Design Analysis and Verification of PMSM Motor For Dishwasher Machine

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***Abstract*— In this paper an interior permanent magnet (IPM) synchronous motor (PMSM) is analytically designed and analyzed by Ansys Maxwell 2D software, and fabricated in Bader Motor Technology Company.**

Currently, single phase induction motors (IM) are used in dishwasher machine. According to customer requirements; due to controlling of speed, lower price and higher efficiency the PMSM motor are preferred instead of single phase IM.

In respect to customer requirement the motor is designed, with 3400 rpm, 0.2 Nm and 0.5 Arms. The designed motor is capable to operate in (2000-3800) rpm range of speed without applying field weakening method. The designed motor is lighter 0.50 kg lower than the IM motor and thanks to efficiency the new motor efficiency is 12 percent higher than the old one. As experiments, noise, heating up and vibration issues of new designed motor are less than the IM.

Keywords*— *Permanent Magnet Synchronous Motor (PMSM), Ansys Maxwell 2D, Finite Element Method (FEM), Interior Permanent Magnet (IPM)

I. INTRODUCTION

PMSM is a type of widely used motor in industrial. These are becoming popular as a key technology and are good choice in many applications, aerospace, electric vehicle, automatic production systems in the industry and home appliances applications such as dishwasher machine as shown in Fig.1, [1,2]. These motors are preferred instead of DC and induction motors in industry. The most important advantages of such motors are; high efficiency, high power density, low maintenance and low cost [1],. These motors are general purpose and more useful due to their low maintenance, power density, low rotor inertia, lifespan, torque versus speed characteristics, electromagnetic interference, communication and controlling [2],. Usually these motors are used at steady state and rated values. Speed of synchronous motors can be controlled by varying the frequency of the rotating magnetic field, which is called synchronous speed [1],.

Since the traditional IM have low efficiency and low-power factor, how to design a highly efficient PMSM has become a hot topic, [1]. Compared with the conventional induction motors, the PMSM has more simple structure and higher efficiency, and it has higher output torque, [2].

The synchronous motors with IPMs buried inside of rotor and a low pole number are often used for high-speed direct-drive applications. The main advantages of such a motor structure is working against the centrifuge force and relatively lighter compared with other designs of motors with PMs. The motors with this type PM are especially advantages in the application where high speed is required, for home appliances applications such as dishwasher, washing machine and vacuum cleaner, blender, mixer and so on, [4].

PM is the main part of PMSM it generates flux in machine. This part is more expensive part of motor as it is possible it should be small in size. This part is generally produced in China and European country such as Germany. There are several types of magnets they are: Ceramic Cobalt (SmCo), Neodymium (NdFeB) and Ceramic (Ferrite). Each one has its own advantage and disadvantage. Due to low price in this design Ferrite PM is preferred. Its remanent absolute value is lower and demagnetization absolute value is higher than NdFeB. To have magnets with high remanent values will increase the performance of motor, and in absolute value, higher demagnetization value will protect PMs from undesired demagnetization situation such as overloading and heating, [5].

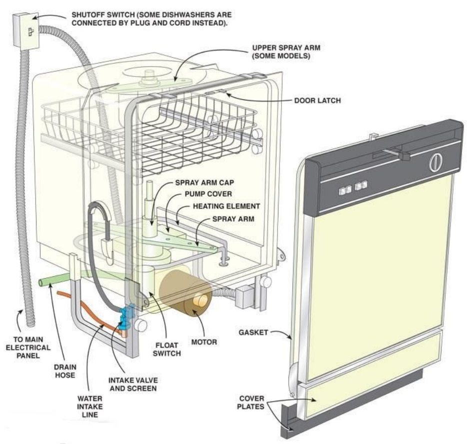

Fig. 1. The application area of the motor is shown on dishwasher machine figure

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II. Design Steps of PMSM

The flow diagram representing the design steps of the PMSM is given in Fig. 2. As given in the flow diagram, design steps are discussed in the following section after PMSM parameters are determined according to the application area. The stator, rotor and slot dimensions, electromagnetic electrical equations are calculated together. When the motor is reached to desired performance, this operation is terminated, otherwise the designing calculations will repeat again. The flow diagram in Fig.2 is explained in detail in the following sections.

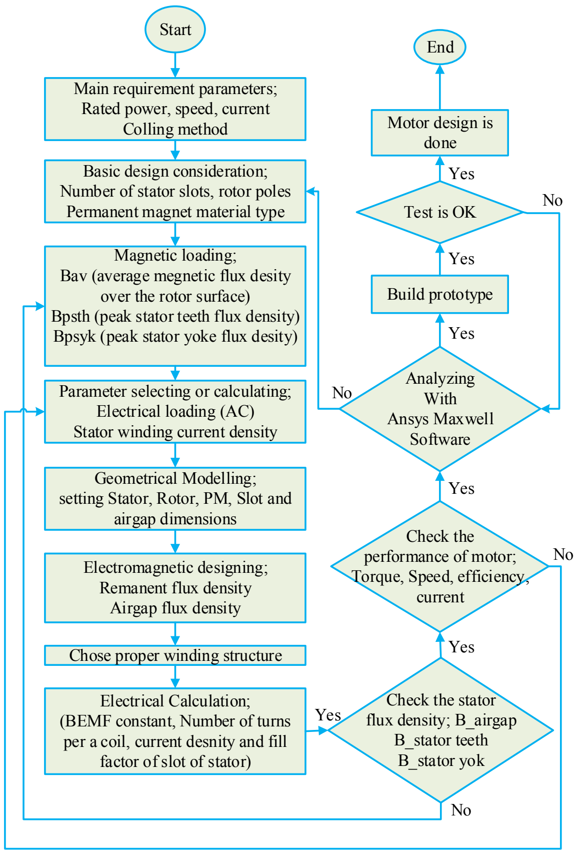


Fig .2. Flow chart for design procedure

A. Parameters Detecion

Rated values are determined according to the place and application where the motor will be used. This is usually updated according to customer requirements. The following general table is verified according to customer requirements.

In respect to special requirements, extra dimensional limitations can be included in Table.1 or removed completely.

To design the motor for the rated values, the geometry design, electromagnetic and electrical calculations will be done. During designing the geometrical calculations, the motor usage location limitations must be considered by designer and they are axial length and stator outside diameter as shown in Table.1.

TABLE. 1. MOTOR RATED VALUES

Abb	Parameter	Value	Unit
P_{out}	Power	77	Nm
N_{rpm}	Speed	3400	rpm
I_r	Current	0.5	A
L_{stk}	Axial length	18	mm
D_{so}	Stator outside diameter	90.35	mm

B. Parameters selecting and/ or calculating

Electrical machine design usually starts with the famous sizing equation as shown in (1), [10,11]. With this equation the stack length of the motor is calculated.

$$L_{stk} = \sqrt[3]{\frac{P_{out} \cdot \lambda^2 \cdot \pi^2 \cdot 6 \cdot 10^{10}}{11 \cdot k_{w1} \cdot B_{av} \cdot AC \cdot N_{pole}{}^2 \cdot N_{rpm}}} \tag{1}$$

Where P_{out} is the motor rating power in watt (W), B_{av} is the specific magnetic loading in Tesla (T), AC is the specific electrical loading in ampere per meter (A/m), D_{si} is the stator bore diameter in millimeter (mm), L_{stk} is the axial length in millimeter (mm), K_{w1} is maximum fundamental winding factor, and N_{rpm} is the rated speed in revolution per minute (rpm) [14] [15]. Values for B_{av} and AC are selected by the designer at the start of the design process.

The electric loading AC is defined as the linear current density around the airgap circumference, that is, the number of ampere-conductors per meter around the stator surface that faces the airgap is calculated as [12];

$$AC = \frac{\text{Total ampere-conducotrs}}{\text{Airgap circumference}} = \frac{2 \cdot N_{phase} \cdot N_{tph} \cdot I_r}{\pi \cdot D_{si} \cdot 10^{-3}} \ A/m \tag{2}$$

Where I_r is the RMS phase current, N_{phase} is the number of phases, N_{tph} is the number of turns in series per phase.

The specific electric loading AC is generally limited (8000-45,000 A/m) by the copper loss in the conductors, the effectiveness of the cooling strategy, the temperature limitation of the insulation material, the load profile, and the duty cycle. In the traditional design, the selection of B_{av} and AC are primarily based on the designer's experience. Some textbooks provide guides from previous design experiences [14,15].

The magnetic loading B_{av} is defined as the average flux-density over rotor surface. The magnetic loading B_{av} is limited (0.40-0.7 T) by the saturation point of the materials used, the hysteresis losses and eddy current losses, the stray losses, the effectiveness of the cooling strategy, the load profile, and the duty cycle [14,15].

In AC motors the flux is calculated by (3), that is distributed sinusoidal in airgap as shown in the analysis graphic is given in Fig.5. [12];

$$\Phi_1 = B \frac{\pi D_{si} L_{stk}}{N_{pole}} \quad \text{Wb} \tag{3}$$

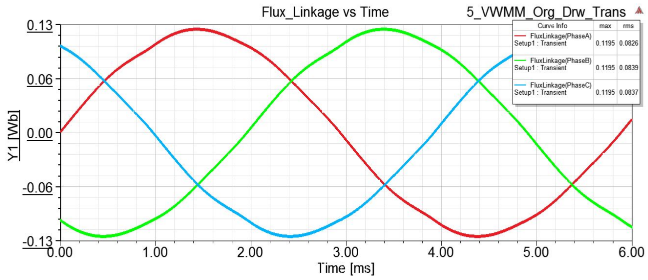


Fig. 3. Flux linkage of graphics of the three phase

Fundamental winding factor (k_{w1}) is calculated by (4), for some standard motors a table of maximum fundamental winding factor is given as shown in Table.2;

$$k_{w1} = \frac{1}{q_1} \frac{\sin(\pi/6)}{\sin(\pi/6q_1)} \tag{4}$$

Where q_1 is number of slots per pole phase;

$$q_1 = \frac{N_{slot}}{N_{pole} \cdot N_{phase}} \tag{5}$$

TABLE 2. OF MAXIMUM FUNDAMENTAL WINDING FACTOR FOR SOME STANDARD MOTORS

Integer-slot winding
Fractiona-slot winding
Concentrated winding
Unbalanced winding

	2	4	6	8	10	12	14
3	0.9	0.9		0.9	0.9		0.9
6	1	0.9		0.9	0.5		0.5
9	0.9	0.6	0.9	0.9	0.9	0.9	0.6
12	1	1		0.9	1		1
15	1	1		0.7	0.9		1
18	1	0.9	1	0.6	0.7	0.9	0.9
21	1	1		0.5	0.7		0.9

Where N_{slot} is number of slots, N_{pole} is number of poles and N_{phase} is number of phases. After B_{av} and AC are selected, the L_{stk} value of the machine is then calculated by (1). In this paper to design a motor with minimum cost in relation to the Table.3 the aspect ratio value is selected 1.7, [28].

TABLE 3. ASPECT RATIO WITH DESCRIPTIONS

No	Aspect ratio	Description
1	1.5-2	Minimum cost
2	1.5	High efficiency
3	1.0-1.5	Best power factor
4	1.0	Equivalent design

To go further to designing PMSM, the current density values is also important parameter. This parameter directly affects the operation temperature of the stator winding. The current density is typically selected by the designer's experience or can be chosen consistent with the motor cooling types, as calculated according to certain empirical rules, the current density is generally selected in the range of (3 to 7 A/mm2) [14,15,17].

$$J = \frac{I}{A_{coil}} \quad A/mm^2 \tag{6}$$

Where A_{coil} is stator coil area per a slot.

After considering the necessary limitations, the specified basic dimension parameters of the motor between (1) and (6) are determined as in Table 3.

Table.4- Motor geometrical dimensions

No	Parameter	Value	Unit
1	J	7.04	A/mm^2
2	AC	22637	A/m
3	B_{av}	0.40	T
4	λ	1.7	-
5	q_1	0.5	-
6	K_{w1}	0.866	-

C. *Stator Dimensions*

After calculating axial stack length by using the (1) whole the stator dimensions can be determined step by step by geometrical calculation.

Using calculated L_{stk} and selecting aspect ratio parameters with (7) the stator inside diameter can be determined as follow

$$D_{si} = \left(\frac{L_{stk} \cdot N_{pole}}{\lambda \cdot \pi}\right) \text{ mm} \tag{7}$$

Rotor outside diameter can be calculated by eliminating the air gap from stator inside diameter

$$D_{ro} = D_{si} - 2 \cdot g \text{ mm} \tag{8}$$

The rotor inside diameter can be designed in keeping with usage of the motor and mechanical design.

The tooth pitch is directly proportional with the tooth width as given in (9), is clarified as shown in Fig.4 [12].

$$\tau = \frac{W_{th}}{\tau_s} \tag{9}$$

On the word of designer experience the stator tooth width is usually equal to half of tooth pitch (Slot pitch), so,

$$W_{th} = \frac{\pi \cdot D_{so}}{(3N_{slot} + 2\pi)} \tag{10}$$

The stator yoke length can be equal with the stator tooth length as,

$$T_{hsy} = W_{th} \tag{11}$$

With the equations (8-11) approximately whole the dimensions of stator except the stator dimensions are calculated. The slot dimensions are discussed in next sections.

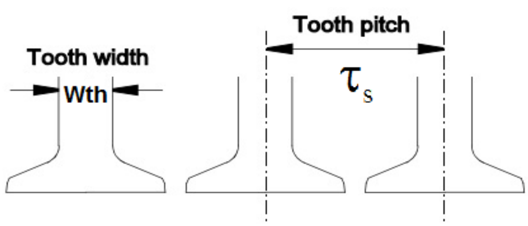


Fig.4. The tooth width and tooth pitch

D. Stator Slot Dimensions

PMSMs are usually composed three types of materials which are: rotor and stator steel, PMs and stator coil winding. Furthermore these materials dimensions and properties are so important.

In designing process. As shown in Fig,5 to model geometrical dimensions, some proved assumptions could be used to design the stator slots, [13].

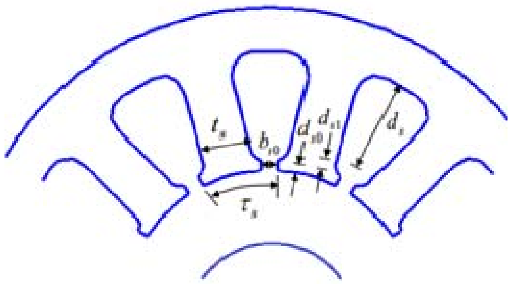


Fig.5. Geometrical dimensions of stator slot

Equation (12) explains each slot pitch, this is obtained, dividing the stator circumference by number of slots.

$$\tau_s = \frac{\pi \cdot D_{si}}{N_{slot}} \tag{12}$$

D_{si}, stator inside diameter; N_{slot}, number of stator slots in motor geometrical model. By using slot pitch parameter, as seen in (12) the stator tooth width can be easily determined.

$$0.4\tau_s \le t_s \le 0.6\tau_s \tag{13}$$

After determining the stator tooth, by (14) stator slot height is designed.

$$3t_s \le d_s \le 7t_s \tag{14}$$

$$b_{s0} \approx (0.1 \cong 0.5)(\tau_s - t_s) \tag{15}$$

b_{so}, slot opening length is calculated as follow,

$$d_{s0} \approx (0.1 \cong 0.5)(\tau_s - t_s) \tag{16}$$

d_{so}, this parameter shows the tooth opening depth.

$$d_{s1} \approx (0.1 \cong 0.5)(\tau_s - t_s) \tag{17}$$

d_{s1}, is stator slot bottom radius.

Based on the determined basic motor parameters, stator slot parameters were calculated as in Table 4.

TABLE 4. DIMENSIONS OF STATOR SLOTS

Dimensions	Values (mm)
τ_s	22.50
t_s	7.50
b_{s0}	3.75
d_{s0}	0.95
d_{s1}	0.25

E. Proper winding Schematic

There are two types of winding for PMSM, they are concentrated and distributed winding. They are also classified into two class as, double layer or single layer. Type of winding for each motor is determined in respect to number of poles, slots and phases. If the ratio, number of slots per pole per phase (q_1), is greater or equal to one, distributed winding type will be preferred in other case concentrated winding will be used.

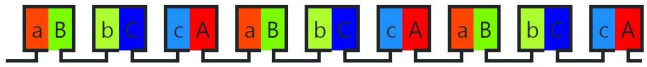


Fig.6. preferred winding schematic

F. Electrical calculation

Other more important parameter to discuss is open circuit test. By test the back electro-motive force (BEMF) maximum induced voltage in rated speed will be known. This value must be smaller than the bar voltage, otherwise the driver of this motor will be so complex because of field weakening strategy, it is undesired case. Therefore, during specifying the number of turn per a coil the designer should be more consider on this parameter. As calculated in (18) the number of turns per a coil directly proportional to BEMF.

$$E = \frac{\pi^2 k_{w1} N_{tph} B_{av} D_{si} L_{st} f}{\sqrt{2}\, N_{pole}} \quad V \tag{18}$$

Where f is the fundamental frequency, and the product $k_{w1}.N_{tph}$ is the effective number of turns in series per phase.

The number of turn per a coil is calculated by (19) or (20).

$$N_{turn_1} = (J_{cu} \cdot A_{coil}) / (I_r \cdot L_{win}) \tag{19}$$

$$N_{turn_2} = (\pi \cdot AC \cdot D_{si} \cdot 10^{-3}) / (2 \cdot N_{phase} \cdot N_{cph} \cdot I_r) \tag{20}$$

The current is calculated as follow,

$$I_r = P_{out} / (N_{phase} \cdot E) \tag{21}$$

A_{coil} is calculate;

$$A_{coil} = k_{fill} \cdot A_{slot} \tag{22}$$

N_{cph} is coil per phase is calculated as,

$$N_{cph} = \frac{N_{slot}}{N_{phase}} \tag{23}$$

PMs locations are usually different regards the driver and motor's usage duty, PMs directly determine air gap flux curve. To run motors with square current waveform, the PMs must be surface mounted and to run with sine wave it can be inset, buried and surface mounted [16]. Stator winding is another magnetic flux source and it is also one more important factor to determine the air gap flux curve. To run the motor with square current waveform concentrated winding are preferred to get the BEMF in square waveform [16]. It is another critical topic to understand, which motor run with sine wave and square wave. After the number of turns are determined the BEMF is in square wave it means the designed motor should be run by square current waveform as BLDC motor. If the

BEMF is in sine waveform the motor should be run as BLAC motor with sine current waveform, [16].

III. ANSYS MAXWELL

ANSYS Maxwell is the industry-leading finite element (FEM) method based developed electromagnetic field simulation software for the design and analysis of electrical motors, actuators, sensors, transformers and other electromagnetic and electromechanical devices. The Maxwell capable precisely characterize the nonlinear, transient motion of electromechanical components and their effects on the drive circuit and control system design, [14].

IV. ANALYSIS RESULTS

The analytical calculations were verified by using design and analyzing software Ansys Maxwell, the analysis results as graphics were obtained.

All figures which are obtained during analyzing the motor are, the direction of PMs in rotor, the cogging torque graphics, meshing the model, open circuit BEMF electromagnetic flux lines and flux density FEM view and BEMF induced voltage curve, full load electromagnetic flux lines and flux density FEM view, full load shaft torque, shaft power, current, stator winding loss, iron loss, Ld and Lq inductance, electromagnetic air gap flux density graphics are given respectively as follow.

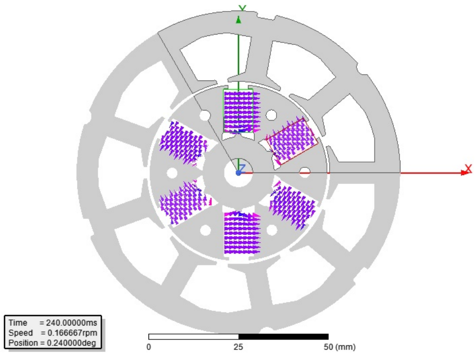


Fig.7. Shows the direction of PMs

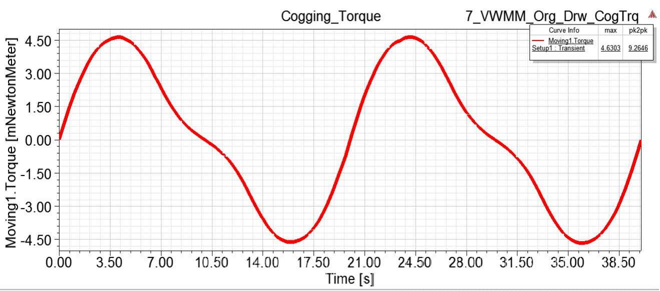


Fig.8. The Cogging Torque is due to the shape of the teeth and the PMs, when all the coils excitations are zero, is equal to 9.2 mNm peak to peak.

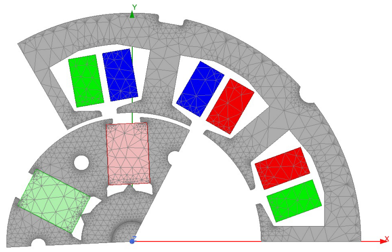


Fig.9. To get the results quickly and more accurate the 1/3 symmetry of the motor is analyzed based FEM

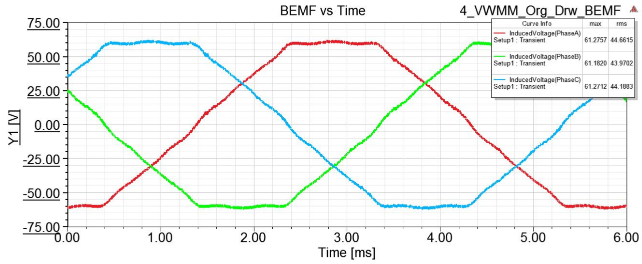
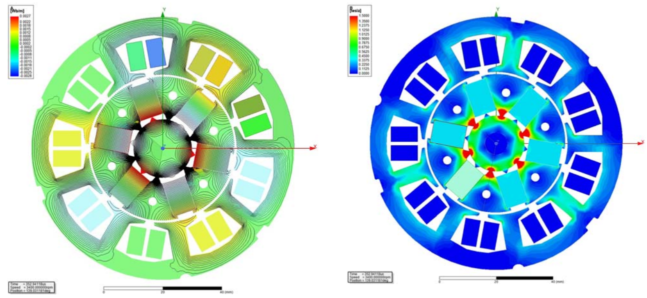
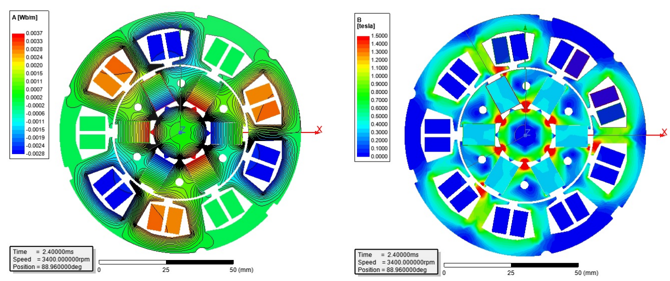


Fig.10. This figure shows the BEMF voltage curves, is obtained when the motor is running at 3400 rpm, induced voltage is 76.7 V_{rms}.



a. Flux lines FEM view b. Flux density FEM view

Fig.11. Shows the electromagnetic flux lines and flux density FEM view of open circuit test when the rotor is rotating in 3400 rpm.



a. Flux lines FEM view b. Flux density FEM view

Fig.12. Shows the electromagnetic flux lines and flux density FEM view of open circuit test when the motor is running in 3400 rpm under the full load.

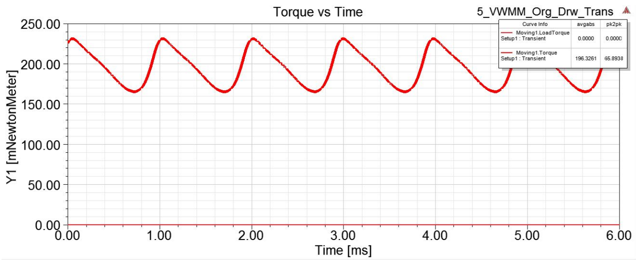


Fig.13. The figure shows the motor rated shaft torque graphics is equal to 0.2 Nm when the motor is running at 3400 rpm.

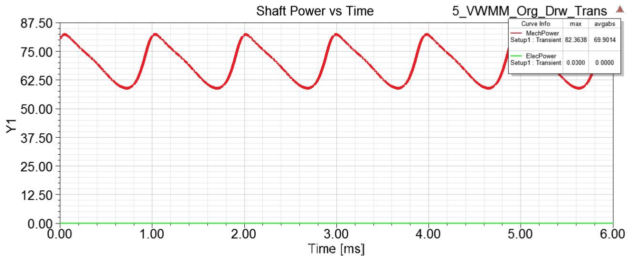


Fig.14. The figure shows the motor rated shaft power graphics is equal to 77 w when the motor is running at 3400 rpm.

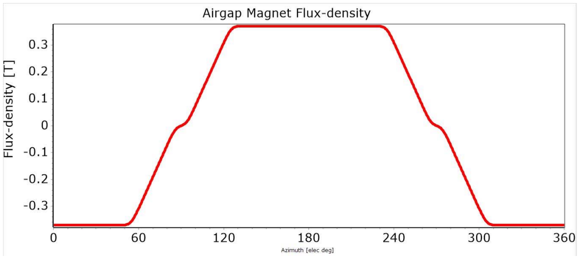


Fig.15. Shows the air gap electromagnetic flux density change vs rotor position.

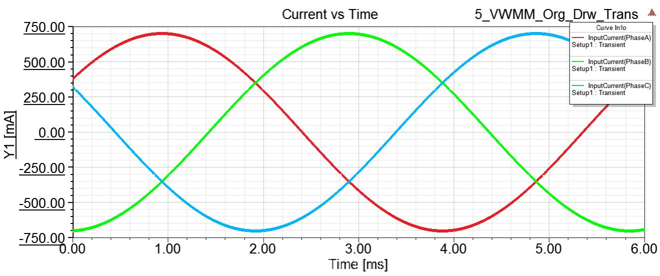


Fig.16. Shows the current which is injected to get the rated torque 0.2 at 3400 rpm is equal to 0.5 Arms.

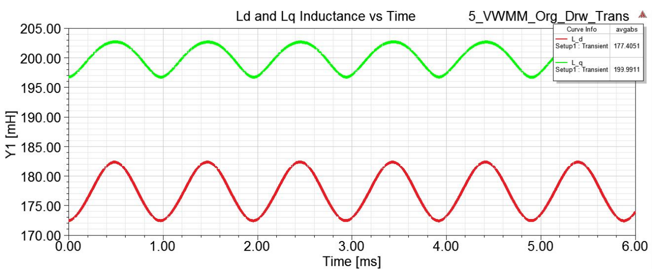


Fig.17. Shows the two different axis (dq) inductances

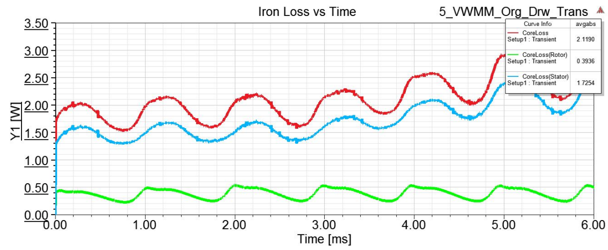


Fig.18. Show the iron loss
a) Red; Total iron loss is 2.2 w, b) Blue; Stator iron loss is equal to 1.75 w, c) Green; Rotor iron loss is equal to 0.4 w
they are 177 and 200 mH respectively.

V. CONCLUSION

In this study a PMSM for dishwasher machine is designed analyzed and fabricated with less price, high efficiency, high power density, capable to run in a range of speed then the previous used single phase induction motor.

The prototype motor is with 12% higher efficiency and 0.50 kg lighter than the induction motor. The designed motor is capable to run in as speed range (2000-3800) rpm without applying the flux weakening strategy with a 0.2 Nm and 0.5 Arms rated values. As experiments, noise, heating up and vibration issues of new designed motor are less than the IM.

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