to torque production in the absence of external control circuitry.*

Keywords: *Dual stator winding, Steady-state, Power factor, Torque, capacitance injection, Equivalent circuit*

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I. Introduction

Recently, permanent magnet synchronous machines (PMSM) have attracted increasing interest for industrial drive applications. The improvement in permanent magnet materials and the availability of low-cost power electronic devices have contributed immensely to the utilization of permanent magnet motors even in some more demanding applications [1-3]. Some special characteristics make the PMSM drives ready to meet up sophisticated needs such as high power factor, wide operating speed range and fast dynamic response. In a PMSM, the dc field winding of the rotor is replaced by a permanent magnet to produce the air-gap magnetic flux. Having the magnets on the rotor, electrical losses due to field winding of the machine get reduced and the absence of the field losses enhances thermal characteristics of permanent magnet motor and its efficiency [4, 5].

In the face of wide industrial use of inverter for variable voltage and variable frequency supply to PMSM, line-start operation of permanent magnet synchronous motors is still highly relevant in low, medium and fractional horsepower applications. Since the permanent magnet synchronous machines are inherently not self-starting, a rotor cage is employed to help start the motor on a fixed frequency supply. The motor starts as an induction motor by the resultant of two torque components, which include cage torque and magnet component torque (braking torque). When the motor speed reaches near synchronous speed, a synchronization process begins and motor operation is transferred to synchronous state when no eddy current flows into the cage bars except harmonic field currents. In the synchronous state, two torque components comprising reluctance and a synchronous torque components cause the rotor motion. Although, several attempts have been reported at improving the performance of line-start permanent magnet synchronous motors, none really provides an acceptable option that can guarantee the large industrial assent to match the line-start induction motors, which are still manufactured in large quantity yearly [6].

The Survey of Dual Stator Winding Machines

The field of modeling and analysis of dual winding machine drive system has attracted considerable attention during the last three decades. Study in this area is ongoing and a lot of interesting developments have been reported in numerous available literature. This is due to several advantages that dual stator winding machine possesses over the conventional three-phase machines, such as reduction in space and time harmonics, reduction in amplitude and increase in the frequency of torque pulsations, reduction in current per phase without increasing the voltage per phase, lowering the dc link current harmonics, increase in power to weight ratio, and higher reliability etc. Consequently, the use of dual winding machine can be found in many applications such as electric ship propulsion, electric/hybrid electric vehicle propulsion, aircraft, thermal power plant to drive and induce draft fans, nuclear power plant, etc. [7, 8, 9].

As far as steady-state model of interior permanent magnet synchronous motor with two independent stator winding is concerned, limited literature is available as the field is in its primitive stage. The steady state performance analysis of a connection scheme that improved the power factor and torque with a lower magnetizing current for a line-start synchronous reluctance motor was reported by [6]. In the paper, the machine stator winding was split into two equal halves, one connected to the mains and the other connected to a balanced capacitor. There was an improved performance of the machine if the capacitor value was such that the winding to which it was connected operated at or very close to resonance in the d-axis. Currents in both windings contributed positively to torque production and external control circuitry was not required. Steady state equations derived from the d-q model gave a direct insight on the operating limits and how the capacitance aided the machines torque and power factor by boosting its direct axis reactance. However, the quadrature axis reactance remained fairly constant. An equivalent circuit was also deduced from the steady- state equations from which an explicit expression for input impedance of the new machine can be derived. The author further examined the conditions for unity-power factor at varying load conditions. A comparison with conventional single-winding synchronous reluctance motor was given.

The paper [10] presented the mathematical model of dual stator squirrel-cage induction motor formulated in phase co-ordinate system and in general transformed space vector form. The two types of models of dual stator induction motor were considered. The first type of model considered the dual stator induction motor as two independent three-phase motors coupled together by a common rotor winding. This approach was based on modeling principles used for classical three-phase machines. In the second type of model, the dual stator induction motor was considered as a six-phase induction motor. This approach was based on modeling principles used for multiphase induction machines. The control systems of field-oriented control (FOC) and direct torque control (DTC) of the dual stator induction motor were discussed. Simulation studies of FOC and DTC methods used for the control of dual stator induction motor (DSIM) were performed and results presented.

The analysis of dual stator permanent magnet BLDC (PMBLDC) was reported in [11]. The suggested dual stator PMBLDC motor composed of two separate concentric stators having different number of slots with a common rotor on the same shaft. Two stator stampings of different radii were used for design of stators. The analysis of the designed dual stator was then performed resulting in the total output torque corresponding to the algebraic sum of two independent torques.

A research on novel dual three-phase permanent magnet synchronous motor with asymmetrical stator winding was conducted by [12]. In the research, a novel PM multiphase motor was designed with dual three-phase asymmetric stator winding. The winding structure of the proposed machine was unconventional due to selected slot-pole combination. Proposed motor performance data was also compared with symmetric multiphase PM motor with dual three-phase AC windings to illustrate the benefits. It was shown that the novel unconventional multiphase PM motor has excellent torque quality and slightly higher torque density levels.

In [13], an overview of the topological variation of multi-winding induction machine and drives was presented. The study was restricted to induction machines having two distributed windings on the stator and a brushless rotor. The mathematical modeling techniques and control algorithms available in literature were highlighted. Being magnet-less and brushless, dual stator winding induction machine was highly reliable, maintenance free and economic. Thus, the paper concluded that the machine possessed the necessary potential to becoming a part of AC and DC micro-grid, and summarized different forms of dual stator winding induction machines and drives together with detailed methods of analysis and control strategies.

Dual Winding Machines with Capacitance Injection

Generally, capacitors are famous for power factor compensation as poor power factor adversely affects the distribution system and a cost penalty is frequently levied for excessive VAr consumption. However, for power factor improvement in Ac motors, two sets of three-phase stator windings are essential. This machine winding configuration is suggested because if the capacitor is in series connection with a single-winding machine, the impedance drastically reduced leading to abnormally high current in the system. On the other hand, if connected in parallel, the power factor of the supply source is enhanced with negligible improvement in the motor performance [6].

A report of two previous schemes that have been applied to induction motors without success was given by [6]. One of which is referred to as "Wanlass motor" invented by Wanlass and the other is "unity-plus winding motor" invented by Roberts. The winding configuration adopted in this paper is similar to the one in [6] but applied to line-start interior permanent magnet synchronous motor. Utilizing the split-wound machine concept and capacitance injection as presented here is to seek an alternative to the expensive solid-state devices used in the enhancement of torque and power factor of AC machines.

Normally, electrical motor operates at steady-state condition at a particular output load, therefore, steady state analysis is desirable for a better understanding of the operational behavior of a dual stator winding interior permanent magnet synchronous motor under sudden load changes. It will be advantageous to examine its describing equations followed by the development of the steady-state equivalent circuit. Similarly, knowledge of steady-state behavior is indispensable for checking the correctness of the simulation results. The steady-state analysis of an interior permanent magnet synchronous motor with two independent stator winding and capacitance injection is not yet reported to best of the authors' knowledge. Therefore, the main contribution of this paper is to explore the steady-state operation of the proposed motor during its normal operating condition.

II. Materials and Methods

Machine Structure

The proposed interior permanent magnet synchronous motor has two independent stator windings and capacitance injection. The two independent stator windings are magnetically coupled through the stator core but electrically isolated. For the purpose of distinction, one of the two sets of three-phase stator windings is referred to as the main winding and is connected to the three-phase mains supply. The main winding is designated as ABC. The second set of the stator windings is referred to as the auxiliary winding, represented as abc and connected to a balanced set of capacitors for leading current injection. The injection of leading current will enhance the electromagnetic torque of the machine. The machine winding configuration as adopted in this paper is as depicted in Figure 1.

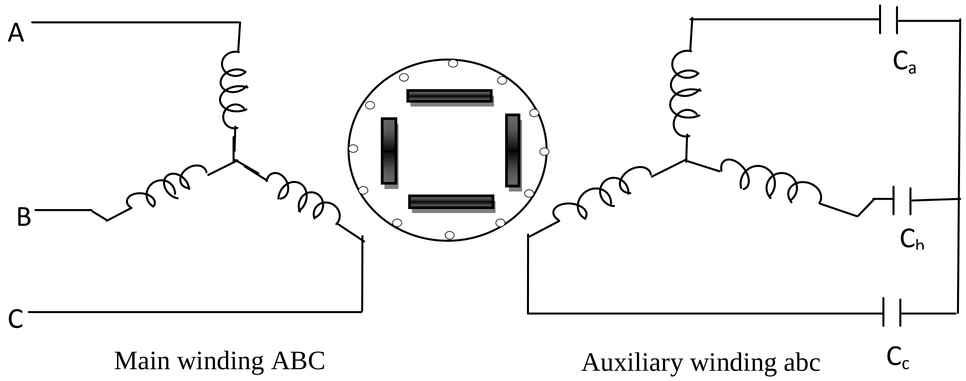

Figure no. 1: Machine winding arrangement of the proposed Motor

Steady-State Model

Adopting the equations used in the development of d-q equivalent circuit in [6], setting all derivative terms to zero and ignoring all rotor voltage equations, the stator voltage equations in rotor reference frame variables for the proposed machine of Fig. 1 are:

$$V_{q1} = r_1 i_{q1} + \omega_r \lambda_{d1} \tag{1}$$

$$V_{d1} = r_1 i_{d1} - \omega_r \lambda_{q1} \tag{2}$$

$$0 = r_2 i_{q2}^{'} + \omega_r \lambda_{d2}^{'} + V_{cq2}^{'} \tag{3}$$

$$0 = r_2 i_{d2}^{'} - \omega_r \lambda_{q2}^{'} + V_{cd2}^{'} \tag{4}$$

where, V_{q1}, i_{q1} and λ_{q1} are q-axis voltage, current and flux linkage of the main winding respectively while, V_{d1}, i_{d1} and λ_{d1} are d-axis voltage, current and flux linkage of the main winding respectively. ω_r is the rotor speed.

$$pV_{cq2}^{'} = \frac{i_{q2}^{'}}{C} - \omega_r V_{cd2}^{'} \tag{5}$$

$$pV_{cd2}^{'} = \frac{i_{d2}^{'}}{C} + \omega_r V_{cq2}^{'} \tag{6}$$

where, $p = \dfrac{d}{dt}$

$V_{cq2}^{'}$ and $V_{cd2}^{'}$ are the capacitor quadrature and direct axes voltages respectively while ω_r is the synchronous angular frequency in radians per second. $V_{cq2}^{'}$ and $V_{cd2}^{'}$ can be obtained from equations (5) and (6) as $pV_{cq2}^{'}$

and pV'_{cd2} are set to zero at steady-state. Upper case letters are adopted here for all variables to denote that they are simple constants.

$$0 = \frac{I'_{q2}}{C} - \omega_r V'_{cd2} \tag{7}$$

$$0 = \frac{I'_{d2}}{C} + \omega_r V'_{cq2} \tag{8}$$

From equations (7) and (8),

$$V'_{cd2} = \frac{I'_{q2}}{\omega_r C} \tag{9}$$

$$V'_{cq2} = -\frac{I'_{d2}}{\omega_r C} \tag{10}$$

Substituting for V'_{cq2} and V'_{cd2} in equations (3) and (4) using equations (9) and (10) yields:

$$0 = R_2 I'_{q2} + \omega_r \lambda'_{d2} - \frac{I'_{d2}}{\omega_r C} \tag{11}$$

$$0 = R_2 I'_{d2} - \omega_r \lambda'_{q2} + \frac{I'_{q2}}{\omega_r C} \tag{12}$$

The flux linkage equations are defined as:

$$\lambda_{q1} = L_{l1} I_{q1} + L_{mq}(I_{q1} + I'_{q2}) \tag{13}$$

$$\lambda_{d1} = L_{l1} I_{d1} + L_{md}(I_{d1} + I'_{d2} + I'_m) \tag{14}$$

$$\lambda'_{q2} = L_{l2} I'_{q2} + L_{mq}(I_{q1} + I'_{q2}) \tag{15}$$

$$\lambda'_{d2} = L_{l2} I'_{d2} + L_{md}(I_{d1} + I'_{d2} + I'_m) \tag{16}$$

Substituting for flux linkages in stator voltage equations (1), (2), (11) and (12) results in equations (17), (18), (19) and (20).

$$V_{q1} = R_1 I_{q1} + \omega_r (L_{l1} + L_{md}) I_{d1} + \omega_r L_{md} I'_{d2} + \omega_r \lambda'_m \tag{17}$$

$$V_{d1} = R_1 I_{d1} - \omega_r (L_{l1} + L_{mq}) I_{q1} - \omega_r L_{mq} I'_{q2} \tag{18}$$

$$0 = R_2 I'_{q2} + \omega_r L_{md} I_{d1} + \omega_r \left(L_{l2} + L_{md}\right) I'_{d2} - \frac{1}{\omega_r C} I'_{d2} + \omega_r \lambda'_m \tag{19}$$

$$0 = R_2 I'_{d2} - \omega_r L_{mq} I_{q1} - \omega_r \left(L_{l2} + L_{mq}\right) I'_{q2} - \frac{1}{\omega_r C} I'_{q2} \tag{20}$$

Let

$$X_{q1} = \omega_r \left(L_{l1} + L_{mq}\right)$$

$$X_{d1} = \omega_r \left(L_{l1} + L_{md}\right)$$

$$X_{md} = \omega_r L_{md}$$

$$X_{mq} = \omega_r L_{mq}$$

$$X_{q2} = \omega_r \left(L_{l2} + L_{mq}\right)$$

$$X_{d2} = \omega_r \left(L_{l2} + L_{md}\right)$$

$$X_c = \frac{1}{\omega_r C}$$

Therefore, equations (17), (18), (19) and (20) become:

$$V_{q1} = R_1 I_{q1} + X_{d1} I_{d1} + X_{md} I'_{d2} + \omega_r \lambda'_m \tag{21}$$

$$V_{d1} = R_1 I_{d1} - X_{q1} I_{q1} - X_{mq} I'_{q2} \tag{22}$$

$$0 = R_2 I'_{q2} + X_{md} I_{d1} + X'_{d2} I'_{d2} - X_C I'_{d2} + \omega_r \lambda'_m \tag{23}$$

$$0 = R_2 i'_{d2} - X_{mq} I_{q1} - X'_{q2} I'_{q2} - X_C I'_{q2} \tag{24}$$

Rearranging equations (23) and (24) results:

$$0 = R_2 I'_{q2} + X_{md} I_{d1} + \left(X'_{d2} - X_C\right) I'_{d2} + \omega_r \lambda'_m \tag{25}$$

$$0 = R_2 I'_{d2} - X_{mq} I_{q1} - \left(X'_{q2} + X_C\right) I'_{q2} \tag{26}$$

According to [6, 14], there is an established relationship between the main and the auxiliary winding rotor reference frame state variables and synchronously rotating phasors at synchronous speed steady-state mode. This relationship is described by equations (27) and (28).

$$K_1 = \left(K_{q1} - jK_{d1}\right) e^{j\delta} \tag{27}$$

$$K_2 = \left(K'_{q2} - jK'_{d2}\right) e^{j\delta} \tag{28}$$

where K can be current, voltage or flux linkage phasors, δ is the load angle.

As stated previously, the auxiliary winding has no voltage supplied to it, hence, V_{q2} and V_{d2} equal zero. However, the main winding has voltage supplied from balanced sinusoidal set of voltages [6], which are defined by equations (29) and (30).

$$V_{q1} = V \cos\delta \tag{29}$$

$$V_{d1} = -V \sin\delta \tag{30}$$

Substituting for V_{q1} and V_{d1} in equations (21) and (22) respectively through equations (29) and (30) produces equations (31) and (32).

$$V \cos\delta = R_1 I_{q1} + X_{d1} I_{d1} + X_{md} I'_{d2} + \omega_r \lambda'_m \tag{31}$$

$$-V \sin\delta = R_1 I_{d1} - X_{q1} I_{q1} - X_{mq} I'_{q2} \tag{32}$$

Further simplification with equations (27) and (28) yields equations for the phase voltages of the main and auxiliary windings respectively as equations (33) and (34)

$$V_A = \left[R_1 + j(X_L + 2X_{mq})\right] I_A + \left(E_1 + E_2\right) e^{j\delta} + jX_{mq}\left(I_A - I'_a\right) + \omega_r \lambda'_m e^{j\delta} \tag{33}$$

$$0 = \left[(R_2 + j(X_L - X_{md} - X_c)\right] I'_a + E_1 e^{j\delta} + jX_{mq}\left(I_A - I'_a\right) + \omega_r \lambda'_m e^{j\delta} \tag{34}$$

where, X_L = leakage reactance of the machine, X_{mq} = q-axis magnetizing reactance, I_A = phase current of the main winding, I'_a = phase current of the auxiliary winding, E_1 and E_2 represent excitation due to flux linkage λ'_m , X_{mq} = q-axis magnetizing reactance.

Equations (33) and (34) are used to develop the steady-state equivalent circuit of the proposed machine depicted in Fig. 2.

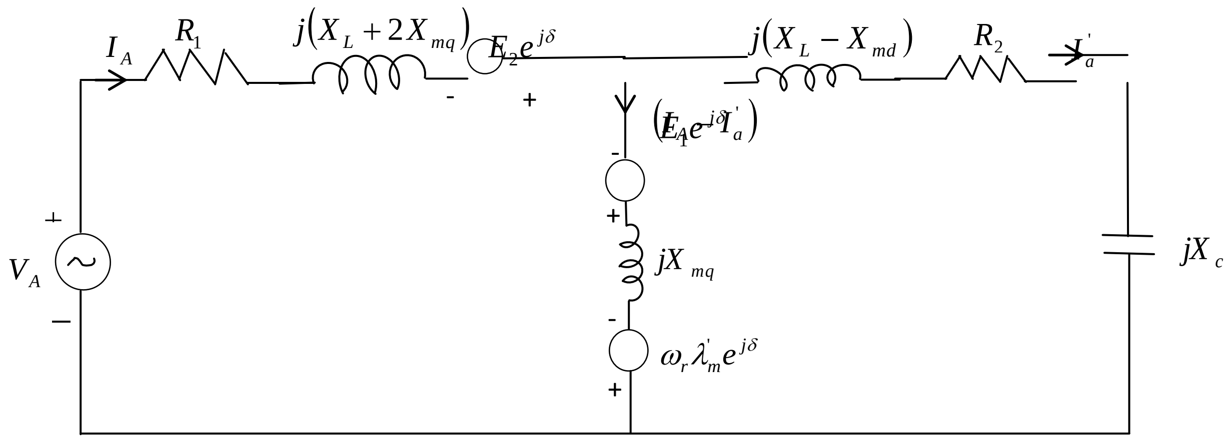

Figure no. 2: Steady-state Equivalent Circuit of the Proposed Machine

III. Results

In this section, the steady-state model of the proposed motor is implemented in MATLAB/Simulink environment using the parameters shown in Table 1.

Table 1: Machine Parameters

Frequency, f = 50 Hz	No. of Poles, P = 4
Stator leakage Inductance, L_{ls} = 0.0028 H	q-axis Inductance , L_{mq} = 0.0441 H
Moment of inertia, J = 0.42 Kgm^2	d-axis Inductance , L_{md} = 0.0206 H
q-axis Cage Inductance , L'_{lkq} = 0.0057 H	d-axis Cage Inductance , L'_{lkd} = 0.0057 H
Stator Resistance , r_s = 0.301 Ω	q-axis Cage Rotor Resistance , r'_{kq} = 1.912 Ω
d-axis Cage Rotor Resistance , r'_{kd} = 0.957 Ω	Permanent magnet Flux linkage, λ_m = 0. 8 Wb

turn

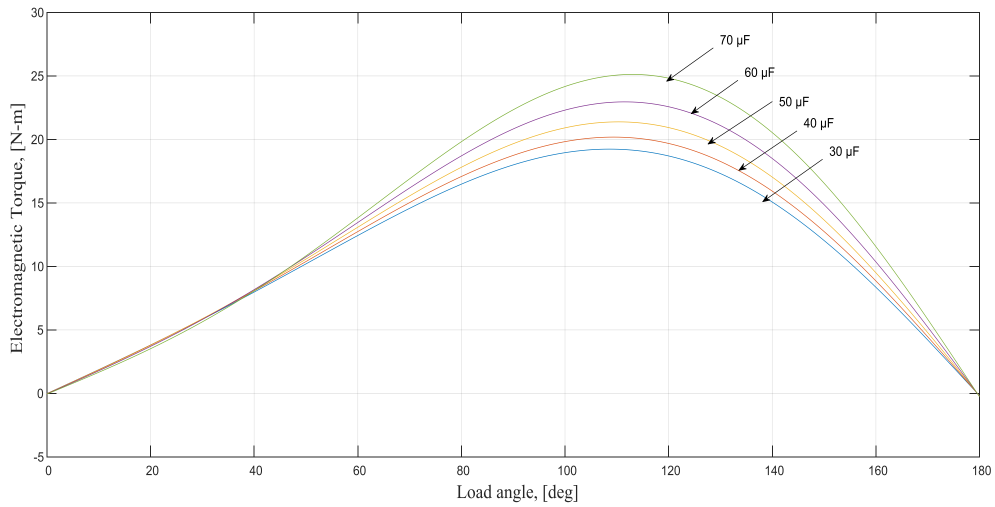

Figure no. 3: Torque - Load Angle Curve of Proposed Machine for various Capacitor value

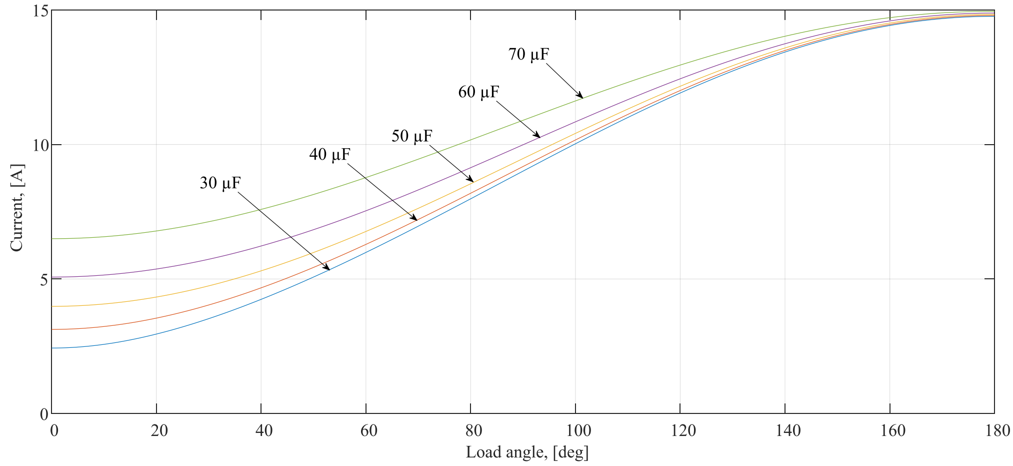

Figure no. 4: Main Winding Current – Load angle Curve for various Capacitor values

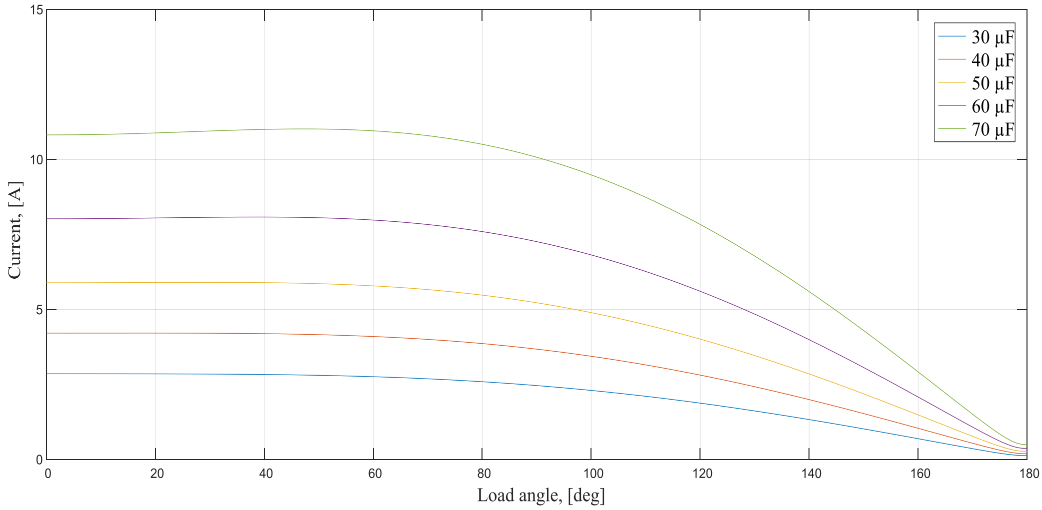

Figure no. 5: Auxiliary Winding Current – Load Angle Curve for various Capacitor values

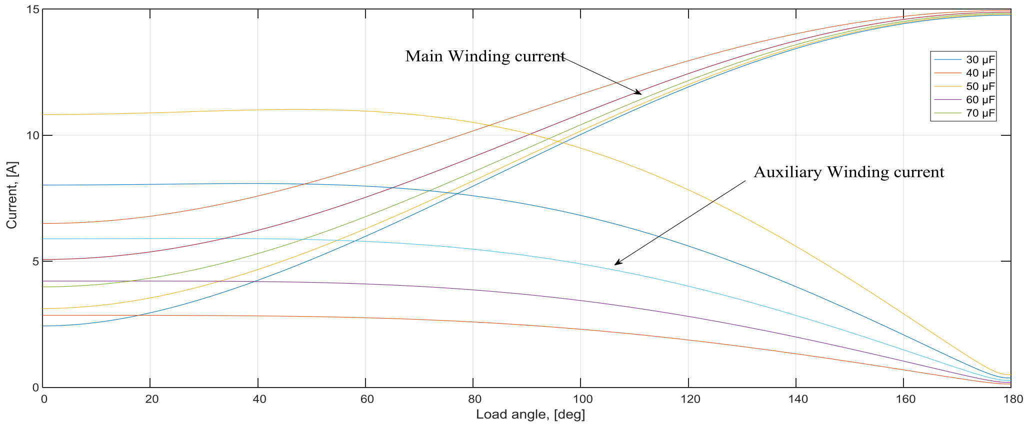

Figure no. 6: Current – Load Angle Curve for various Capacitor values

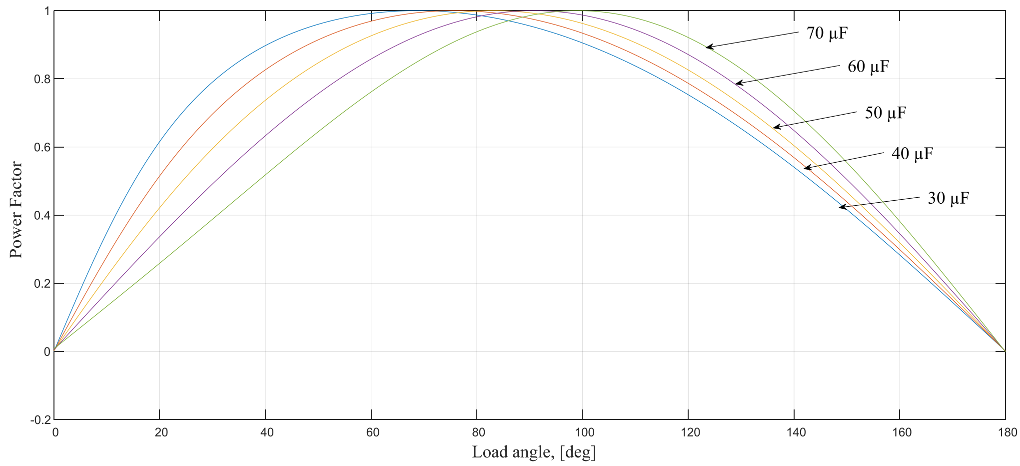

Figure no. 7: Plot of Power Factor against Load Angle at different values of Capacitance

IV. Discussion

Figure no. 3 shows the variation of electromagnetic torque as a function of the load angle for various values of capacitors in the steady-state. The plot reveals torque enhancement proportional to the size of the capacitance. The optimal value of torque was observed at the capacitance value of 70 μF. It is obvious from this figure that the relative improvement in torque of the proposed machine is at a load angle of 48.84° and higher.

Displayed in Figure no. 4 are the currents for various values of capacitors in the main winding during steady-state operation. The plots indicate that the main winding current is influenced by the size of capacitance or load torque, thus it increases relatively over the range of operation.

Figure no. 5 shows the currents for various values of capacitors in the auxiliary winding during steady-state operation. The plots indicate that the auxiliary winding current is influenced by the size of capacitance or load torque, thus it remains relatively constant over the range of operation.

Figure no. 7 shows a comparative display of simulated power factor through the injection of reactive power in the auxiliary winding, which reveals an improvement in the power factor of the motor. The whole essence of modeling an additional set of three-phase stator windings referred to as the auxiliary winding is to enhance the power factor of the proposed permanent magnet synchronous motor. Thus, a critical consideration at the performance of the motor parameters that involve the power factor during reactive power injection is made. The injected reactive power is directly proportional to the size of the capacitor. In other words, the larger the size of the capacitor, the more reactive power is injected and hence improved power factor. This figure further illustrates the possibility of operating this machine at unity power factor for different load angles as well as capacitance values. Unlike the conventional IPMSM, the proposed machine has a relatively high power factor over a wide range of load angles, which is due to the additional set of three-phase winding and capacitance injection. For the proposed machine for this study, the capacitor of 70 μF connected per phase as in Figure 1 gives a power factor of 0.997, which is very close to unity at a load angle of 94.97°.

V. Conclusion

A self-starting interior permanent magnet synchronous motor with two independent stator windings and capacitance injection has been presented. Power factor improvement up to near unity is observed in the steady-state studies. A power factor improvement over a wide range of load and value as high as 0.99, compared to the theoretical value of 0.70 for conventional line-start interior permanent magnet synchronous motor was attained. This implies about 42.2% improvement in power factor utilizing the appropriate capacitor value of 70 μF per phase in the auxiliary winding. This power factor improvement invariably translates to higher efficiency, lower losses, and reduction in unnecessary electric utility charges.

The steady-state analysis also reveals that the motor winding configuration adopted offers a slight torque enhancement. This was made successful by treating one of the two sets of stator windings as the main winding and connecting it to a balanced three-phase mains supply. While the remaining set of the three-phase stator winding considered as the auxiliary winding was connected to a balanced capacitance for leading current injection.

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