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INFLUENCE OF POLE ARC OFFSET ON THE FIELD AND OUTPUT PARAMETERS OF BRUSHLESS DC MOTORS

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Abstract*— In this study, for optimization of pole arc, parametric approach method of a 16 W powered, high efficiency permanent magnet brushless DC motor (BLDC) which is used especially in rotary cryogenic coolers and other specific applications is discussed. In the study, for the magnets composing rotor poles, the effects of motor on electromagnetic field and output parameters are examined by changing parametrically the offset point of the pole arc. For new magnet geometries acquired by change of pole arc offset point, motor parameters such as magnetic flux distribution, output power, output torque, cogging torque and efficiency were obtained by using analytical and finite element analysis. Motor parameters and parametric solution method used as optimization technique are effectively introduced. Finally, effects of pole arc offset distances to fields and output parameters of the motor are simulated and represented graphically. The proposed machine has 18 slot, surface mounted 6-pole and inner runner configuration. *(Abstract)

Keywords*— BLDC, pole arc offset, cryogenic cooling, parametric approach, *(key words)

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I. Introduction

The popularity of BLDC motors which are frequently used especially in the defense industry, the healthcare industry, aerospace applications, electrical vehicles and other specific industrial applications has been increasing in recent years. BLDCs have a number of important superiorities such as high efficiency, low moment of inertia, high power density, quiet operation, not requiring maintenance and longevity. Moment-speed characteristic is linear in conventional direct current (DC) motors and excitation performed mechanically by using brush and collector mechanism. Motor needs frequently maintenance due to mechanical excitation and cannot be used in dangerous environments because of the arches appearing during the operation of the motor. BLDC motors were developed with excitation occurring electronically by presenting the same moment- characteristic in conventional DC motors. In this way, the problems appeared in conventional DC motors were removed with BLDC motors. On the other hand, the absence of rotor windings in BLDC motors enables disappearing of rotor copper losses and development of a high efficiency motor. BLDC motors have higher torque compared to asynchronous motors in the same power or conventional brushed DC motors. [1]-[3].

At present, the production of magnets having high energy density has been possible with developments appearing in materials science. Thus, the realization of special designs for more compact motors gets easier. The designer should calculate the performance of the motor which is designed by taking into account the specific dimensions and material factor and then the performance should be compared with the targeted features. In case of not reaching the targeted values, it should be revised by taking motor design again [4]. Detailed torque, power, inductance and sizing equations of BLDC motors are available in literature [5]-[7].

In the study, pole arc offset point belonging to magnet which forms BLDC motor pole is defined as variable. For each defined parameters, Ansys Maxwell and RMxprt simulations were carried out by analytical and finite element analysis methods. The results obtained were compared and the effects of the offset arc point values were investigated by taking into consideration the distribution of flux and output parameters for the BLDC motor used in the study.

II. Parametric Solution of Pole Arc Offset

At present, a lot of techniques are used in size optimization of electrical machines. Among these techniques, parametric solution method differs from others due to some reasons like being practical, result- oriented and fast. In parametric solution method, a variable parameter instead of a fixed value is defined by basing on a geometrical structure of the machine or the electrical parameters. Analyses in desired sensitivity are performed by determining solution steps and bottom and top limits of the variable. By evaluating the obtained results, suitable parameter for targeted outputs is selected. Solution interval and the amount of solution step have a direct impact on sensitivity of the solution. At this point, as sensitivity increases, the number of solution steps will also increase, therefore, the solution period will string out. In the study, pole arc offset point of the rotor shown in Fig. 1 is determined as variable. The solution interval of pole arc offset is determined as min. 0 mm and max. 6 mm by taking into account the physical limitations and solution step is determined as 0.5 mm.

Thus the effects of pole arc offset points located between min. and max. values on field and output parameters were investigated.

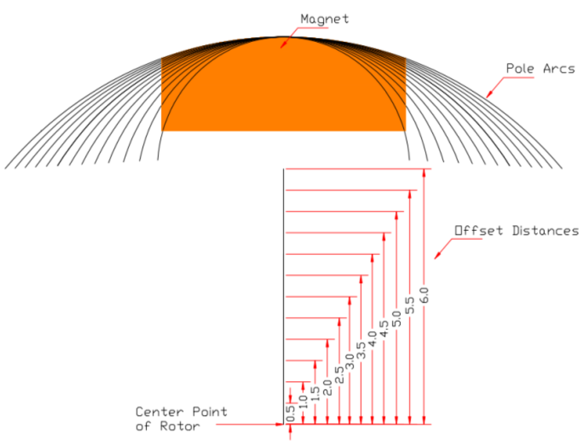

Fig 1. The change of pole arc offset point

III. Output Equations of BLDC Motor

Output equations of the proposed radial flux BLDC motor are defined as following;

$$T = \frac{P_o}{\omega_m} = \frac{\eta N_c E_{ph} I_{ph}}{\omega_m} \quad (1)$$

$$= \frac{\eta N_c \left(\frac{N_m N_{spp} K_w B_g L D_{ro} n_s \omega_m}{2}\right) I_{ph}}{\omega_m}$$

$$= \frac{\eta N_c N_m N_{spp} K_w B_g L D_{ro} I_s}{2}$$

$$L D_{ro} = \frac{2T}{\eta N_c N_m N_{spp} K_w B_g I_s} \quad (2)$$

Here, P_o is rated output power, ω_m is rated speed, L is the stator stack length, D_{ro} is the outer diameter of rotor, T is the output torque, N_c is the number of momentarily energized conductor, N_m is the number of poles, N_{spp} is the number of slots/pole/phase, K_w is winding factor, B_g is specific magnetic loading and I_s is spesific slot loading. Output equation, Eq. 1 and Eq. 2 can be written by arranging as the one in Eq. 3 [4],

$$L D_{ro} = \frac{2T}{\eta N_c N_m N_{spp} K_\omega B_g L D_{ro} I_s}\left(\frac{P_o}{\omega_m}\right) \quad (3)$$

Output power of the machine (mechanical power),

$$P_o = P_i - \left(P_{fw} + P_{Cua} + P_t + P_{Fe}\right) \quad (4)$$

In Eq. 4, P_i is input power, P_{fw}, P_{Cua}, P_t, P_{Fe} are friction and wind loss, copper loss, the transistor / diode loss and iron loss respectively. Efficiency expression which is obtained by taking into consideration output power, input power and all losses is expressed as Eq. 5 [8],

$$\eta = \frac{P_o}{P_o + \left(P_{fw} + P_{Cua} + P_t + P_{Fe}\right)} \quad (5)$$

Parameters of the motor whose design was achieved are given in Table I.

Table I. DESIGN PARAMETERS

Parameter	Value
Stator Material	M19(0.35mm)
Rotor Material	Steel 1010
Permanent Magnet	N35
Efficiency (%)	85.0078
Rated Power (W)	16
Rated Voltage (V)	24
Rated Speed (rpm)	3000
Pole Number	6
Magnetic Pole Embrace	0.64
Air Gap (mm)	0.56
Stator Outer Diameter (mm)	35.32
Length of Stator (mm)	14.5

Three dimensional model of internal rotor BLDC whose design and analysis were achieved is given in Figure 2.

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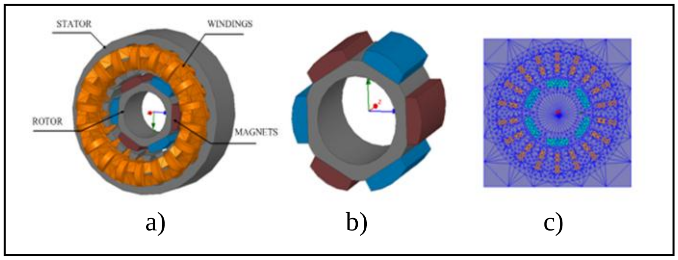

Fig 2. (a) General motor model, (b) Rotor and magnets, (c) Mesh model of BLDC motor

IV. Simulation Results

Output parameters are obtained and presented graphically in response to the change of pole arc offset point of designed BLDC motor. In the study, in addition to the value of the pole arc offset point, output power parameter of the motor was defined parametrically and simulated. Thus, changes in various operating conditions of the motor became possible to investigate.

A. *Air Gap Flux Density versus Pole Arc Offset*

The change of air gap flux density in response to the change of pole arc offset point is given at Fig. 3. In every offset point here, the motor was run at rated power. When the distance of offset point to the rotor center increases, then air gap distance at pole edges increases and in response to this, the density of air flux increases in accordance with the curve in Fig. 3.

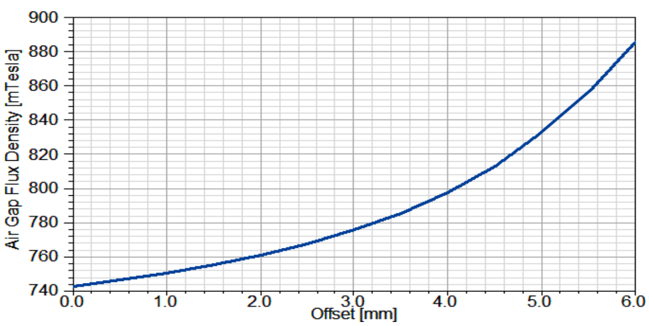

Fig. 3. The change of air gap flux density with variation of pole arc offset points

B. *Cogging Torque versus Pole Arc Offset*

Cogging torque originates from magnetic interaction between magnets placed on the surface of the rotor and stator slots. This effect is an undesirable situation because it causes noise and vibration in permanent magnet machines. The most common method used to reduce the cogging torque is slot slewing. The change of cogging torque in response to the change of offset point is given in Fig. 4.

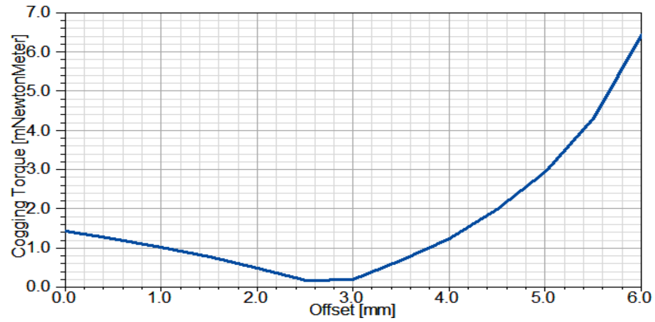

Fig. 4. The change of cogging torque in response to the change of pole arc offset points

On the other hand, cogging torque depends on the distribution of flux between the rotor and stator. Magnet geometry has great importance in the distribution of flux. When offset point gets its maximum value (6 mm), namely, when the distance of air gap in pole edge is maximum, cogging torque also reaches its maximum value. The offset point in which cogging torque is minimum is 2.5 mm.

C. *Cogging Torque versus Pole Arc Offset and Output Power*

Fig. 5 illustrates the change of cogging torque with the variation of pole arc offset points and output power. As it can be seen in the figure, cogging torque is an independent parameter from output power of the motor and takes fixed values. The values in Fig. 4 stay the same and when cogging torque offset point gets 6 mm, it takes its maximum value and when offset point gets 2.5 mm, it takes its minimum value.

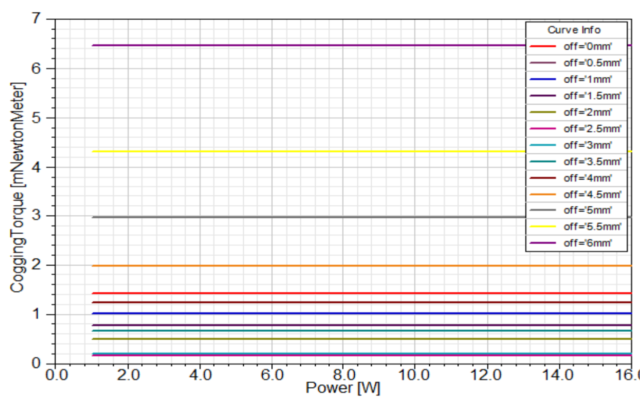

Fig. 5. The change of cogging torque with the variation of pole arc offset points and output power

D. *Rated Torque versus Pole Arc Offset and Output Power*

The change of rated torque value depending on the change of the pole arc offset point and the output power is given in Fig. 6. When the distance of pole arc offset point increases, the distance of effective air gap increases, therefore, the torque induced in the rotor decreases. Around 10% difference occurs between the torques induced for maximum and minimum pole arc offset point. Therefore, the output torque should be considered when determining the pole arc offset point.

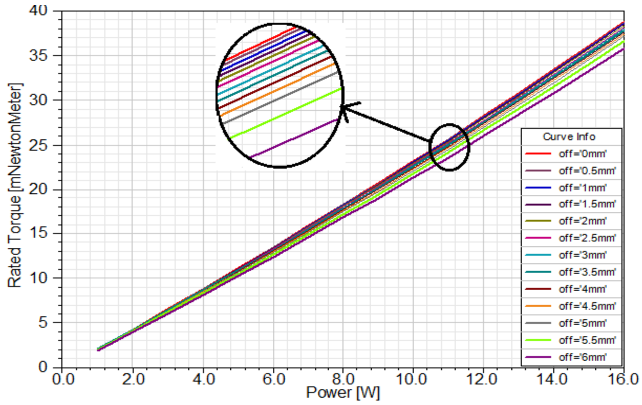

Fig. 6. The change of rated torque with the variation pole arc offset points and output power

E. Total Loses versus Pole Arc Offset and Output Power

The change of all losses according to output power and pole arc offset point is given at Fig. 7. When the distance of pole arc offset point increases, the total losses will increase. When the distance of pole arc offset point increases, the output power of the motor will decrease. As output power in the simulations is assigned like being fixed, the motor increases its input current, thus its losses to enable the same output power against the increasing distance of pole arc offset point. When offset point is at 0 mm, the losses takes minimum value, when it is at 6 mm, they takes maximum value.

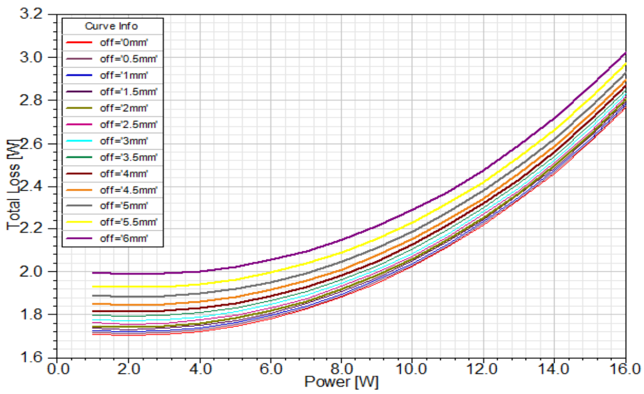

Fig. 7. The change of total loses with the variation pole arc offset points and output power

F. Efficiency versus Pole Arc Offset and Output Power

The change of pole arc offset point and output power in response to efficiency of motor is given at Fig. 8. When the curve that expresses the total losses in Fig. 7 is taken into consideration, the effect of the output power and pole arc offset point on efficiency of motor will be like the curves in Fig. 8. Each curve shows the value of efficiency of motor in response to output power for each offset point value. The maximum efficiency value for the motor occurs when the offset point is minimum. On the other hand, when the offset point increases, the total losses increase to ensure the rated output power and the efficiency of motor drops.

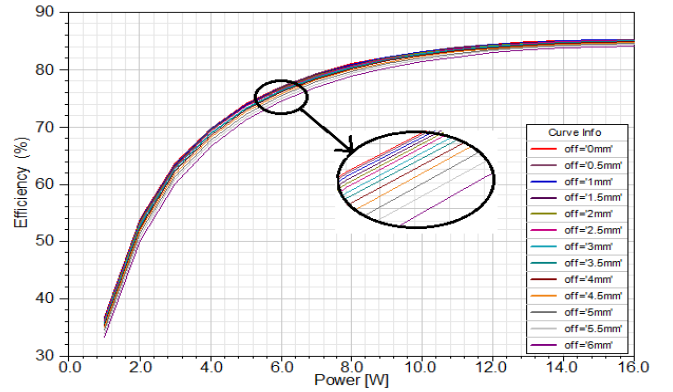

Fig. 8. The change of efficiency with the variation pole arc offset points and output power

G. No Load Air Gap Flux Distribution versus Pole Arc Offset

No load flux distributions in air gap, rotor and stator surfaces caused by the effect of variation of pole arc offset point between 0-6mm are presented at Fig. 9. As the distance of pole arc offset point distance increases, the air gap distance at pole edges increases, therefore, the effective reluctance of the magnetic circuit increases. So that, the value of magnetic flux decreases in motor. Similarly, when the pole arc offset point distance increases, opposite poles on the magnets come closer and leakage flux between opposite poles increases.

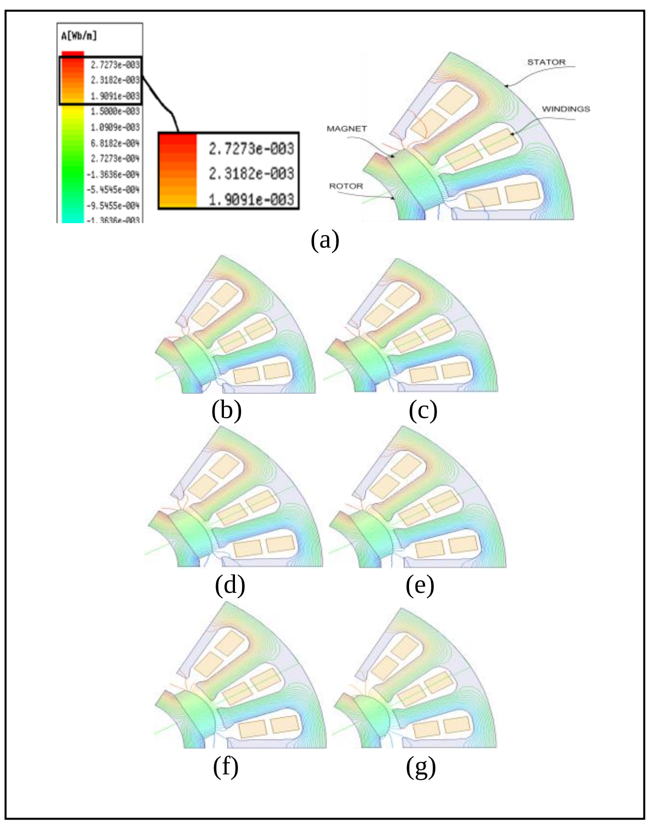

Fig. 9. Air gap flux density with the variation of pole arc offset (a: 0mm, b: 1mm, c: 2mm, d: 3mm, e: 4mm, f: 5mm, g: 6mm)

V. Conclusion

In this study, the effects of pole arc offset point of permanent magnet BLDC motor which is used especially in the applications requiring high efficiency on the motor performance was examined by changing parametrically. With the change of the pole arc offset point, loaded air gap flux density, output torque, efficiency, cogging torque, total losses and the no load flux distribution were investigated. As the distance of pole arc offset increases, air gap flux density and the total losses increase. Therefore, the motor efficiency and output torque decrease. On the other hand, cogging torque parameter gets constant regardless of output power. Cogging torque value decreases till the distance of pole arc offset point being 2.5 mm and after this value, it increases. At this point, while the decrease of pole arc offset point at the beginning shows decreasing effect on cogging torque by affecting the distribution of flux, it increases because air gap flux started to concentrate on one stator slot for the values of offset point distance after 3 mm. However, the no load air gap flux decreases because of the air gap distance that increases due to increasing pole arc offset point distance. The change of magnet thickness and determining the best magnet arc/ pole arc ratio are the following phases of the study. Finally, the study aims to present effective information to electrical machine designers.

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