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Influence Of Stator Winding Turns On Performance Parameters Of Design Optimized Spoke-Inset Type Fractional Slot Ipm Synchronous Motor

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Abstract **—** The spoke-inset type, fractional slot synchronous motor with an inside permanent magnet has a wider range of industrial applications due to its higher efficiency and maximum power output. The motor must run at a nominal speed and rated power in high-power applications. To meet the motor's high-power demand, the coil's stator turns have been changed. The increased number of turns lengthens the conductor, resulting in a more rotating magnetic field that provides the necessary horsepower. If the number of turns increases more, the undesirable effects of, a drop in speed, a rise in total loss, the density of current changes, and a decrease in efficiency, can aggravate the performance of the motor. To demonstrate the impact of turn variation on IPMSM performance, a 12.45 kW, 2000 rpm IPMSM is employed, and a 3D transient electromagnetic field model is developed. Initially, Electromagnetic behavior analysis was made by the Finite Element Method (FEM). The optimum performance-determining parameters are then obtained by sensitivity analysis. The IPMSM's performance is quantitatively analyzed based on the significance of turn variation, including the amount of current, rated speed, torque, and power. In addition, the effect of turn number variation on eddy current, copper, and hysteresis loss is being addressed further. Finally, the IPMSM temperature profile is analyzed using the coupling method of electromagnetic field and thermal field, and the various parts of temperature distribution in IPMSM are obtained. The effectiveness of the IPMSM design optimization is demonstrated in this study.

Index Terms **-** Copper loss, Fractional slot, FEM, IPMSM, Iron loss, Number of turns variation.

I. Introduction

IPMSMs are the preferred electric vehicle motor choice for the majority of automobile industries, despite price instability and restricted raw material availability. Inner rotors with inserted permanent magnet designs offer superior performance, a wide ranging of speed, a less weight, and more rugged geometrical construction. [Bianchi N, 2004]. Different rotor structures with various PM combinations were presented, and their impact on machine performance was studied in [Jung H (2005), Du J (2016), Asef P (2021)]. Several rotor designs for electric vehicles were studied, and their electromagnetic field features, such as efficiency, torque production, and flux reduction capability over a wide working range, were compared [Hwang M.-H (2018), Li Y (2019)]. Many studies were performed to overcome the drawbacks of generating more ripples and non-uniformity distribution of air gap magnetic field while constructing an optimal rotor design. [Chu G (2020), Chang Y.-H (2021)]. Because of its flux concentration capability, the spoke-type rotor became more popular among the several IPMSM rotor types that offer high torque density and more robustness [Kwon B. I (2015), Breban S (2022), Suganthi S (2023)]. In motor design construction, three-phase stator winding is another important part. The stator winding turns have an important role in the energy interchange process takes place which determines the operation of the motor [Ali Ihsan Canakoglu (2016)].

In references [Hu K (2019), Gu B.-G (2023)], It can be found that the winding number of turns had an impact on energy efficiency improvement with considering motor losses. The impact of turn variation on motor losses was addressed. In [Chaithongsuk S (2015)], rotor losses were reduced by modifying the flux path of the armature reaction based on the pulse width modulation technique in the fractional slot concentrated winding PMSM motor. In reference [Chiba M (2012)], proposed a method for reducing the maximum stator current of switched reluctance motor by increasing the number of winding turns. In reference [Al-Habshi S.M (2014)], it can be seen that a significant reduction of unbalanced magnetic force was achieved possibly by employing an uneven number of turns per coil. In reference [Corda J (1996)], suggested a method for determining the optimal number of turns per phase winding of a switching reluctance motor with a specified magnetic configuration and operating parameters in terms of output power and speed. In reference [Qiu H (2020)], The current generated by the stator coil provides an alternating magnetic field, which has a direct impact on the motor's performance. The characteristics of the PMSM were studied using a 2D transient electromagnetic field. An IPMSM temperature field was studied using the electromagnetic field-thermal field coupling technique [Chen L (2018)]. In recent years, many scholars have made relevant studies on the winding turns of motors. But, many scholars have not fully studied on the influence of the armature winding turns on PMSM performance, and the influence of the variation mechanism was not demonstrated properly.

The main objective of this research is the influence of the number of winding turns per coil on IPMSM performance and the optimum selection of the number of turns of IPMSM is achieved by sensitivity analysis for the specified operating conditions in terms of rated power, speed, and torque. The performance parameters such as induced electromotive force (EMF), winding resistance, power factor, iron loss, copper loss, efficiency, speed, torque, output power, and torque ripples are directly impacted by turn variations. Due to these parameters changing, the motor performance will then be shifted to some more extent by the influence of the turn variations. The stator winding turn value has been effectively optimized to increase the motor's performance. The FEM of 3D electromagnetic field is established and the behavior of the electromagnetic field influence on variation in winding turns is studied in this paper. In addition, based on the electromagnetic field-thermal field coupling method, the sensitivity of the temperature field to motor winding turns is also studied in our manuscript.

II. GEOMETRICAL DESIGN ASPECTS

A 12.45 kW, 2000 r/min, IPMSM is considered in this paper as an example to analyze the performance of a three-phase fractional slot spoke-type IPMSM. This machine has an 8-pole/36-slot configuration, with q=1.5 slots/pole/phase. This fractional slot motor has a double layer of lap-type winding with 4 number of parallel paths. The basic parameters and geometrical data used in the 3D FEM simulation studies are listed in Tables 1 and 2. According to the design structure and parameters required, electromagnetic analysis of the 3D finite element model is established. In the finite element model study, the total number of meshes is 19830, which can meet the solving accuracy.

Table 1. Specifications of Motor Parameters

Parameters	Value
Output power capacity	12.45 (kW)
Speed	2000 (r/min)
Peak Current	35.5 (A)
Torque	60.2 (Nm)
No of Poles	8
No. of stator Slots	36
Phase resistance	0.34 (Ω)

Rotor magnetic structure	Interior-Spoke
Number of turns per coil	50

TABLE 2. IPMSM DESIGN PARAMETERS

Design Parameters	**Dimension Value in mm**
Outer diameter	183 (mm)
Inner diameter	102 (mm)
Core length	105 (mm)
Sleeve width	0.2 (mm)
Width of PM	3.85(mm)
Air-gap	0.9
PM type	Nd Fe B

III. ANALYSIS OF SPOKE TYPE OF IPMSM

A. Theoretical Investigation on Winding Impedance

This study investigates the effect of turn variation on phase resistance and end leakage reactance. When the number of stator turns changes, the winding resistance and reactance also change accordingly. This can be found from the calculation of resistance and reactance equations (1) and (2) that The resistance of the winding changes with the number of turns, whereas the reactance changes with the square of the number of turns, when other parameters are unchanged. As the turns vary, the overall length of the conductor increases. resulting in an increase in phase resistance. When the number of turns increases, the polar distance and airgap length increase as well, resulting in an increase in end leakage reactance.

$$R = \frac{\rho \, x 2 N_1 x L_{mean}}{A_1 a_1} \quad (1)$$

$$X_m = 4 \, f \, \mu_0 \frac{m}{\pi} \, \frac{m(N_1 K_{wf1})^2}{p} \, l_{eff} \, \frac{\tau}{\delta_{eff}} \quad (2)$$

Where, R_1 is stator phase resistance, ρ is the resistivity of copper at 75°C, N_1 is the number of ampere-turns, L_{mean} is the mean length of half turns, A_1 is conductor cross-section, a_1 is the number of parallel branches, X_m is the end leakage reactance of stator winding, K_{wf1} is winding factor, μ_0 is the permeability of vacuum, p represents pole-pairs, δ_{eff} is effective air gap length, l_{eff} is armature calculation length, τ is polar distance.

B. Design Optimization using 3D FEM Simulation

The FEM technique has been widely used in the Electromagnetic field domain to analyze the complete behavior of electric machines under a steady state or transient state. This method provides an accurate value of necessary parameters and this will be used for fault diagnosis and analysis of real-time operation. The Maxwell equation has been solved by the FEM method to study the behavior of magnetic fields in the time and frequency domain. FEM analysis includes three steps: pre-processing, during, and post-processing. In pre-processing, the geometries of IPMSM are defined such as inner diameter, out diameters of stator and rotor cores, pole shoe, the core length, number of poles and slots, type of winding, the structure of permanent magnet, PM thickness and depth, magnet position, Slot width open and airgap. The simulation tests are carried out to investigate the performance parameters of IPMSM. The main contribution of this study is the impact of a number of turns variation in a stator coil on the performance of the motor. This analysis can serve as a theoretical foundation for optimizing IPMSM designs. Figure 1 displays the geometrical design of IPMSM's FEM, which includes radial geometry and a winding diagram. Figure 1 also shows the magnetic field lines distribution and electromagnetic flux density B(T), vector potential, current density, and 3D mesh view of IPMSM.

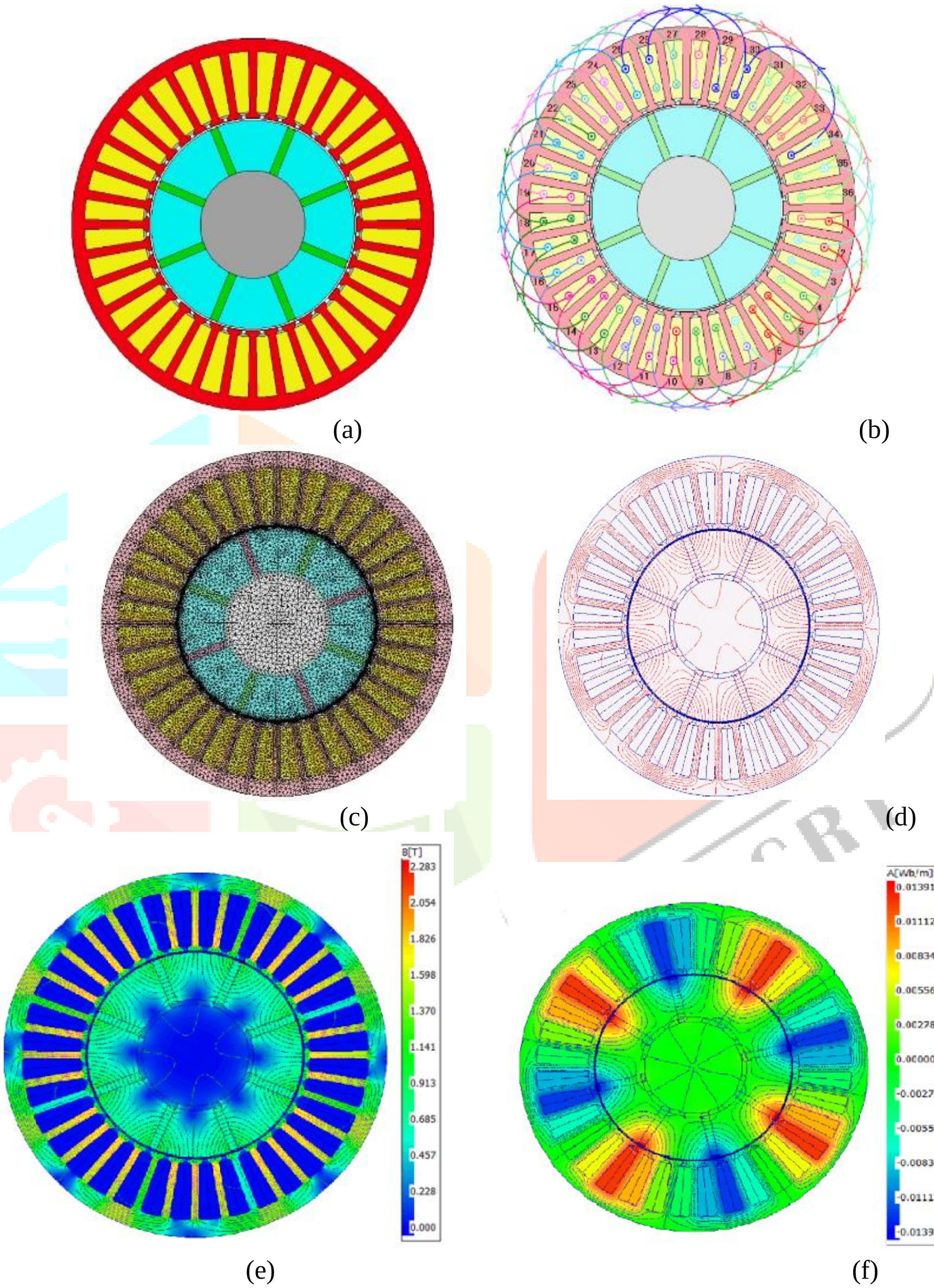

Fig.1. Finite Element model of spoke type of IPMSM ((a)radial geometry (b)winding diagram (c)3D mesh view (d)current density (e) magnetic flux density (f) vector potential.

IV. THE EFFECT OF TURN VARIATIONS ON THE PERFORMANCE OF IPMSM

A. Impact of winding turns on rated torque

The quantity of turns in each coil is one of the crucial parameters in a PMSM design. If that is not taken into consideration properly, the excessive current will harm the stator windings. Furthermore, this will lead to a higher torque ripple, which in turn increases the vibration and noise during motor operation. As a result, the focus of this work is on identifying the precise turn number and the effect of turn variation on IPMSM performance metrics, as well as obtaining the rated values of IPMSM performance parameters such as speed, output power, and maximum electromagnetic torque output.

When the number of turns is changed from 41, 44, 47, 50, 53, 56, and 59 respectively, the performance parameters of PMSM are shown in Fig.2. From Fig. 2, it shows that the output torque increases by 12%, and torque ripple reduces by 28.7% when the turn quantity increases by 3. As the quantity of turns rises, the maximum torque output is increased to maintain the fixed stator winding current. The increased winding turns with a fixed winding current produce a reduced torque ripple and constant magnetic field distribution.

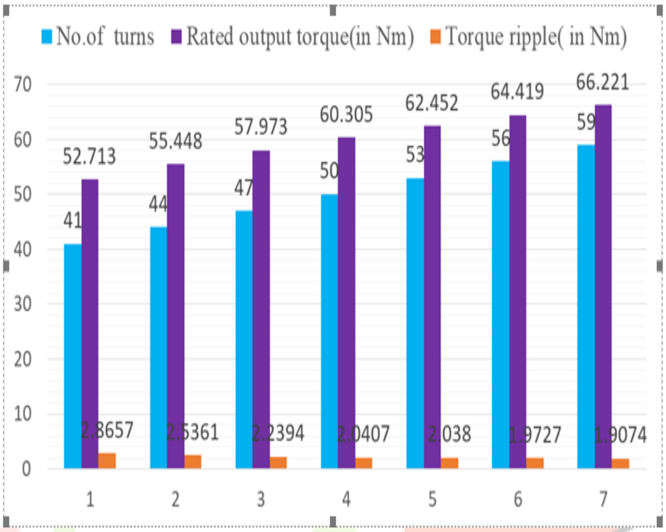

Fig.2. Torque output and torque ripple variation on the influence of winding turns.

B. Impact of winding turns on current density and winding loss due to copper wire

The armature current density increases linearly as the number of winding turns increases, and the rated speed and torque are reached at 50 turns in a coil. Fig.3 depicts the current density, phase resistance, and copper loss as the number of turns varies from 41 to 59. A linear increase is associated with the current density for the corresponding ampere turns increment so as to maintain the required stator current. The increment of current density causes a temperature rise along with it, and more heat is generated in the winding. Therefore copper loss of the winding is also increased due to the use of copper wire as the number of turns increases.

When armature turns increase, current density increases by 6.5% and armature winding's copper loss increases by 14%. The back EMF shows an exponentially increasing trend with the number of turns increment. The back EMF is an important parameter that can be used to evaluate the performance of the IPMSM, and it must be precisely determined. Fig.4 shows the impact of turns variation on speed and back EMF of the IPMSM. If turns varies, speed of the motor decreases and the back EMF of the machine increases due to the rate of change of flux variation.

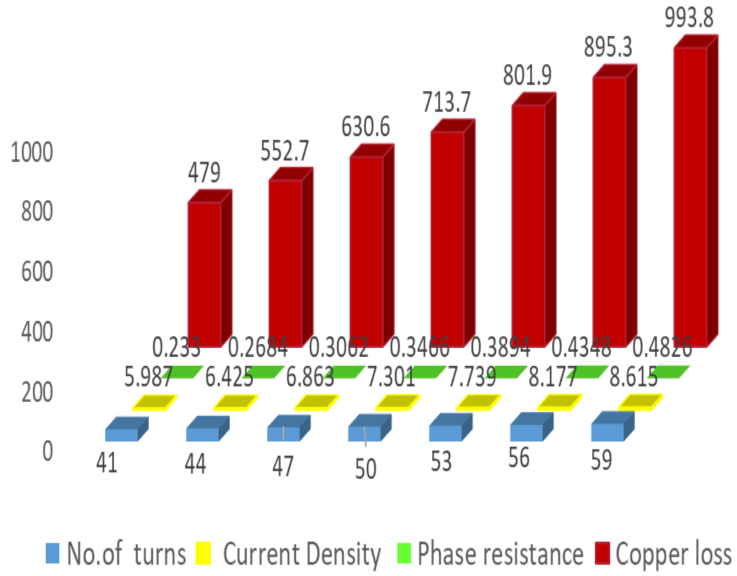

Fig.3. Influence of number of turns variation on copper loss.

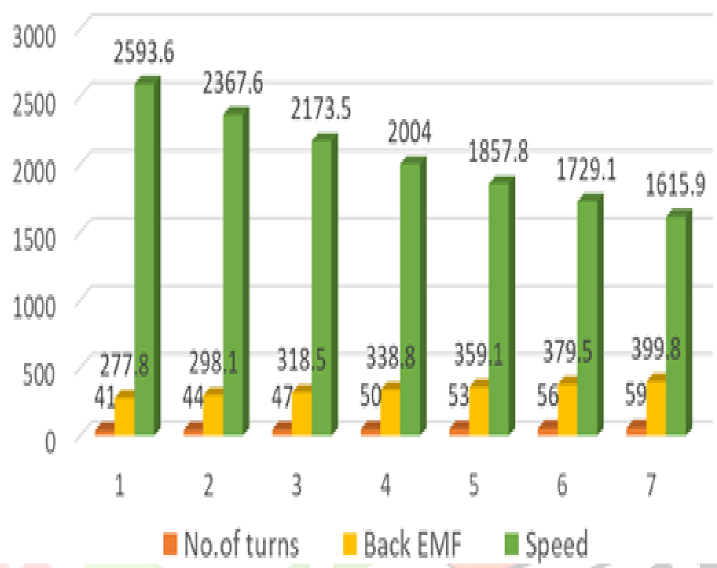

Fig.4. Influence of number of turns variation on speed and back EMF.

C. Impact of winding turns on iron loss of IPMSM

Fig.5 illustrates the effect of variation in the number of turns on iron loss, which includes hysteresis and eddy current losses. As observed in Fig.5, the stator iron loss is increased due to increased hysteresis and eddy current loss as the increased winding turns. The increment is due to more magnetic flux distribution in stator back iron and tooth because iron loss mainly depends on frequency and magnetic flux density. Because of the larger winding turns, the airgap flux density is not uniform, resulting in increased eddy currents on the stator's inner layer. This in turn leads to an increase in stator iron loss.

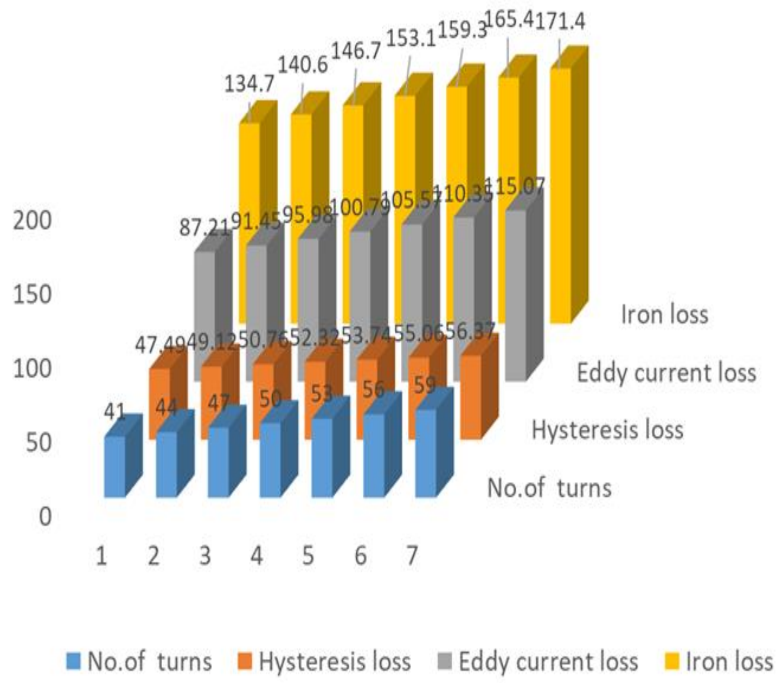

Fig.5. Influence of number of turns variation on Iron loss

D. The influence of the number of turns on power capacity and efficiency

Fig.6 shows the variation in the number of turns with the power factor at different power angles. Fig.7 indicates the power factor and efficiency of the IPMSM, respectively. Fig.8 shows the impact of load angle on the output power and Electromagnetic torque of the motor. It is proven that from Fig. 6,7, and 8 the power factor and efficiency of the motor decrease as the winding turns increase by 3 from 41 to 59. The decrement has been done due to an increase in the load angle δ. This in turn, the distance between the position of the rotor and the rotating magnetic field of the stator increases as the ampere winding turns increase. In a synchronous motor, load angle is an important key parameter and the load angle variation has more impact on the performance of motor. If load angle δ increases, electromagnetic torque increases, and the power output of the motor also increases. Thus, increasing the load angle δ increases the rated output power which is directly proportional to the output power of the synchronous motor. We cannot increase load angle δ beyond 90 degrees because the motor will lose the synchronism due to the increase in distance between the stator and rotor field poles. This load angle δ will affect the stable operation.

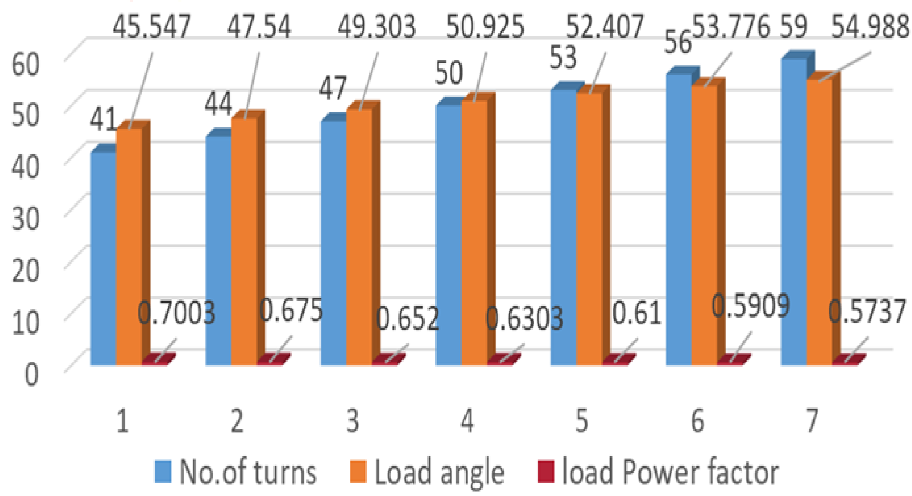

Fig.6. Significance of turn variation on load angle

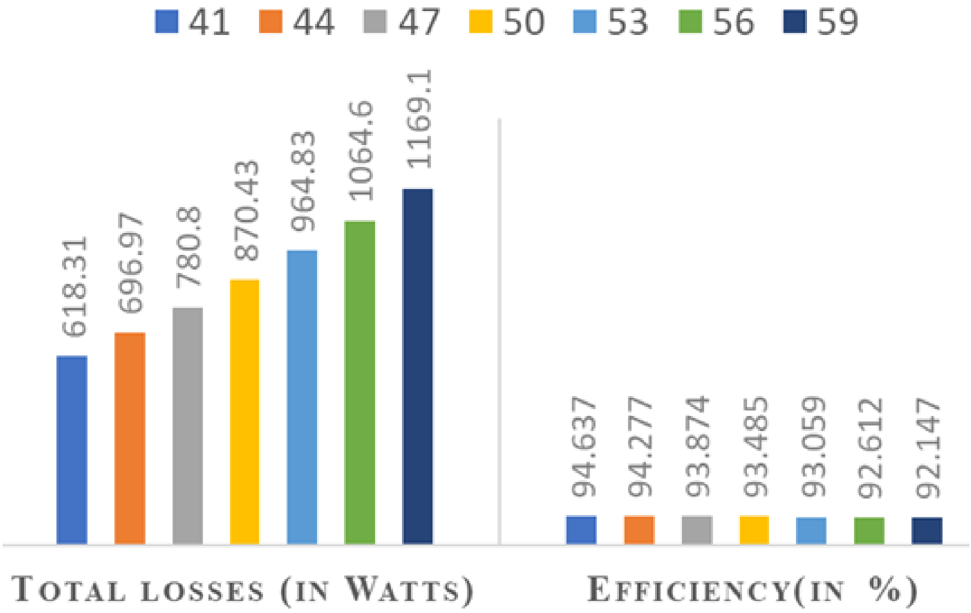

Fig.7. Impact of turn variation on efficiency

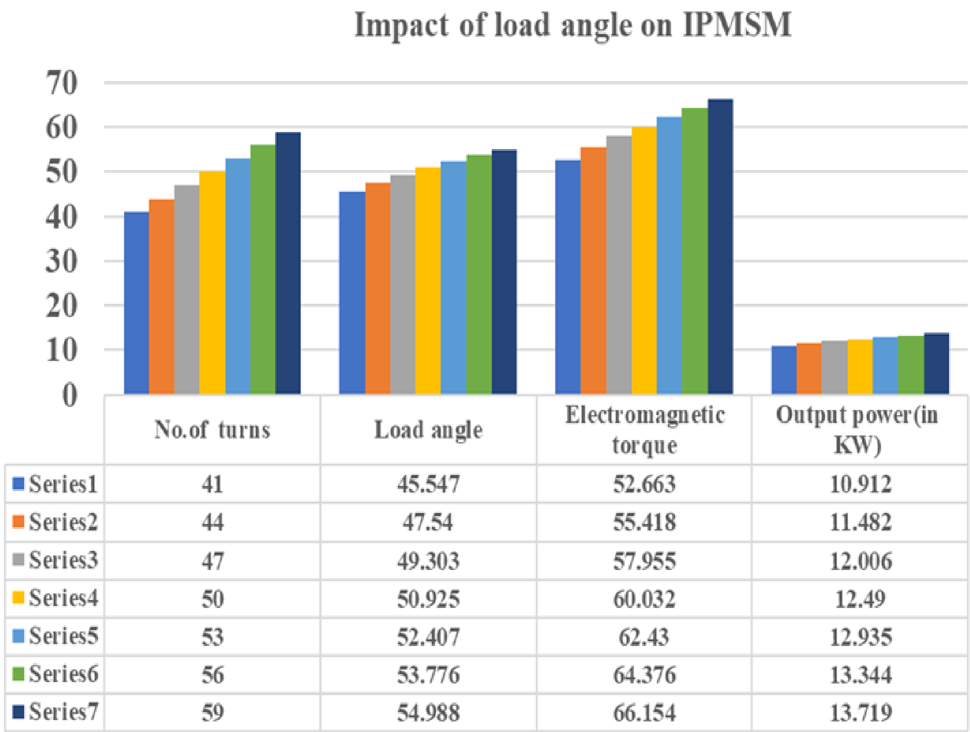

Fig.8. Effect of turn variation on output power capacity

Table 1: Influence on no. of turns on performance parameters of IPMSM

No.of turns	Speed (RPM)	Electromagnetic torque (in Nm)	Output power (in KWs)	Efficiency (in %)	Torque ripple (in Nm)	Cogging Torque (in Nm)
41	2593.6	52.663	10.912	94.637	2.8657	4.1599
44	2367.6	55.418	11.482	94.277	2.5361	4.1599
47	2173.5	57.955	12.006	93.874	2.2394	4.1599
50	2004	60.032	12.490	93.485	2.0407	4.1599
53	1857.8	62.430	12.935	93.059	2.038	4.1599
56	1729.1	64.376	13.344	92.612	1.9727	4.1599
59	1615.9	66.154	13.719	92.147	1.9074	4.1599

IV. OPTIMIZED PERFORMANCE PARAMETER SIMULATION RESULTS USING FEM APPROACH

The study results show the best IPMSM performance characteristics with the optimum finding value of armature winding turns as 50 for a given rated current. Figures 9,10, 11, 12, 13, and 14 illustrate the optimum performance parameters of IPMSM for 50 turns in terms of rated current, back EMF, output torque, cogging torque, efficiency, and efficiency map.

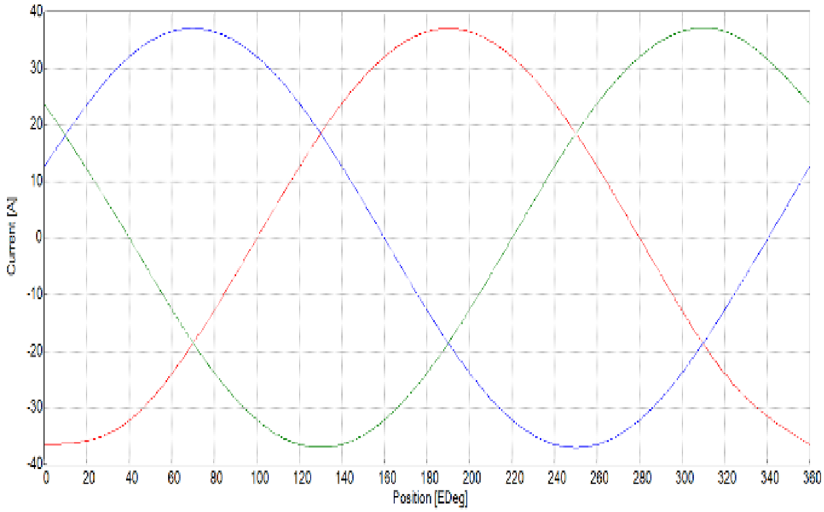

Fig.9 stator current(peak) of IPMSM

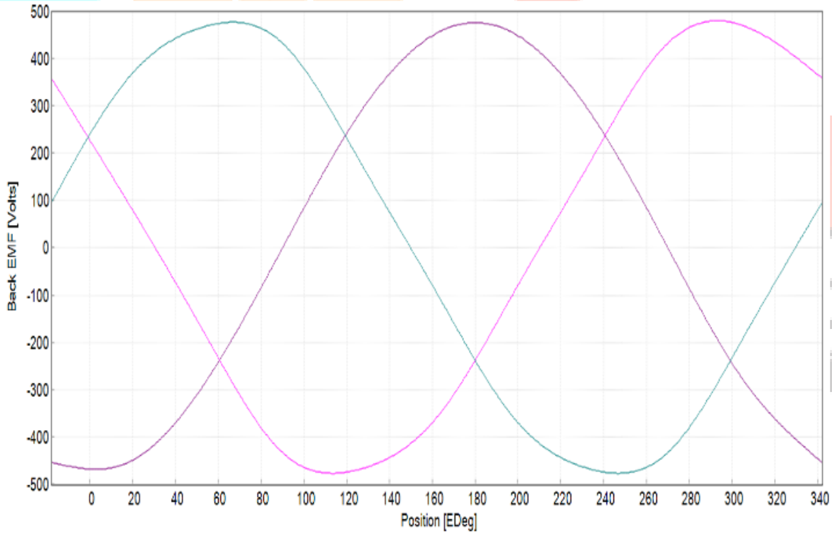

Fig.10 Back EMF of IPMSM

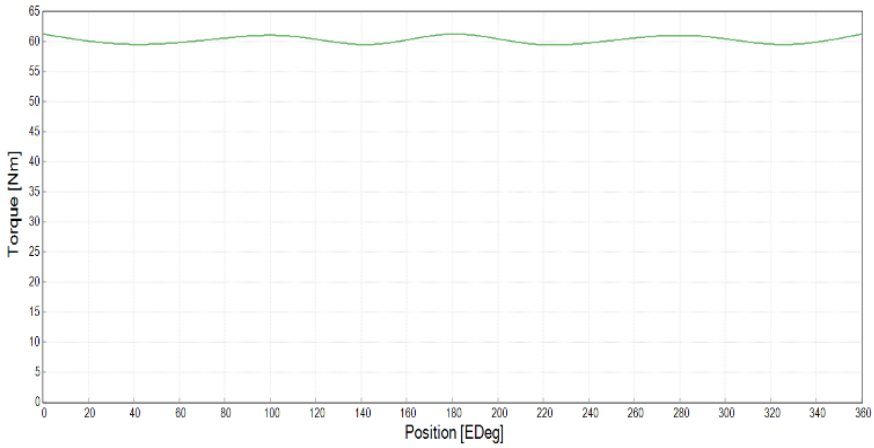

Fig.11 Rated output torque of IPMSM

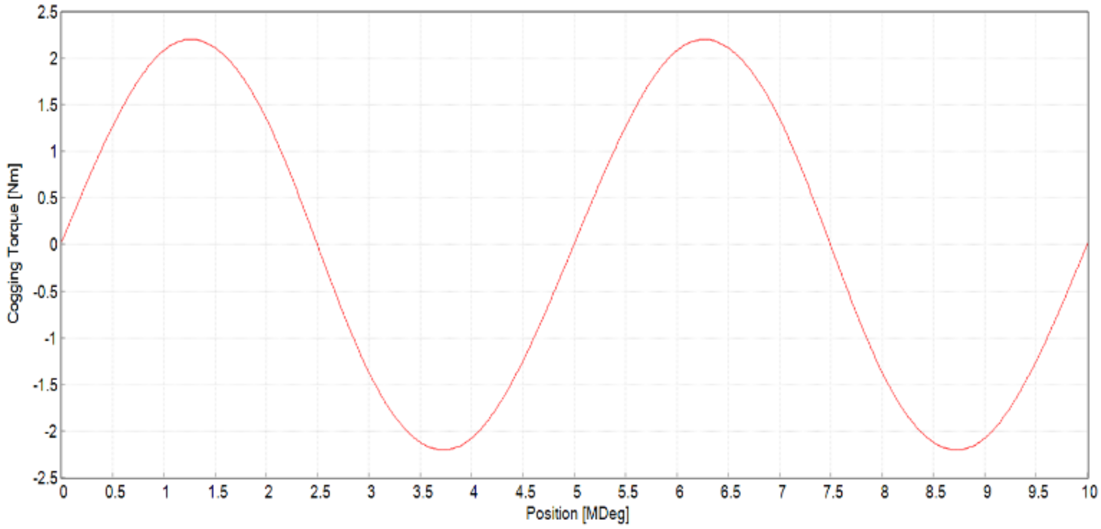

Fig.12 Cogging torque of IPMSM

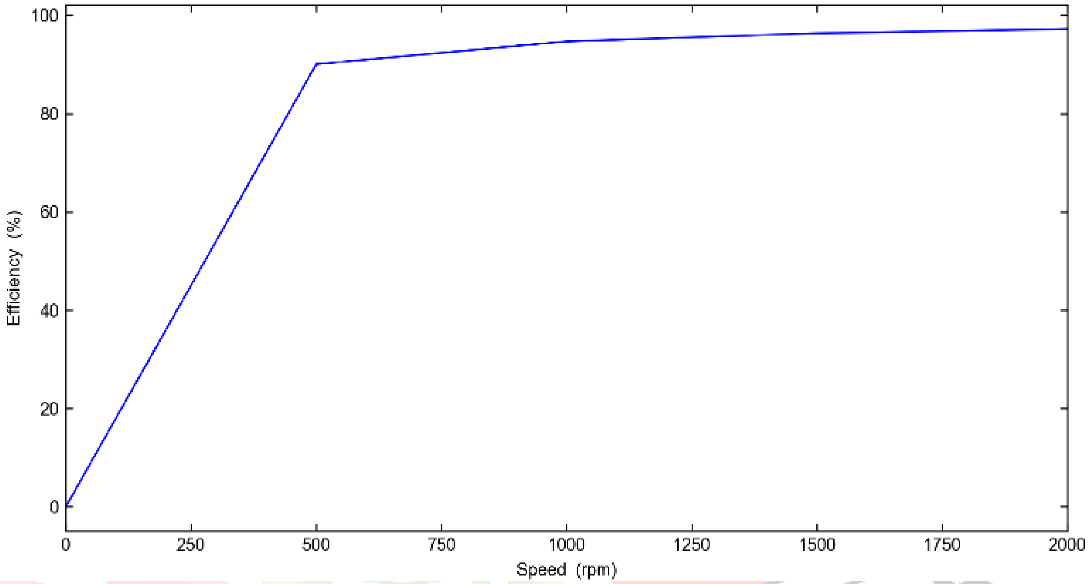

Fig.13 Efficiency of IPMSM

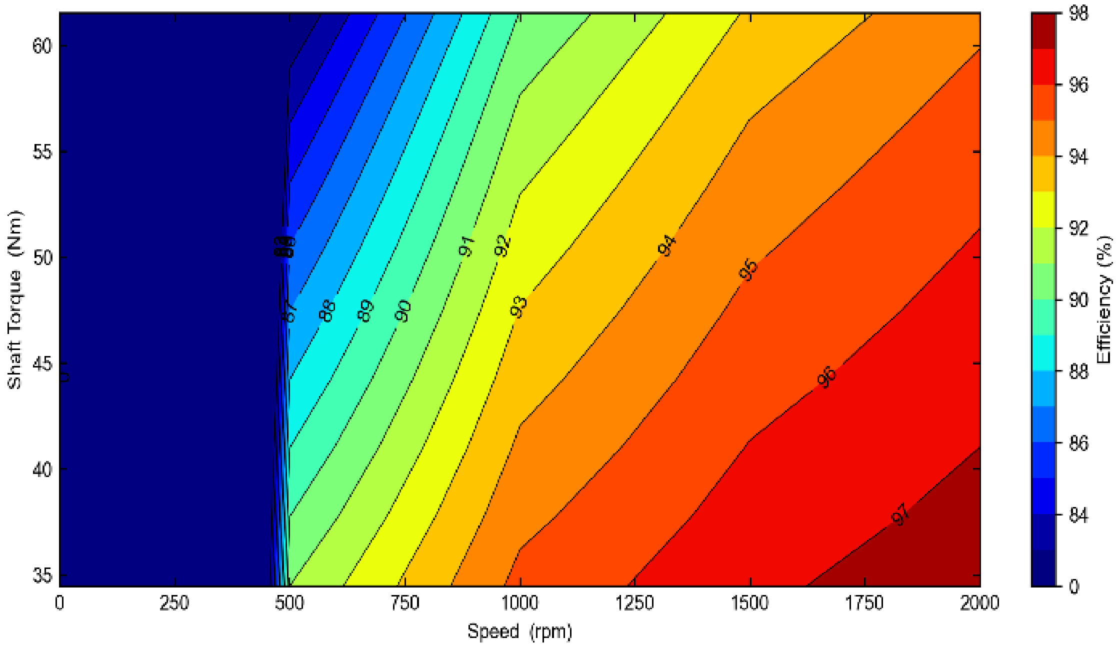

Fig.14 Efficiency map of IPMSM

V. Investigation on Temperature Field distributions of IPMSM

Temperature rise is the major factor, that threatens the magnetic behavior of PMs, winding insulation, reliable operation, and life span. The demagnetization effect of the permanent magnet takes place when the operating temperature exceeds the highest possible allowed temperature of the PMs. To illustrate the influence of the turn variations on the IPMSM's thermal field, the thermal and electromagnetic field of the coupling method is adopted. Fig.15 shows the temperature distribution of IPMSM. Because of the consistent magnetic field distribution, the temperature distribution field has no effect on turn variation, as seen in Fig.15. When the quantity of turns changes, the motor's loss increases, yet the temperature distribution on IPMSM remains constant. The high-temperature withstanding insulating materials are used in the stator winding of IPMSM to prevent leakage of fluxes and various classes of insulating materials are also utilized for various motor parts according to the requirement of various environments. The ambient temperature of IPMSM running is 40°C.

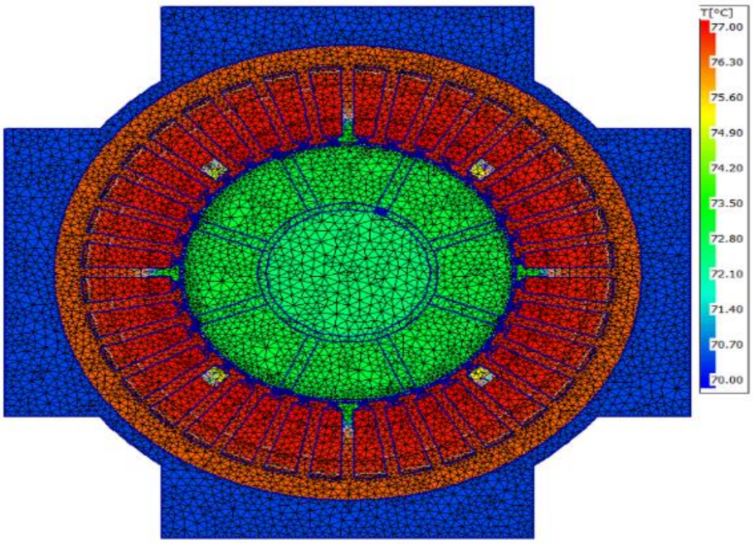

FIG.15 TEMPERATURE DISTRIBUTION OF IPMSM.

VI. CONCLUSION

In this investigation study, a 12.45 KW IPMSM is utilized as the research resource to investigate the significance of the coil’s turn variations in the electromagnetic field and temperature field distribution produced by the IPMSM. The outcomes of this investigation lead to the following conclusions.

- For fixed stator winding current, the highest possible magnetic flux density of IPMSM is constant for all winding turns per coil variations. As the quantity of coil turns increases, the magnitude of the flux density in the airgap also increases, resulting in increased current density and copper loss. When armature turns increase, the current density increases by 6.5%, and armature winding's copper loss increases by 14%.
- When the quantity of coil turns increases, the current density is increased to maintain the winding current constant. Due to this increase, stator phase resistance and length of the conductor are increased, and the area of the conductor is decreased. when the quantity of turns changes, hysteresis and eddy current loss fluctuate considerably, increasing the iron loss of the motor.
- As the number of turns is increased by 3, the maximum output torque increases by 12% and torque ripple reduce by 28.7%. The cogging torque maintains a constant value for all numbers of turn variations.With the increase of winding turns per coil, the efficiency of the motor has decreased due to increased iron loss and copper loss. The power factor of the IPMSM is decreased due to an increased load angle, as the turns increase.
- As the number of turns decreases by 3, back EMF, output capacity, and maximum torque also decrease dramatically, while torque ripple increases significantly. When winding turns are 50, the speed of the motor is attained the required rated rpm of 2000 rated torque 60Nm and efficiency of 93.5% at a rated rms current of 26.2 A. A suitable choice of a number of turns is essential for the design optimization and performance enhancement of fractional slot of spoke type of IPMSM.

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