DESIGN AND DEVELOPMENT OF A NOVEL OUTER ROTOR PERMANENT MAGNET MACHINE

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Abstract
Newer types of synchronous generators are being developed recently due to the rapid availability of high power density rare earth magnets. An outer rotor generator that typically be applied for wind power and electric vehicle applications is proposed in this paper. The design of the structure is done through analytical calculations and the analysis to optimize the machine parameters are done through numerical analysis. The electromagnetic analysis of a novel outer rotor permanent magnet generator of 18 slots and 20 pole generator produces voltage of 150V when running at 1200 rpm. The design procedure of such a novel machine with electromagnetic analysis on the static and dynamic conditions is analyzed and the results are presented in this work.

Keywords: Outer rotor generator, Machine design, Electromagnetic analysis, FEA.

1. Introduction
In the permanent magnet machine, the rotor is positioned in two ways which is in the inside (inner rotor type) and on the outside (outer rotor type). The key factor in designing an efficient machine lies in maximizing the power density of the machines. This is usually done through the optimization of parameters like the position and shape of the magnet with respect to the static applied magnetic source [1]. Placing the rotor on the outer surface yields a better torque compared to that of the inner rotor [2]. Attempts by researchers on the study of placing the rotor in inner and outer surface is documented in the literature [3]. The outer rotor PMSM derives significant improvement due to the longer radius compared to the inner rotor design. They are found in significant applications such in mechanical
### Nomenclatures

- **$A_g$**: Area of the air gap, $m^2$
- **$A_R$**: Net area of rotor, $m^2$
- **$A_{rc}$**: Area of rotor core, $m^2$
- **$A_{rt}$**: Area of rotor tooth, $m^2$
- **$A_s$**: Area of stator pole, $m^2$
- **$A_{sp}$**: Area of stator pole base, $m^2$
- **$A_{st}$**: Area of stator pole tooth, $m^2$
- **$A_y$**: Area of yoke surface, $m^2$
- **$a_c$**: Specific electric loading, amp-conductors/m
- **$C_0$**: Output coefficient
- **$C_{ry}$**: Rotor back iron thickness, m
- **$C_{sy}$**: Stator back iron thickness, m
- **$B_{av}$**: Specific magnetic loading, wb/m$^2$
- **$B_r$**: Rotor magnetic flux density, wb/m$^2$
- **$B_s$**: Stator magnetic flux density, wb/m$^2$
- **$C_y$**: Net yoke back iron, Tesla
- **$D$**: External diameter, m
- **$D_o$**: Exterior diameter, m
- **$D_{sh}$**: Shaft diameter, m
- **$d_c$**: Diameter of the coil, m
- **$H_g$**: Magnetic flux intensity, At/m
- **$h_c$**: Height of the coil, m
- **$h_i$**: Height of the stator pole base, m
- **$I_z$**: Current in the coil, A
- **$L$**: Stack length, m
- **$l_g$**: Length of the air gap, m
- **$l_r$**: Length of the rotor flux, m
- **$l_{rc}$**: Length of the rotor core, m
- **$N_s$**: Synchronous speed, rpm
- **$n_c$**: Number of coil turn
- **$n_{cut}$**: Nett coil turns
- **$P_d$**: Developed power, syn-watts
- **$Q$**: Generator capability
- **$R_g$**: Reluctance in the air gap, At/wb
- **$W_s$**: Width of the stator, m
- **$w_c$**: Width of the coil, m
- **$Z$**: Total number of coils

### Greek Symbols

- **$\eta_m$**: Machine efficiency
- **$\mu_0$**: Permeability of free space, H/m
- **$\mu_r$**: Relative Permeability, H/m
- **$\Phi_r$**: Flux in the rotor, wb
- **$\Phi_s$**: Flux inside the core, wb
- **$\Phi_y$**: Flux in the yoke, wb
- **$\omega$**: Rotational angular speed, rad/s
cutters [4] and wind turbines [5-6]. The purpose of this research is to design an outer rotor structure generator that is to be coupled with a wind turbine generator. A fractional horse power outer rotor permanent magnet generator with 18 slot and 20 poles catering to the three blade structure of the wind turbine in place is designed and analyzed for its performance on voltage generating capability.

2. Design Methodology

2.1. Design aspects

2.1.1. Sizing of the machine

The sizing of the machine and the design approach presented in this work is based on the step by step design procedure for universal machines presented in [7]. The ratings of the generated voltage \( Q \) based on the sizing is as in Eq. (1).

\[ Q = \text{Specific Electrical Loading (ac)} \times \text{Specific Magnetic loading (B_{av})} \]  

(1)

The specific electric loading is the amount of ampere-conductors per unit length of the gap surface surrounding the perimeter of the machine [6]. The equation for the specific electric loading of a machine is shown in Eq. (2).

\[ ac = \frac{I_2(2z)}{\pi D} \]  

(2)

The specific magnetic loading is the ratio of the total amount of flux available around the air gap to the total area of the flux path at the air gap. The specific magnetic loading is also known as the average magnetic flux density that covers the whole air gap surface of a machine. The equation for the specific magnetic loading is shown in Eq. (3).

\[ B_{av} = \frac{Nia_4}{\pi DL} \]  

(3)

The power developed \( (P_d) \) by the machine is shown in Eqs. (4) and (5).

\[ P_d = (\pi DL)(\pi D) \omega \]  

(4)

\[ P_d = C_0 D^2 L \omega \]  

(5)

The volume of the machine is found using Eq. (6).

\[ D^2 L = \frac{P_d}{\omega C_0} \]  

(6)

2.1.2. Stator Design

The design of the stator pole for this machine is shown in Fig. 1. The area of the pole is found using Eq. (7).

\[ A_s = \frac{2}{3} L A_{st} \]  

(7)

The area of the middle pole is found using Eqs. (8) and (9).

\[ A_{sp} = P_s L \]  

(8)

\[ A_{st} = A_s + A_{sp} \]  

(9)
Therefore the net flux present in the yoke is found using Eq. (11).

\[ \Phi_y = \frac{\Phi_s}{2} = \frac{A_{st}B_s}{2} \]  

(11)

Assume that the flux density of the yoke equals to half the flux density of the stator, the flux density is shown in Eqs. (12) and (13).

\[ \Phi_y = A_yB_y \] 

(12)

\[ \Phi_y = \frac{A_yB_s}{2} \] 

(13)

\[ A_{st} = A_y \] 

(14)

The thickness of the stator back iron is found using Eq. (15):

\[ C_{sy} = \frac{A_y}{L} \] 

(15)

The width of the stator is found using Eq. (16):

\[ W_s = L \times 0.7 \] 

(16)

2.1.3. Rotor Design

The area of the rotor pole is found using Eq. (17):

\[ A_R = \left( \frac{D_o}{2} + l_g \right) L \] 

(17)

The flux density of the rotor pole is found using Eq. (18):

\[ B_r = \frac{A_{st}B_s}{A_R} \] 

(18)

\[ A_{rc} = \left( \frac{D_o}{2} - 2l_g - \frac{D_s h}{2} \right) L \] 

(19)

The thickness of the rotor back iron represented using Eq. (20):

\[ C_{ry} = \frac{A_{rc}}{L} \] 

(20)

Half of the flux is carried by the core of the rotor and is limited to a flux density of approximately 80% of the maximum value. Therefore the flux density is found using Eqs. (21) and (22):

\[ \Phi_r = \frac{\Phi_s}{2} = \frac{A_{st}B_s}{2} \] 

(21)
\[
\phi_r = (0.8) \frac{A_{rc}B_s}{2} \quad (22)
\]

With a 1.6 ratio of flux density, the area of the rotor is found using Eq. (23).

\[
A_{rc} = \frac{A_{sp}}{1.6} \quad (23)
\]

The height of the pole of the rotor is found using the Eq. (24).

\[
h_r = \left(\frac{D_o}{2} - C_{ry} - 2l_g - \frac{D}{2}\right) \quad (24)
\]

The average area is found using Eq. (25).

\[
A_g = \frac{A_{R}+A_s}{2} = \left(\frac{1}{2}\right) \left(\frac{D_o}{2}\right) (A_R) + \left(\frac{D_o}{2}\right) (A_s) \quad (25)
\]

The reluctance present in the air gap is found using Eq. (26):

\[
R_g = \frac{4l_g}{\mu_0 A_g} \quad (26)
\]

The design of an individual rotor pole and the complete rotor design for this machine is shown in the Fig. 2.

![Fig. 2. Design of rotor.](image)

### 2.1.4. Yoke Design

The mean path lengths for different parts are found using Eqs. (27) and (28).

\[
l_r = h_r + \frac{C_y}{2} \quad (27)
\]

\[
l_{rc} = (\pi) \left(\frac{D_o}{2} - \frac{C_y}{2}\right) \quad (28)
\]

The flux density present in the air gap is found using Eq. (29).

\[
B_g = \frac{A_{R}B_s}{A_g} \quad (29)
\]

The magnetic field intensity present in the air gap is found using Eq. (30).

\[
H_g = \frac{B_g}{4\pi \times 10^{-7}} \quad (30)
\]

### 2.1.5. Shaft Design

In a machine, the shaft is responsible for transmitting power from one rotating part of the machine to another rotating part of the machine. The shaft also acts as a
support structure for the rotating parts of a machine like the rotor and the permanent magnets in this case. Shafts are either hollow or a complete solid and are generally circular in shape. The diameter of the shaft is designed using Eq. (31):

\[ D_{sh} = (0.55)(\frac{P_d}{\omega})^{\frac{1}{3}} \]  

(31)

2.1.6. Winding Design

The armature windings in a machine are made up of conductor wires which are wound around a core in a concentrated manner. When there is a current passing through the coil, these windings behave like normal magnets each with its own north and south poles. The design of the coils and their basic dimensions are shown in Fig. 3. The width of the armature coils are calculated using the Eqs. (32) and (33).

\[ w_c = (\theta_{s1}) \left( \frac{\pi}{180} \right) \left( \frac{D}{2} \right) \]  

(32)

\[ n_c = \frac{n_cw_c}{d_c} \]  

(33)

When the windings are done manually, the number of turns is estimated to be between 60% and 70% [7-8]. The total or net number of turns is calculated using Eq. (34).

\[ n_{net} = n_c \times 0.7 \]  

(34)

Once the number of slots of the stator and the number of poles are fixed, the Eqs. (35) and Eq. (36) is used to determine the pole-slot combination.

\[ \frac{360}{\text{number of slots}} = \frac{360}{18} = 20 \]  

(35)

\[ \frac{360}{\text{number of poles}} = \frac{360}{20} = 18 \]  

(36)

The angle value is now calculated for each slot of the stator. This is done by beginning from 0° for slot 1. 200° is then added to 0° for slot 2 and this process continues until slot 18. Figure 4 summarises the angle value for all 18 slots. The slots with the same angle values are then grouped together to form the corresponding phases. Based on the above design equations the proposed machine is designed and the optimisation of the design is converged to the final structure and the dimensions are shown in Fig. 5. A complete design procedure and the numerical analysis including the analysis on the data are documented in [9].

![Fig. 3. Design of armature coils.](image-url)
3. Numerical Analysis

3.1. Finite element analysis (FEA)

In order to derive the torque characteristics of the double rotor reluctance machine it is constructed using the FEA tool. Finite element analysis is a numerical method of solving linear and non-linear partial differential equations. FEA tool is used to obtain the magnetic vector potential values due to the presence of complex magnetic circuit geometry and non-linear properties of the magnetic materials. The force on the object in the magneto-static field is calculated from Maxwell’s equation stress [9-10]. In two dimensional analysis, the current density $J$ is assumed to have a $z$-direction component. Similarly the magnetic vector potential $A$ have $z$-direction component are developed using Poisson equations that is used to build the finite element tool. This yield the path of flux flow, magnetic flux density from which the static torque characteristics is derived.

3.2. Electromagnetic analysis

The structural design of the machine is constructed or drawn again using another soft computing tool called JMAG Designer. Once this is done, FEM simulation is conducted on the 2D drawing of the designed model. The flowchart of the design
procedure involved in the FEM simulation and the machine structure in JMAG design is as shown in Fig. 6. Figure 7 shows the electromagnetic field analysis under the dynamic operating conditions for various pole positions. This analysis is carried out for one rotor pole pitch. For optimization in this design the pole arc is shaped such a way that the machine is able to produce a symmetrical waveform over the observed pole pitch. This presents the average torque to be higher and also at the same time the harmonic distortion to be of minimal value.

For the analysis of the proposed machine as generator the machine is analysed for both the no load condition and also for the loaded conditions. For the load
circuit condition, the circuit is designed as shown in Fig. 8. The three FEM coils shown in the diagram represent Phase A, Phase B and Phase C. Since the number of poles in each phase is the same, therefore the resistance value and the number of turns for each phase are set to be the same. The right hand side of the circuit is grounded. A star connection consisting of three resistors is made on the left hand side of the circuit. Each resistor is connected to each phase. The value of all three resistors is fixed to be the same. Voltmeters are connected to each phase in order to measure the amount of voltage produced. Analysis is then done by varying the value of all three resistors from 0 Ohms till 100 Ohms.

![Open Circuit (No load Analysis).](image) ![Loaded Circuit Condition.](image)

**Fig. 8. Design using FEA tool.**

4. Results and Discussions

4.1. Static characteristics

The magnetic flux density for one pole pitch value is shown in Fig. 9. This magnetic flux density computed through simulation confirms with the designed value earlier for proper excitation and operations of the proposed machine. The electrical parameters of the voltage, current and power are computed in order to conduct an analysis on the performance of the machine. The voltage and the power generated are calculated using a dummy resistive load and the rotor is rotated. The computation is done for both static and dynamic conditions. The voltage and power generated is then computed for various positions of the rotor when a constant current is applied. The same procedure is done with constant frequency applications and the rotor is rotated for various speeds as shown in Fig. 10.

4.2. Dynamic characteristics

Figure 11 shows that as the rotational degree value increases, the magnetic flux decreases slightly during the static condition. The voltage generated increases from 0 V to 25 V, there is a drastic increase in the magnetic flux. However, as the voltage increases further, there is only a slight increase in the magnetic flux. In a machine, when the voltage increases, this results in an increase in the magnetic flux as the voltage is proportional to the flux when the speed of rotation in a machine is fixed. Also as the speed of rotation increases, there is a gradual linear increase in the voltage generated by the design because in DC machines, the
speed of rotation is directly proportional to the voltage of the machine. Based on the graphs, it is concluded that the voltage of the machine produced is 150V. The maximum power produced is 250W at 1200 rpm.

5. Conclusions
In this research paper, a novel Outer Rotor Internal Permanent Magnet Synchronous generator is proposed. The design of the structure is then done using the relevant
design equations. Once the physical parameters are fixed, the physical structure of the design is done using a CAD tool. Once the design is completed, it is analysed for static and dynamic conditions. For the static condition, the circuit is shorted and the rotational degree is varied from 0 degrees to 20 degrees and the results obtained were recorded. The static condition is repeated but with an addition of a star connection of three resistors. Therefore, in other words, the machine is tested for no load condition and load condition. For the dynamic condition, the circuit with the star condition is tested when the speed is varied from 0 rpm to 1500 rpm. Through mechanical variations on the design, a better torque is produced when the diameter of the rotor is increased. By optimising the pole design a novel structure is proposed in this research. The electromagnetic design analysis of such a machine presents encouraging power density improvements. Initial investigations reveal a generated voltage of 150V when the machine runs at 1200 rpm producing a nominal output of 350W under loaded condition.

References


