Design and Analysis of Variable-Reluctance Stepping Motor as Actuator Element of New Type Automatic Transfer Switch

By Budhi Anto

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***Abstract*—This paper describes design process and analysis of single-stack variable-reluctance (VR) stepping motor for use as actuator of transition mechanism of a new type automatic transfer switch. Design procedure is explained and flux density inside all machine parts is analyzed using finite-element analysis based software package MagNet Infolytica. The material for stator and rotor cores uses high permeability magnetic material such as Carpenter silicon steel. The stepping motor will have 6 poles at the stator and 4 teeth at the rotor and produces 0.3 N.m maximum torque with 1 A excitation current. The golden ratio is introduced during design stages. Based on the simulation results, the dimensions of stator and rotor cores of VR stepping motor are as follows, motor axial length 80 mm, stator outer diameter 122 mm, stator bore diameter 72 mm, rotor outer diameter 71 mm and rotor shaft diameter 20 mm, and also the coil at each stator poles will have 800 turns.**

Keywords—automatic transfer switch, single-stack VR stepping motor, cam switch, golden ratio, MagNet Infolytica.

I. INTRODUCTION

A new type of automatic transfer switch was introduced in [1,2]. The apparatus uses VR stepping motor as actuator element of the transition mechanism between 2 sources of electricity as they are main supply from grid network and secondary supply from generating set or genset. During abnormal condition when the grid network fails to supply electricity to the load then the switch will automatically transfer its contacts to the genset so the load will be supplied by the genset. When the condition has returned to normal then the switch will reconnect the load to the grid network.

The contacts transition mechanism of novel automatic transfer switch is explained referring to Fig. 1. This apparatus is basically a cam operated switch with two groups of contacts. The cam is directly driven by Single-stack VR stepping motor. The cam switch has 3 positions, i.e. position 0 or neutral position, position I and position II. If the cam is at position I, electrical supply to the load is maintained by the grid network. If the cam is at position II, the load is supplied by the genset. Transition from position I to position II or from position II to position I passes through position 0. Cam motion from position 0 to position I is 30 degree counter clockwise rotation, whereas its motion from position 0 to position II is 30 degree clockwise rotation. Those patterns of cam motion can be precisely tracked by stepping motor drive, in this case a stepping motor with 30-degree of step angle.

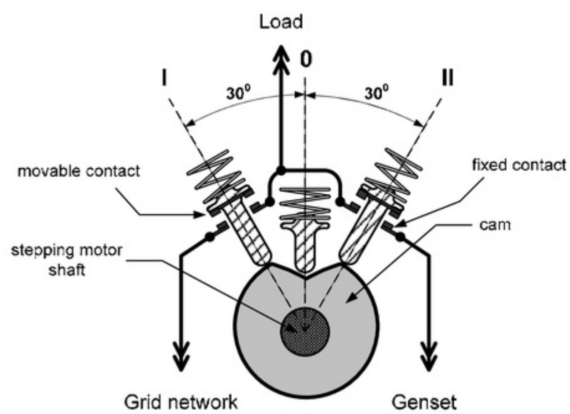

Fig. 1. Contract transition mechanism of new type automatic transfer switch.

An attempt to design a single-stack VR stepping motor that produces specified maximum torque for driving the cam is described in this paper. Basic coarse design of the machine components is obtained by applying several equations that derived from electromechanical conversion theory. The design is then fined to yield machine's dimensions that fulfills the specification by utilizing finite-element analysis software package MagNet Infolytica.

Electrical machines design process always includes formula derived from the designer experience and it could be possible

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to involve the arts into the process. In this paper, the golden ratio of 1.6180339887 approximately [3.4] is introduced in basic coarse design formula as it defines the ratio between the bore diameter of the machine to the length of the stator's core.

There are not many research articles dealing with designing VR stepping motor. One of them was published by Athani in 1983 that described computer-aided design for VR stepping motor, namely CADSTEP [5]. But CADSTEP only focused on VR stepping motor that has 2 stacks with a rotor neck in between. Other paper was written by Acarnley and Hughes in 1981 dealing with predicting maximum torque and speed curve characteristic of VR stepping motor [6].

Single-stack VR stepping motor has the same construction as the switched reluctance motor (SRM). The major difference between them is that SRM is operated under continuos rotation whereas VR stepping motor is operated in stepping mode. Therefore the formula used for designing the single-stack VR stepping motor will much refer to the ones used for SRM design.

There are many papers dealing with the designing of SRM. Kumar and Nagarajam have designed SRM for driving elevator [7]. They used software package RMxprt to simulate the SRM design in order to obtain flux linkage at aligned and unaligned positions, torque profile and efficiency of the motor. Argiolas, Muhammadi and Mierlo have reported their work of design optimization of 12/8 SRM for electric and hybrid vehicles [8]. The objectives of their work are to obtain highest average torque and minimize torque ripple with constraint of minimum material cost. Roy, Mainuddin and Sengupta have designed a 1-hp, 48-VDC, 3000-rpm 8/6 SRM for application in submersible pumps [9]. They used hand calculation in basic coarse design and applied computer iteration with standard FEA software for modification of the design. The SRM design formula and parameters used by the above authors will become references for designing the single-stack VR stepping motor.

II. Operating Principle of Proposed Transfer Swicth

A. *Single-stack VR Stepping Motor Construction*

A stepping motor is electric motor that converts digital pulses into rotation of its rotor. One digital current pulse fed to stator winding of stepping motor will cause its rotor to rotate along predetermined angle. This angle is named step-length [10] or step-angle [11]. One digital current fed to the stator phase winding will cause the rotor to rotate along one step-angle. In order to rotate in a complete one revolution (360 degrees), several current pulses must be applied to stator phase windings. Hence the stepping motor rotates in steps with the same step.

Stepping motor has served as actuator element in many control system applications such as in printer, disc drive and CNC machines. Application of stepper motor to drive valves is described in [12,13]. Based on its operating principle, Krause has classified the stepper motors into 2 types. They are variable reluctance types and permanent magnet types. Major difference between them lies on an existent of permanent magnet at axial of rotor shaft [10].

Single-stack variable-reluctance stepping motor with 30-degree of step angle has been chosen to drive the cam. Basic construction of the motor is determined using the following equation [11],

$$SA = \frac{|N_S - N_R|}{N_S \cdot N_R} \times 360 \qquad (1)$$

where SA is step angle (in degree); N_S is numbers of stator poles and N_R is numbers of rotor teeth. From (1), 30-degree of step angle can be obtained by choosing $N_S = 6$ and $N_R = 4$. The construction of variable reluctance stepping motor is shown in Fig. 2. One coil is wound at each stator pole and connected in series with the coil at the opposite pole to form one phase winding. Since there are 6 poles and also 6 coils at the stator, then there will be 3 phase windings. Fig. 3 shows wiring diagram of phase windings. The switches S1, S2 and S3 are used to energize each phase winding. When S1 is closed then phase A winding is energized, if S2 is closed then phase B winding is energized and if S3 is closed then phase C winding is energized.

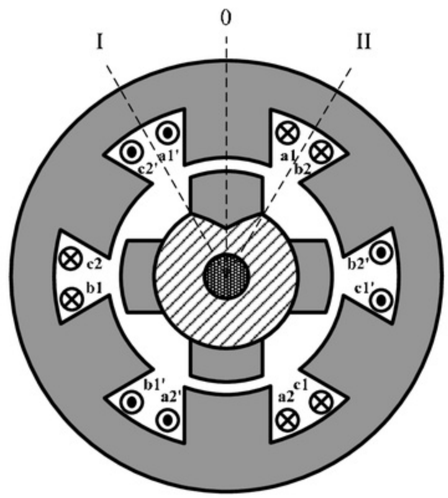

Fig. 2. Construction of single-stack VR stepping motor for driving cam switch.

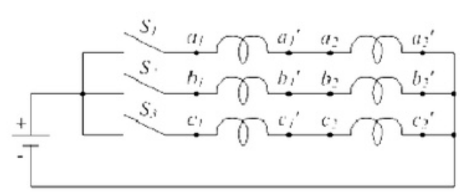

Fig. 3. Wiring diagram of stator phase windings of VR stepping motor.

The torque T produced by 6/4 (6 stator poles and 4 rotor teeth) VR stepping motor is calculated by equation as follows [10],

$$T = (L_{\max} - L_{\min}) i^2 \sin 4\theta \qquad (2)$$

where L_{max} and L_{min} are machine's inductances at aligned and unaligned rotor positions, i is excitation current of each phase winding and θ is rotor position that refers to the aligned position. Equation (2) is derived by assuming that the machine's inductances varies with sinusoidal function of the rotor position and machine is operated at linear region of magnetization curve of core material. From (2), the maximum torque T_m is as follows,

$$T_m = (L_{\max} - L_{\min})i^2 \tag{3}$$

By assuming that the machine is operated at linear conditions and using core material with high permeability, the machine's inductance at the aligned position will only be determined by reluctance of the air gap, hence L_{max} is as follows,

$$L_{\max} = \mu_0 (2N)^2 \frac{A}{2g} \tag{4}$$

where μ_0 is permeability of air $4\pi \times 10^{-7}$ H/m, N is numbers of turn of the coil at stator pole, A is area of stator pole face and g is the length of air gap.

By applying the ratio of L_{max}/L_{min} as one of design parameters and substitutes it into (3) and (4), then the dimensions of the machine that produces specified maximum torque can be determined.

B. Design Equations

The stepping motor must deliver enough torque to drive the cam to the required position. By applying $L_{max} = 1.2L_{min}$, the maximum torque produced by the motor is calculated using equation as follows,

$$T_m = \frac{1}{6} \frac{\mu_0 (2Ni)^2 A}{2g} \tag{5}$$

Rearranging (5) to determine A as follows,

$$A = \frac{2gT_m}{\frac{1}{6}\mu_0 (2Ni)^2} \tag{6}$$

The design process is started by stating maximum torque produced by the motor from the specification and the number of turns per coil, N, phase excitation current, i and the length of air gap, g.

The stator and rotor core dimensions shall refer to Fig. 4. R_{sh} is the radius of rotor shaft, R_{ry} is radius of rotor yoke, R_r is radius of outer rotor, R_{si} is radius of inner stator, R_{sy} is radius of stator yoke, R_{so} is radius of outer stator, W_s is width of stator pole and W_r is width of rotor teeth.

Area of stator pole face is calculated by equation as follows,

$$A = W_s \times \ell \tag{7}$$

where ℓ is axial length of machine's core, the length of stator and rotor cores are taken as equal.

Applying trigonometry, R_{si} is calculated as follows,

$$R_{si} = \frac{W_s}{2\sin\frac{1}{2}\beta_s} \tag{8}$$

where β_s is stator pole angle.

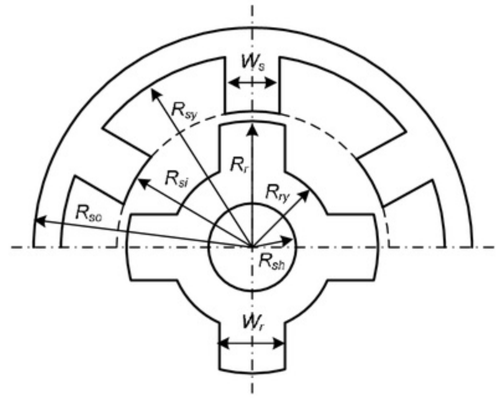

Fig. 4. Stator and rotor core dimensions of single-stack VR stepping motor.

Stator pole pitch τ_s (in degree) and stator slot angle σ_s are calculated as follows,

$$\tau_s = \frac{360}{N_S} = 60 \text{ degree} \tag{9}$$

$$\tau_s = \sigma_s + \beta_s \tag{10}$$

Bore diameter D_{si} of the machine is calculated as follows,

$$D_{si} = 2R_{si} = \frac{W_s}{\sin\frac{1}{2}\beta_s} \tag{11}$$

The golden ratio of 1.618 is introduced in design equation where it relates D_{si} and ℓ as follows,

$$\frac{D_{si}}{\ell} = 1.618 \tag{12}$$

From (7), (11) and (12), we will have,

$$W_s = \sqrt{1.618 A \sin\frac{1}{2}\beta_s} \tag{13}$$

$$\ell = \frac{W_s}{1.618\sin\frac{1}{2}\beta_s} \tag{14}$$

Stator pole height H_s is taken as,

$$H_s = 1.5W_s = R_{sy} - R_{si} \tag{15}$$

The width of stator yoke W_{sy} is taken as,

$$W_{sy} = \frac{1}{2}W_s \tag{16}$$

From (16) and (15), we get,

$$R_{so} = R_{sy} + \frac{1}{2}W_s \tag{17}$$

Applying geometry, the slot area A_{sl} is determined as follows,

$$A_{sl} = \frac{\sigma_s}{2}\frac{\pi}{180}(R_{sy}^2 - R_{si}^2) = \frac{\sigma_s}{2}\frac{\pi}{180}\left(\frac{3}{2\sin\frac{1}{2}\beta_s} + \frac{9}{4}\right)w_s^2 \quad (18)$$

The rotor of single-stack VR stepping motor has 4 teeth. The outer radius of rotor R_r is calculated as follows,

$$R_r = R_{si} - g \quad (19)$$

where g is the length of air gap. The width of rotor teeth W_r is determined using equation as follows,

$$W_r = 2R_r \sin\tfrac{1}{2}\beta_r \quad (20)$$

where β_r is teeth angle.

The width of rotor yoke is taken as $½W_r$, hence R_{ry} is determined as follows,

$$R_{ry} = R_{sh} + \tfrac{1}{2}W_r \quad (21)$$

The copper area A_{cu} which is the area of stator slot that uses for putting the phase coil is calculated as follows,

$$A_{Cu} = \tfrac{1}{2}k_w A_{sl} = Na = N\frac{I}{J} \quad (22)$$

where k_w is window factor with value of 0.25 – 0.6. N is number of turns per coil, a is cross-sectional area of coil conductor, I is nominal phase current and J is current density. Rearranging (22) then we have minimum slot area needed for installing the pole coil as follows,

$$A_{sl} > \frac{2NI}{k_w J} \quad (23)$$

III. Method of Research

The design process is started by stating the specification of single-stack VR stepping motor. The specification shall include maximum torque produced by the motor, operating voltage and nominal phase current and shaft diameter. Then the magnetic material for machine's core is selected based on availability in the market and price. The next stage is set up design parameters such as length of the air gap, window factor and current density of the coil conductor. The dimension of main parts of the motor are determined using design equations as explained earlier. The design of the motor is then simulated under MagNet Infolytica to investigate the flux density inside all parts of the motor and the torque profile of the motor. Torque profile is the graph shown torque of the motor versus rotor position. The flux density inside all machine components must be as high as possible but still at linear region of core material that uses. The machine inductance at aligned and unaligned position of the rotor are also resulted from the simulation process. The maximum torque produced by the designed machine is then compared to the specification. If the maximum torque is below the specification then the process iterates with adjustments to axial length of machine's core in order to meet torque specification. The design procedures are described with flowchart shown in Fig. 5.

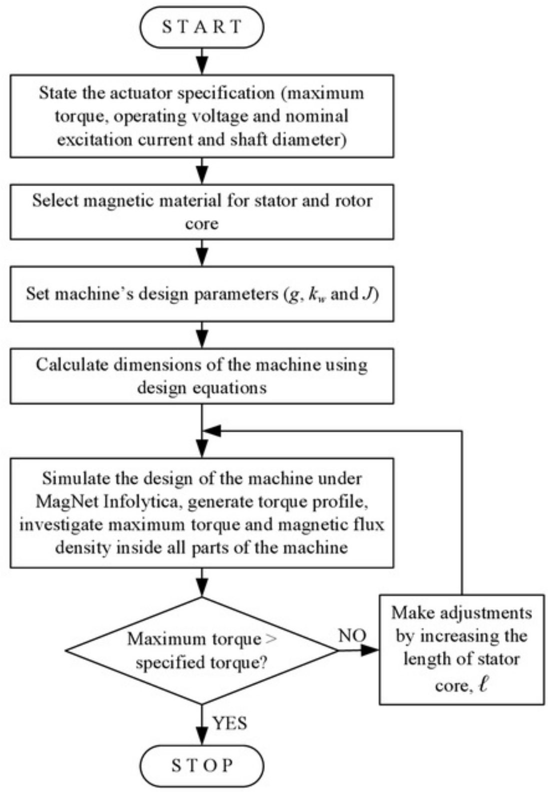

Fig. 5. Flowchart of machine designing process.

IV. Result and Discussions

The actuator of the automatic transfer switch must produce enough torque to rotate the cam under nominal operating voltage and excitation current, so the specification for the actuator must include those items. The specification for the actuator is presented in Table 1.

TABLE I. Specification of Actuator of Automatic Transfer Switch

Item Name	Description
Actuator type	Single-stack VR stepping motor
Number of stator poles	6
Number of rotor teeth	4
Operating voltage	12 VDC
Excitation current	1 A
Maximum torque	0.3 N.m
Shaft diameter	20 mm

The magnetic material for the stator core is same as for the rotor core. It must have high permeability and saturation flux density. The Carpenter silicon steel is chosen for this application. This material has saturation flux density of 2.2 T.

By applying NI = 800 A.turn and g = 0.5 mm into (6), we have A = 559 mm2. Applying β_s = 20 degree into (10), we have σ_s = 40 degree. Applying β_s = 20 degree into (13), we have W_s =12.5 mm. Applying W_s = 12.5 mm into (14), we get ℓ = 44.5 mm. Applying W_s = 12.5 mm into (8), (15) and (17), we get R_{si} = 36 mm, R_{sy} = 54.8 mm and R_{so} = 61 mm.

The rotor core dimensions is obtained as follows. From (19), we have R_r = 35.5 mm. Rotor teeth is made wider than stator pole. By choosing β_r = 22 degree and then applying it into (20) and (21), we get W_r = 13.5 mm and R_{ry} = 16.8 mm.

Since NI = 800 A.turn and I = 1 A, the number of turns per coil N = 800 turn. From (22), choosing J = 10 A/mm2, we get cross-sectional area of coil conductor a = 0.1 mm2. From (23), minimum slot area provided for installing the coil by choosing k_w = 0.3 is 533.3 mm2. Since the slot area that calculated from (18) yielding A_{sl} = 597.5 mm2, then the coil shall fit into the slot. The dimensions of the machine is presented in Table 2. Fig. 6 and Fig. 7 show the CAD drawings of 2-d cross-sectional view of stator and rotor cores.

TABLE II. DIMENSIONS OF 6/4 VR STEPPING MOTOR

Stator Dimension	Rotor Dimension
Pole angle, 20-degree	Tooth angle, 22-degree
Slot angle, 40-degree	-----
Bore diameter, 72 mm	Outer diameter, 71 mm
Pole height, 18,75 mm	Tooth height, 19.48 mm
Yoke thickness, 6.25 mm	Yoke thickness, 6.80 mm
Outer diameter, 122 mm	Shaft diameter, 20 mm
Air gap = 0.5 mm	
Machine axial length = 44.5 mm	
Number of turns per coil = 800	
Cross-sectional area of conductor = 0.1 mm2	

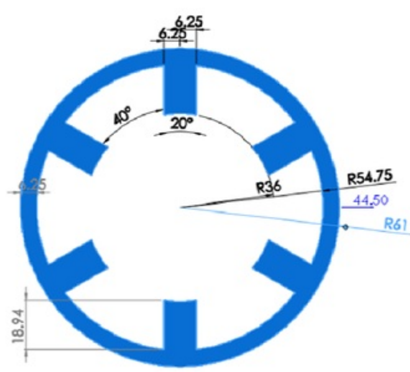

Fig. 6. CAD drawing of 2-d cross-sectional view of stator core.

The design of the machine is then simulated in FEA software package MagNet Infolytica for investigating flux density inside motor parts and to generate motor's torque profile from which the maximum torque of the motor is obtained. Fig.8 shows the model of motor design under MagNet Infolytica. The coil at each pole is represented by a pair of brown squares that hems in the pole. It is clearly shown that rotor tooth is wider than stator pole. Fig. 9 shows the distribution of flux density inside the motor when phase A winding is energized. Flux density at the pole and stator yoke is about 1.5 – 1.6 T and flux density at the teeth and rotor yoke is about the same figures. Flux density inside stator and rotor parts are still below the saturation flux density of Carpenter silicon steel. Flux density at the air gap is about 1.2 – 1.4 T.

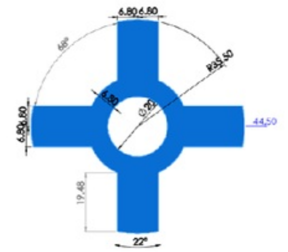

Fig. 7. CAD drawing of 2-d cross-sectional view of rotor core.

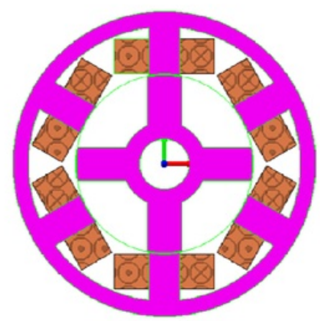
Fig. 8. Model of the VR stepping motor under MagNet Infolytica.

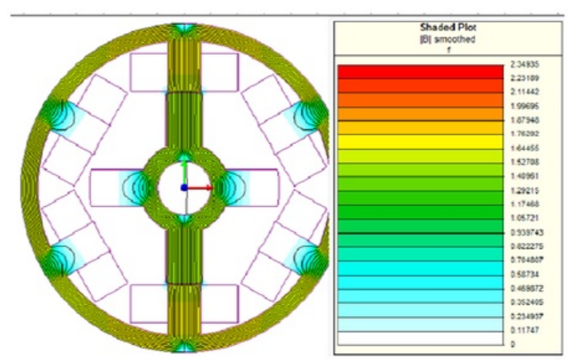

Fig. 9. Distribution of flux density inside the motor parts when phase A winding is energized.

MagNet Infolytica can also generate the torque profile of VR stepping motor from aligned position to unaligned position and it is shown in Fig. 10. From Fig. 10, maximum torque produced by the motor is 0.192 N.m, so it is still below the torque specification.

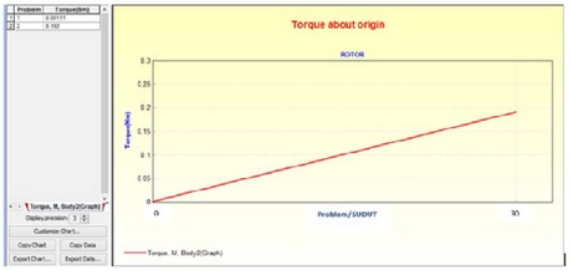

Fig. 10. Torque profile of 6/4 VR stepping motor from aligned position to unaligned position.

Several adjusment must be carried out to raise the torque of the motor. This is done by increasing the axial length of the motor. The simulation is iterated for each adjustment and the result is tabulated in Table 3. From Table 3, at axial length of 80 mm, the motor produces maximum torque 0.345 N.m thus exceeds the specification. The final design will use this value. Fig. 11 shows the tendency of axial length adjusment to the maximum torque of the motor, which tells that by increasing the axial length of the motor, the maximum torque will increase linearly.

TABLE III. AXIAL LENGTH VERSUS MAXIMUM TORQUE OF THE MOTOR

Motor's Axial Length	Maximum Torque
44.5 mm	0.192 N.m.
60 mm	0.258 N.m.
80 mm	0.345 N.m.
100 mm	0.431 N.m.

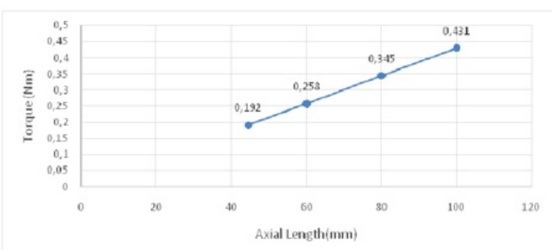

Fig. 11. Maximum torque of 6/4 VR stepping motor versus motor axial length.

V. CONCLUSIONS

Design process of single-stack 6/4 VR stepping motor for use as actuator element of transition mechanism of automatic transfer switch has been presented in this paper. The motor must produce maximum torque of 0.3 N.m with operating voltage 12 VDC. The dimensions of the motor is determined using design equations derived from electromechanical conversion theory by assuming the motor operated at linear region of magnetization curve of magnetic material. The golden ratio is introduced in design equations which relates the bore diameter to axial length of the motor. Computer simulation using FEA software package MagNet Infolytica is done to find the design that meet the specification. With Carpenter silicon steel, the final design that meet the specification shall use dimensions as follows, motor axial length 80 mm, stator outer diameter 122 mm, stator bore diameter 72 mm, rotor outer diameter 71 mm and rotor shaft diameter 20 mm, and also the coil at each stator poles will have 800 turns. In the future work, the design shall be fabricated and tested to verify the design procedures and also the research of optimalization of the motor design will be conducted to find the design with minimum material cost.

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