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Finite Element Electromagnetic Based Design of Universal Motor for Agro Application

Sudhir Kumar Sharma[1] and Manpreet Singh Manna[2]

[1]Research Scholar, Department of Electrical and Instrumentation Engineering, Sant Longowal Institute of Engineering and Technology, Longowal, Sangrur, Punjab, India, sudhirs390@gmail.com
[2]Associate Professor, Department of Electrical and Instrumentation Engineering, Sant Longowal Institute of Engineering and Technology, Longowal, Sangrur, Punjab, India, msmanna@ieee.org

***Correspondence:** Sudhir Kumar Sharma; Email: sudhirs390@gmail.com

ABSTRACT- The commutator part of the universal motor has a considerable effect on the machine's performance. The analysis of pole structure of universal motor becomes important to study the various aspects. The parametric analysis has ratings of 1 kW, 16000 rpm of the universal model designed for different iterations of brush angle for agro applications. The objective of the paper is to improve the efficiency of the model while maintaining the rest of the other parameters at the desirable tolerance range. The customization of the model has been introduced for the various pairs of variables. The transient solution is performed for the better accuracy of the performance of the motor with the help of the finite element method. The designed model offers significant improvement in the design with the improved output torque value.

Keywords: Universal motor, brush angle, Maxwell, steel material, shaft, etc.

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1. INTRODUCTION

Electrical machines play an important part in industries that deal with energy conversion. There are some conventional motors present in the market that has proven their worth, like single phase induction motor, Permanent Magnet DC (PMDC) motor, Brushless DC (BLDC) motor and Universal motor that can be used for industrial and agro applications [1]. The universal motor resembles the DC series motor, as the name suggests, it can operate for both AC and DC supply. This motor has field winding on the stator and armature winding on the rotor, and both windings are series coiled in nature. Universal motors have a high starting torque and a variable speed characteristic. The usual power rating of this motor does not exceed 750 W, and the horsepower rating is considerably smaller than other motors. The typical speed rating of this motor is generally lies between 3000 rpm to 20000 rpm. This motor has works on high-speed rotation, low cost, good power density, reliable, controllable and use simple materials. The universal motors can be used in many domestic applications such as mixers, grinders, vacuum cleaners; small power tools, some industrial products, in ac drive circuits, and agriculture applications. Their applications can also be found in equipment's like air conditioning fans and blowers, dairy machines, hairdryers etc. [2-3]. With so many applications and positive impacts these motors have some limitations also. The disadvantage of the motor is it has complex structure as compared to single phase induction motor, and due to the presence of brushes on the commutator it faces wear and tear mechanism which leads to less efficiency as compared to DC motor [4-6].

The design of electric machine is tedious task; it consumes lot of time and effort. The numerical methods used to design the motor before actual executing to the real world is good practice as it saves lot of consumption of money and time. This more commonly used as computer technology advances, significantly reducing designer's workloads [7]. Previously, equivalent circuit method was developed by the researchers to analyse the performance. But electromagnetic parameters were not analysed properly which diverted the designing of the machine towards the use of advanced technologies of computational electromagnetics. There are various computational methods present to design the electromagnetic device and electromechanical instruments. From those methods, Finite Element Method (FEM) is the most reliable and simple. The complicated geometries can be easily modelled and analysed, whereas other methodologies cannot support. The FEM is suitable for low frequency electromagnetic problems, notably in rotating electrical machine design, among the several techniques available for handling electromagnetic difficulties. Simultaneously, finite element analysis (FEA) tools could assist designers and researchers in performing electromagnetic calculations more accurately [8-11].

In recent years many researchers have done their practices to enhance the performance of universal motor present in the literature. The author presented comparison of the performance of universal motor and BLDC motor drive using Simulink for the application of grinder and mixer [12]. Author presented the behavior scanning of the universal motor works on the AC and DC supply, was achieved with MATLAB Simulink's help to know the motor's better performance on which supply which results that motor perform better on DC supply [13]. The author proposed 550-Watt deep slot universal motor run on 9500 rpm speed for powerful electric tools. The motor was simulated on FEM based MagNet software and experimentally tested. The analysis performed with some different variables to enhance the performance of the respective motor [14]. In another article author was innovatively proposed combination of two windings in the existing design of the universal motor which significantly improves the torque ripples and core losses of the motor [15]. Some of them author was mentioned the efficiency and loss analysis of the universal motor by extracting mathematical modeling. The power loss of the motor universal was improved with the help of MATLAB Simulink software for use in mixer grinder applications [16]. The author was proposed performance comparison of 2 poles and 4 poles universal motor and the results were given at the rated speed of the motor. It was stated that the commutation process of 4-pole motor is better than 2-pole motor which gave the better new design of universal motor by varying the numeral of armature slots and at same time interconnection of armature coil [17]. Author was proposed comparison of induction motor and universal motor model for the application of washing machine. The performance parameters efficiency, induced voltage, current, speed and torque were determined and compared with experimental setup [18]. Author analysed the electrical characteristics of special purpose motors under transient solution with ANSYS Maxwell computer aided design. It mainly emphasis the advantage of single-phase motor rather than three phase motor for use of house applications [19]. Author proposed the design of universal motor for the application of the washer. The model was simulated in Simulink of MATLAB based on the AC and DC supply, the difference between the results of transformer voltage, commutation, saturation effects, and armature reaction were compared and analysed experimentally [20]. D lin et. al. proposed the model of universal motor to improve the commutation process by shifting brush angle from the neutral position by just not concentrating on the d-axis and q axis with FEA [21]. Miller and his co-worker willing analytically calculate all the values of inductances for the design of motor by shifting the lag coil angle then the designed model was analysed with FEA and experimentally [22]. Author proposed commutation phenomenon of universal motor considering the optimum values of fraction of commutator width and brush width using FLUXR software. The effect of this process on the efficiency and brush life was examined [23]. Author proposed the universal motor to determine brush to bar voltage drop through FEA having time stepping analysis. It was observed that design compared with conventional analysis was more accurate [24]. In other article author proposed the universal motor model to determine the self-inductance and mutual inductance coefficients, as well as the electromotive force created in the coil sections taking into account magnetic saturation, the brush-commutator voltage drop, and electric arc was determined. The current waveforms were evaluated using a numerical solution of the equivalent circuit; a comparison of the computed and measured waveforms of the brush-commutator voltage drops allows the model to be verified [25].

The objective of present work is to obtain the improved version of the model of the universal motor. The brush angle has effect on the efficiency of the motor. The variation of the brush angle shift helps to find the improved torque of the motor for agro application. The parametric analysis and transient solution set up of the Finite element method helps to provide the better results. The universal motor generally has low efficiency as compared to the other motors available in the market. The sole motive of the work to enhance the performance of the motor.

2. MATHEMATICAL MODELLING

The universal motor mathematical model based on mathematical equations of voltage is presented in this section. *Figure 1* shown below is the universal motor equivalent circuit. The operating conditions of this motor voltage and current equations are the same as a DC series motor.

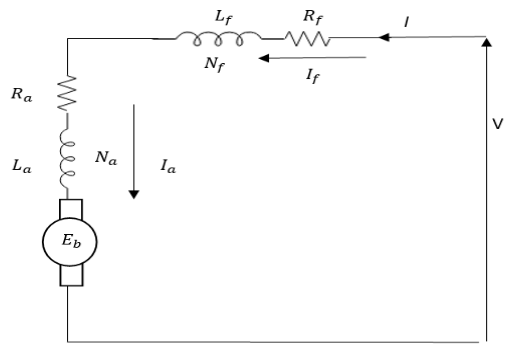

Figure 1: Equivalent circuit of Universal motor

V = supply voltage, I = load current, E_b = back emf, V_{bd} = voltage drop across brushes, I_a = current of armature, I_f = field winding current, R_a = resistance of armature winding, R_f = resistance of field winding, L_a = inductance of armature winding, L_f = inductance of field winding, L_{af} = mutual inductance between armature winding and field, N_f = field winding number of rotational turns, N_a = number of turns of armature winding.

$$I = I_a = I_f \quad (1)$$

Voltage drops across field winding

$$V_f = R_f I_f + L_f (dI_f/dt) \quad (2)$$

Back emf,

$$E_b = \Phi ZNP/60A \quad (3)$$

Voltage drops across armature winding

$$V_a = R_a I_a + L_a (dI_a/dt) \quad (4)$$

Mutual inductance voltage drops

$$E_m = L_{af} (dI/dt) \quad (5)$$

Terminal voltage/ supply voltage

$$V = V_a + V_f + E_m + E_b + V_{bd} \quad (6)$$

The thickness of brushes has a profound influence on the computation conditions. Total brush contact area per spindle is

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the ratio of current carried by each brush spindle to current density in the brushes.

The losses in the commutation processes are the brush contact losses and brush friction losses. The brush contact drop is independent of load current. The typical value of brush drop is around 1 to 1.5 volt.

The brush friction loss depends upon the brush pressure, the peripheral speed of the commutator and the coefficient of friction between brush and the commutator. It may be calculated by

The brush friction loss = $\mu P_b A_b V_c$

Where μ = coefficient of friction, P_b = brush contact pressure on commutator (N/m^2), A_b = total contact area of all brushes, and V_c = peripheral speed of the commutator (m/s)

To avoid delayed communication process heavy short circuit and sparking at the brushes should be shifted backwards opposite to the direction of rotation for motors in order to bring them in the magnetic neutral zone.

The effect of this brush shift is to resolve the armature winding into two component windings. The Winding produces some extra mmf, which acts directly against the field mmf. The armature winding produces cross magnetizing mmf whose axis is at 90 degrees with respect to the main field and therefore demagnetizing mmf is called the cross-magnetizing component of armature reaction [26].

Demagnetizing mmf per pole = Total armature mmf $\left(\frac{2\alpha}{180}\right)$

The cross magnetizing mmf per pole is equal to the difference between the total armature mmf per pole and the demagnetizing mmf per pole.

Cross-magnetizing mmf per pole =Total armature mmf $\left(1 - \frac{2\alpha}{180}\right)$

3. MODELLING OF UNIVERSAL MOTOR

The design of universal motor has been created using ANSYS Maxwell software. The power ratings of the motor considered are 1 kW and 220 V. The dimensional specification of motor has been tabulated in the *Table 1*.

Table 1: Dimensional specifications of universal model

Parameters	Values
Stator core outer Diameter (D_{so})	61.7 mm
Rotor core outer Diameter (D_{ro})	37 mm
Stack length	33.35 mm
Pole Embrace Factor	0.7
Rotor core Diameter (D_{ri})	12.1 mm
frequency	50 Hz
Stator/Rotor Material	Steel_1008

Both stator and rotor core are made of steel_1008. The BH curve of the silicone material used is shown in the *figure 2*. It has shown the transition value of the magnetic field density i.e., 1.6 Tesla. The material used has good thermal stability for the design of the motor having 4/12 pole slot combination.

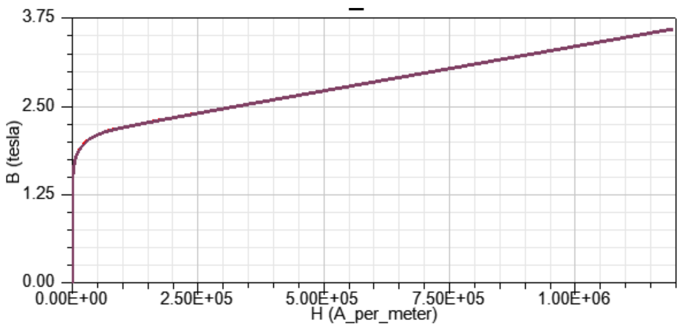

Figure 2: B-H curve of the universal model

4. RESULTS ANALYSIS AND DISCUSSION

The parametric approach method adopted for the performance analysis of universal model. The vital factors that should be taken into account are high efficiency, low loss, low volume and low cost. The parameters of motor efficiency and losses are determined to follow the requirement of the model. There is a trade-off between the two parameters. The variable selected is brush angle and rest of the parameter is constant. The value of the brush angle is varied from 5 to 25 degree with the step value of 5 degree as a result of consideration of physical constraint. The parametric analysis has been performed to check the performance of the motor. Further the optimization techniques are performed to further analyze the results. To select the best optimum value among the region on these various value's maximum efficiency, rated torque and minimum loss criteria followed. But it is not always easy to find the one single value. Sometimes good values lie in some region where one should decide taking into some priorities in the design. The results have been analysed considering the performance of the motor like torque and efficiency of the motor. The graphical representation of torque versus rotor speed is shown in *Figure 3* and efficiency versus rotor speed curve is shown in *Figure 4*. The efficiency is maximum for the 5 degree rotational angle having value 74.19% for the rated speed of 15905 rpm. The minimum value is 68.05% for 25 degree having rated speed of 17055 rpm. Although the rated speed for the least efficiency region is somewhat high but the required speed achieved for the high efficiency region. The rated torque is highest 0.602 Nm for the 0 degree angle of rotation and for 25 degree it is almost lowest of value 0.55 Nm. For highest efficiency region rated torque is 0.601 Nm and starting torque value is 3.13 Nm.

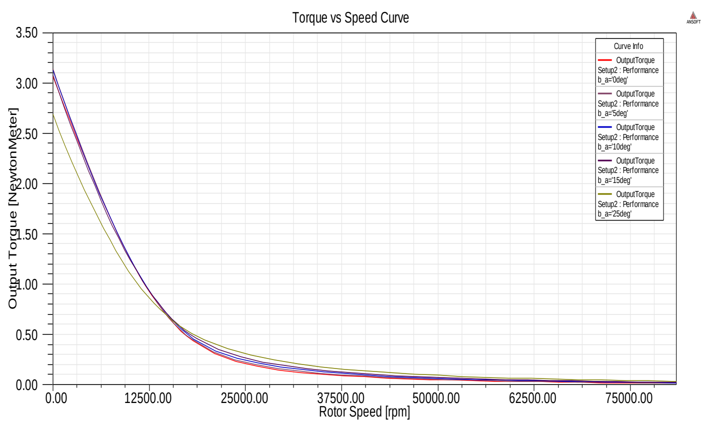

Figure 3: Graphical representation of rated torque vs rotor speed

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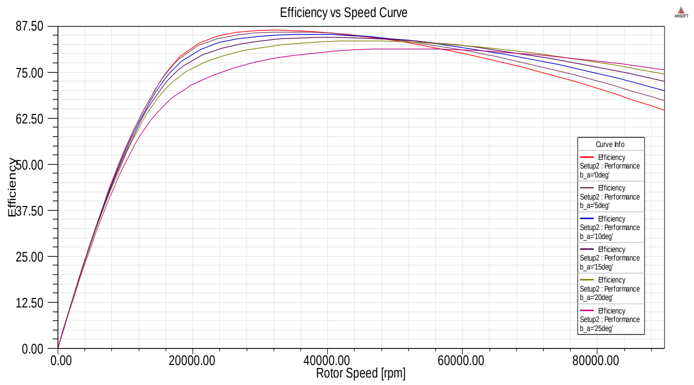

Figure 4: Graphical representation of efficiency vs rotor speed

The total loss versus brush angle and air gap flux density with respect to brush angle is shown in *figure 5* and *figure 6*. The maximum value of loss appears at 25 degree of 469.2 W value and minimum is 347.5W value at 5 degree rotation of motor. The output power with respect of speed rotation of motor is almost same for the all values of variables. Although the output power varies slightly high manner after 20000 rpm of rotation speed of the motor. This shows that at same value losses decreases and the efficiency of the model is high.

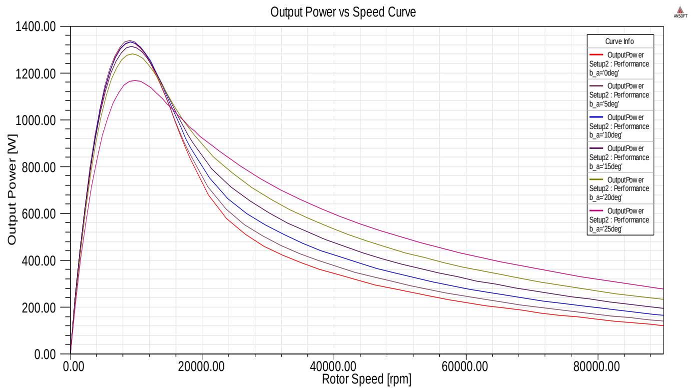

Figure 5: Graphical representation of output power vs rotor speed

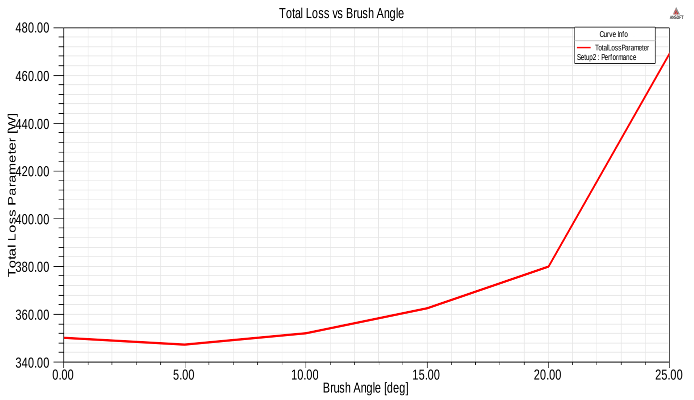

Figure 6: Graphical representation of total loss w.r.t. brush angle

The graph of the air gap flux density with variation of electric degree of rotor is represented in *figure 7*. The value of the air gap flux density decreases with the increase of the brush angle because the increased value increased the peak winding magnetic flux density. The value of air gap flux density is minimum of 0.374 T having high input DC current of 6.7 A. the value of air gap density is 0.49 T for lowest input DC current 6.1 A. The optimum value selected for the better performance of the motor is for 5 degree brush shift angle and motor of lowest performance achieved at 25 degree brush shift rotation.

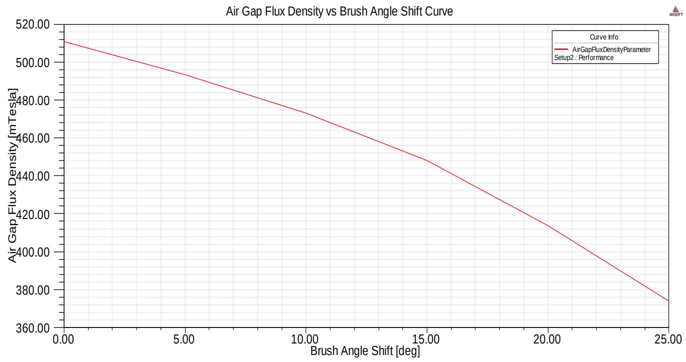

Figure 7: Graphical representation of air gap flux density w.r.t. brush angle

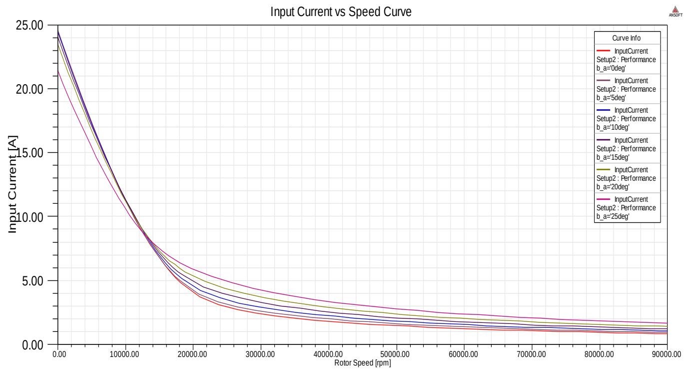

Figure 8: Graphical representation of Input Current w.r.t. rotor speed

4.1 Finite Element Analysis

The motor further exported to transient analysis for the variable 5 degree rotation and 25 degree rotation. The analyzed is carried out using Finite Element Method for the comparison of electromagnetic torque. The meshing formulation of the model is also performed. Then, using the interpolation function, the solution for the entire mesh is approximated, and in the entire domain based from the solution desired parameters or variable derived is computed. The motor with plot meshes of brush angle 5 degree and 25 degree having mesh elements of 2150 is shown in *figure 9* and *figure 10*. It shows the mesh formation at specific time and rotor position.

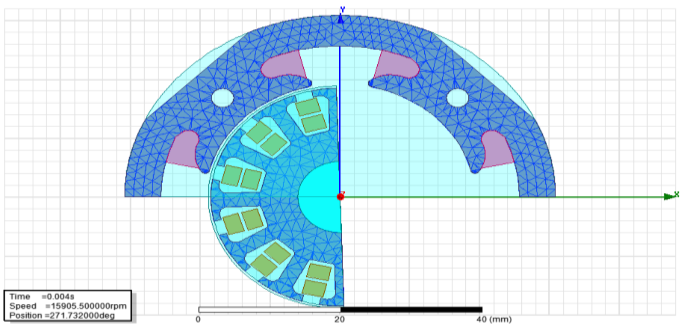

Figure 9: Plot mesh FEM analysis of motor of 5 degree brush shift

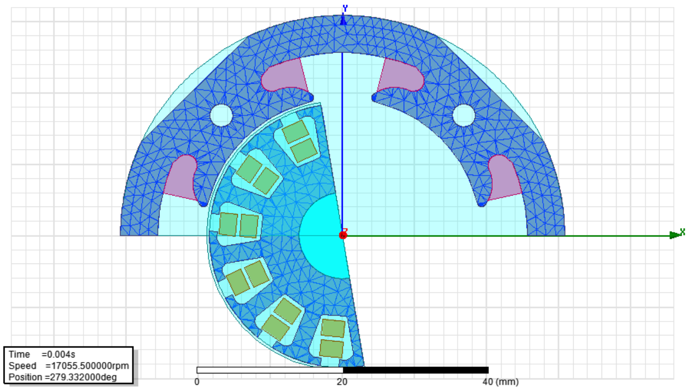

Figure 10: Plot mesh 2D FEM analysis of motor 25 degree brush shift

The electromagnetic torque of the motor with change of time of brush shift 5 degree is shown in *figure 11* having maximum value of torque 0.94 Nm and average value of 0.2101 Nm. The value of ripples for this model are 4.47 Nm. the electromagnetic torque versus time graph having brush shift 25 degree is shown in *figure 12*. The maximum value of torque is 1.194 Nm, average torque 0.3 Nm. The value of ripples for this model is 3.98 Nm. Here the value of average torque is compromised as efficiency is best for the model of 5 degree brush shift angle. So, the optimum point of variable selected is 5 degree brush shift angle.

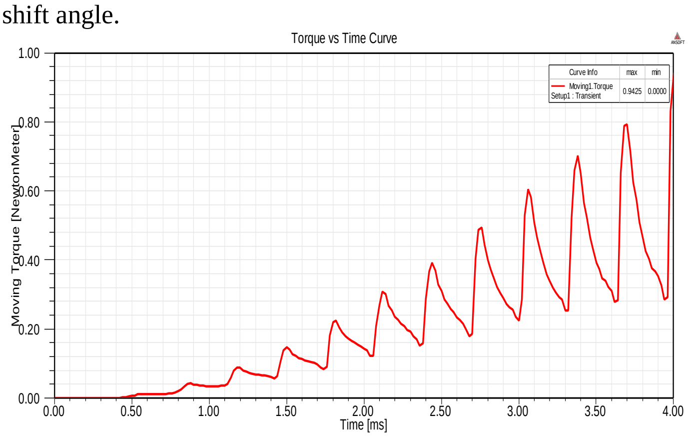

Figure 11: Graph of electromagnetic torque with change of time for 5 degree brush shift

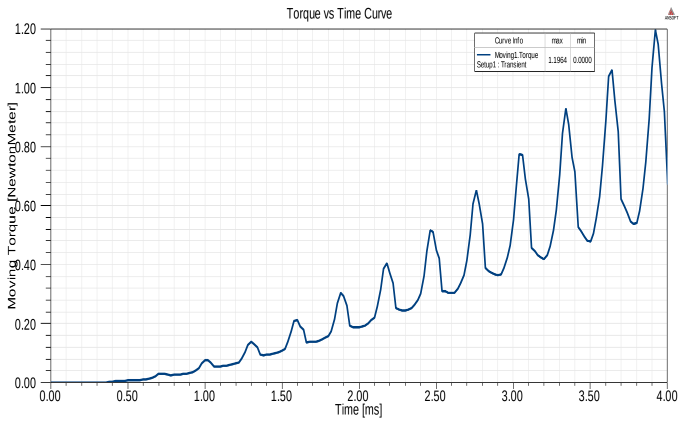

Figure 12: Graph of electromagnetic torque with change of time for 25 degree brush shift

The graphical representation of winding current of coil with the change of time for 5 degree and 25 degree brush shift rotation is shown in *figure 13* and *figure14*.

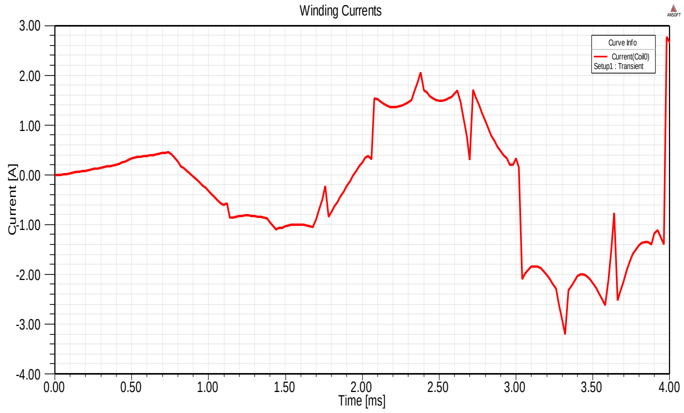

Figure 13: Graph of Winding current with change of time for 5 degree brush shift

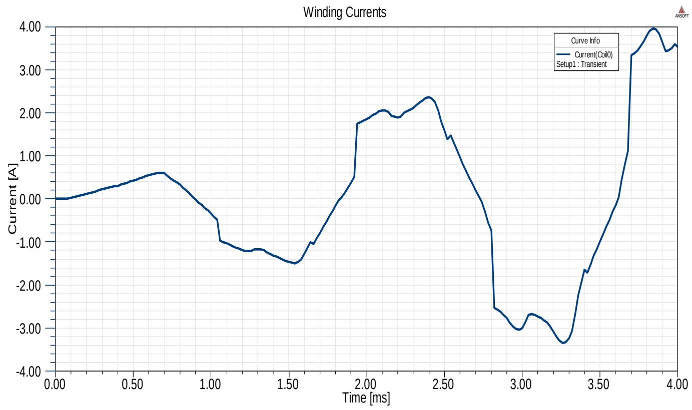

Figure 14: Graph of Winding current with change of time for 25 degree brush shift

The magnetic field density and magnetic flux lines of specific rotor position is shown in *figure 15* and *figure 16*. It shows that motor does not operate at the value close to the density.

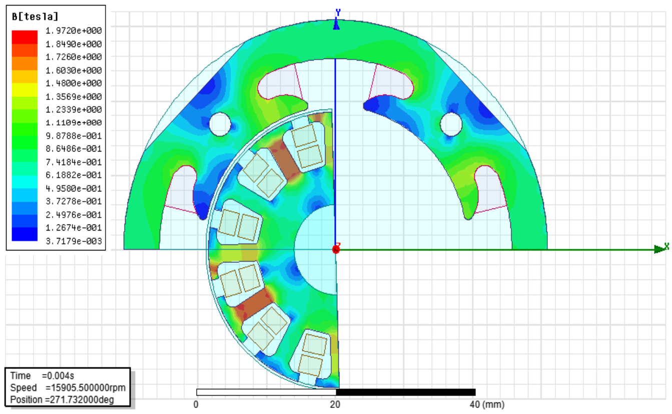

Figure 15: Magnetic flux density of the model of 5 degree shift

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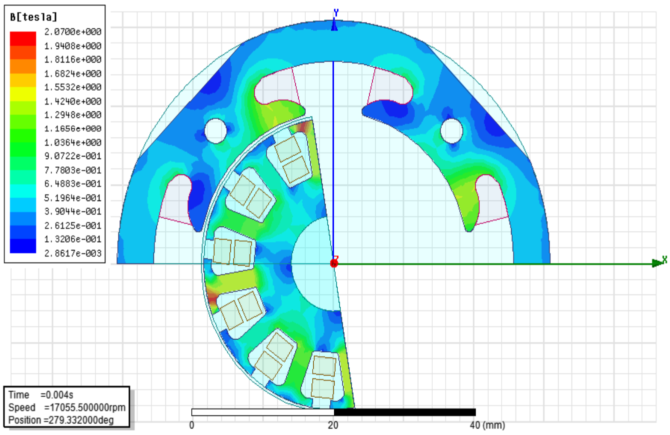

Figure 16: Magnetic flux density of the model of 25 degree shift

5. CONCLUSION

In this research, universal motor is analysed with the help of finite element method for agro application. The motor performance analysed with the variation of brush angle by keeping rest of the parameters same for the models. The optimum value of variable is selected and it's observes that the efficiency of the model is higher than the generalised motor. The model for 5 degree brush shift rotation is selected for the better performance of the motor in contrast to the other models of brush shift angle. This model realised with less losses as compared to the rest of the iterations of the variables. However, for this optimum value the average torque of the motor is compromised to achieve the good efficiency. The rated torque and electromagnetic torque are enough to operate. The flux density of the model is not saturated at the tooth of the universal motor.

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