Electromagnetic Torque Analysis of Wind-Driven SRG with Ferrite Magnet

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Abstract—The present paper analyses the effect of placing the ferrite magnet into the rotor air barrier of synchronous reluctance generators (SRG) on its electromagnetic performance. The paper uses a difference of average electromagnetic torque and ripple torque as a measure of the performance index. Here, in the analysis, a magnetic material is placed in the middle of each air barrier, and its size is symmetrically increased on both sides to increase the percentage of the volume of the magnetic material. The effect of an increase in the volume of the magnetic material on its performance is presented. Moreover, the variation in electromagnetic features such as the d- and q-axes inductance and flux linkage are also explored and compared for different volumes and ferrite materials. In the present work, finite element analysis is used to get the electromagnetic performance. The paper also includes hardware validation on the fabricated prototype of SRG (without ferrite magnet), but SRG with a ferrite magnet only includes the results with FEA simulation.

Index Terms—Ferrite material, FEA, Torque, Synchronous reluctance generator.

I. INTRODUCTION

Synchronous reluctance generator (SRG) is one of the suitable generator to generate electric power for wind energy/remote area applications. It is compact, robust, and it can operate in a self-excited mode using only the input mechanical power from the rotating wind turbine. It is reliable, simple in construction, small in weight and size, efficient, and with the reduced cost of maintenance.

It is observed, that the active volume of the core, surface area, and an arrangement and volume of the ferrite magnets (FMs) in the rotor air barrier will have a significant influence on the performance of FR-SRG [1]-[3]. To enhance the operating performance of SRG, a small percentage of low-cost ferrite magnets (FMs) are placed into the generator rotor air barrier to form an FM-assisted SRG (FM-SRG) [3]-[5]. By filling the air barrier with a suitable volume of the magnetic material, it is possible to improve the average torque, efficiencies, and power factor of the FM-SRG [5]-[7]. The design of the shape of the air barrier has a significant impact on the performance of the SRG. A rectangular shape is preferred while designing the shape of the air barrier, as it reduces the low-cost of the FMs and easy to place them into the air barriers. Hence, significantly reducing the cost of its mass production [7]-[9]. In some designs, additional ribs are provided between the magnets to increase the mechanical strength of the rotor during its operation [10]-[13]. Here, for comparison purposes, only the length of the FM-SRG is reduced with an increasing percentage of the volume of ferrite magnet while keeping the rating of the FM-SRG constant i.e., 2.7-hp. The analysis of the performance of the machine is done using the FEA. The FEA results of SRG (without ferrite magnet) are validated with the experimental result obtained from the fabricated prototype of SRG (without ferrite magnet). The parameters and the rating of the machines i.e., SRG and FM-SRG (30% ferrite magnet volume of the total air barrier volume) are summarized in Tables I and II.

| Dimension of the Generator | Values |
|-----------------------------|--------|
| $D_x$                       | 105 mm |
| $D_m$                       | 180 mm |
| $D_r$                       | 104 mm |
| Phase Voltage               | 150 V  |
| $L_{SRG}$                   | 65 mm  |
| $L_{FM-SRG}$                | 50 mm  |
| $I_{rated}$                 | 9.5 A  |
| Output Power                | 2.7 hp |
The accurate modeling of wind generators is helpful to reduce volume and the cost of the system. From the wind turbine model, the turbine mechanical power is given as (watts):

\[ P_m = \frac{1}{2} R^2 \pi p C_p (\lambda, \alpha) v_w^3 \]  

(1)

The performance coefficient of the turbine in terms of the tip speed ratio (TSR) and blade pitch angle can be represented as (2):

\[ C_p (\lambda, \alpha) = C_1 \left( \frac{\lambda_1}{\lambda} - C_2 \alpha - C_3 \right) \exp \left( \frac{-C_4}{\lambda} \right) + C_5 \lambda \]  

(2)

Letting,

\[ \lambda_1 = \frac{(\alpha^2 + 1)(\lambda + 0.08\alpha)}{\alpha^2 - 0.028\alpha - 0.035\lambda + 1} \]  

(3)

The value of \( \lambda \) has been selected for optimal point of capture. Once the values of \( \lambda \) and \( \lambda_1 \) are found, the turbine speed and the radius have been calculated from (1) and (4). The mechanical speed of the turbine \( \Omega \) rad/s is given as:

\[ \Omega = \frac{\lambda v_w}{R} \]  

(4)

The equation of the torque is given as:

\[ T_m = \frac{P_m}{\Omega} = \frac{1}{2 \lambda} R^2 \pi p C_p (\lambda, \alpha) v_w^2 \]  

(5)

The above equations are used to design the wind turbine, and the designed parameters are shown in Table II:

| Parameters                              | Values                      |
|-----------------------------------------|-----------------------------|
| TSR                                     | 8                           |
| Wind speed                              | 12.5 m/s                    |
| Gearing ratio                           | 2.014                       |
| Blade tip speed                         | 78 rad/s                    |
| Mechanical torque of turbine rotor      | 25.68 Nm                    |
| Performance Coefficient limit           | 0.41                        |
| Mechanical torque of generator shaft    | 12.75 Nm                    |
| Generator rated speed                   | 157.08 rad/s                |
| Turbine blade radius                    | 1.25 m                      |

(6)

Since the objective of placing the ferrite magnets into the air barriers is to increase the torque, it is important to place them in an air barrier in such an orientation, which reduces the flux linkage along the \( q^- \) axis, i.e., \( \Lambda_m \) with FMs is expressed as:

\[ \Lambda_m = \lambda_q - \Lambda_m = L_q I_q - \Lambda_m \]  

(7)

Here, \( \Lambda_m \) is flux linkage of ferrite magnet oriented along the negative \( q^- \) axis. The electromagnetic torque \( T_{em} \) that can be produced by the FM-SRG is expressed as:

\[ T_{em} = \frac{3P}{2} \left( \Lambda_m I_q + (L_d (I_d, I_q) - L_q (I_q, I_q)) I_q I_q \right) = T_e + \frac{3P}{2} (\Lambda_m I_q) \]  

(8)

From (7) and (8), it could be inferred that by placing the ferrite magnet with the correct orientation, the electromagnetic torque of the FM-SRG is increased, but at the cost of increased in the torque ripple. This leads to the development of a performance index that uses the difference of average electromagnetic torque and ripple torque. Moreover, the increase in the volume of the ferrite magnet in the air barrier also has an effect on the reduction of the \( d^- \) axis flux linkage, thus reducing the average electromagnetic torque and ripple torque. This leads to the development of a performance index, \( \eta \) which represents the difference between torque ripple performance ratio \( R \) and the produced electromagnetic torque performance ratio \( T \) at corresponding \( V_{fms} \) is defined as:

\[ \begin{align*}
T &= \frac{V_{fms} T_{em}}{V_{fms} (T_{fem} - T_e) + T_e} \\
R &= \frac{V_{fms} T_{em} \rho}{V_{fms} (T_{fem} - T_e) + T_e}
\end{align*} \]  

(9)

Hence, based on the equation (9) the performance index, \( h \) can be expressed as:

\[ h = T - R \]  

(10)
Here, $T_{emrp}$ is peak-peak torque ripple of FM-SRG, and $\Psi$ and $\Psi_p$ are weight factors of torque and peak to peak torque ripple respectively. Here, $T_{em}$ and $T_{emrp}$ are the average electromagnetic torque and ripple torque when $V_{fm} = 30\%$. The factor $\Psi$ and $\Psi_p$ are adjusted to get the actual average and ripple torque for a different volume of ferrite magnet. It is observed from Fig. 3(a) that initially, with the increase in the volume of the ferrite magnet $V_{fm}$, the performance index increase, but for $V_{fm} > 30\%$, a decrease in the performance index is observed. This is mainly due to the demagnetization along the d-axis and increase in the ripple torque. The plot of the variation of the operational efficiency is shown in Fig. 3(b).

III. CONSTRUCTION TROUBLES OF THE FM-SRG

The main advantage of FM-SRG as compared with the SRG is in terms of increased power factor and efficiency [6], [19].

The design of FM-SRG is similar to that of SRG, except for a few minor changes. The changes are mainly in the shape of the air barriers; typically, the trapezoid shape rotor air barrier is preferred to host low-cost rectangular ferrite magnet, as shown in Fig. 2. In fabrication and design of SRG selection of material for laminations plays a significant role in achieving low core loses, saturation and elevated flux density. The operating frequency depends on the chosen thickness of the lamination. The common available lamination thickness ranges from 0.35 mm to 0.5 mm. The present SRG design applies M-19 grade lamination (i.e., cold rolled non-grain oriented steel) with thickness of 0.5mm. The low core loss is the main advantage of M-19 lamination.

From several available techniques for cutting of laminations, the present design applies wire cutting. The fabrication process starts with core stacking. The fabrication of SRG consists of 130 numbers of laminations, which are compressed and assembled at high pressure to form stack length, whereas FMSRG requires 100 numbers of laminations. For FM-SRG, the selection of ferrite magnet material, the shape of the magnet, and the production number play an important role in reducing fabrication troubles. The fabricating process/procedure is shown as a flow diagram, as depicted in Fig. 4.

Moreover, here some additional ribs may also be provided to fit the magnet in the air barrier securely. While designing the tangential and bridge ribs, the additional safety margin is provided to withstand the mechanical stress induced with the rotation of the FM-SRG machine. From Fig. 3(a), it could be observed that the maximum performance index is obtained at $V_{fm} = 30\%$, i.e., the percentage ratio of the volume of ferrite magnet to that of the total air barrier volume is 30%. The rotor structure and the diameter of the stator of the two machines are the same, only the volume of the FM-SRG is decreased so that the ratings of the two machines could be kept at a constant value of 2.7–hp (11). Due to the presence of flux barriers, the direct axis inductance is higher than the quadrature axis inductance in SRG.

The mathematical expression which relates d–axis inductance, $L_d$ or magnetizing inductance $L_m$ to that of the volume of the SRG is given below:

$$L_d \approx L_m = \frac{12 \mu_0}{\pi^2} \left( \frac{k_c m}{2 P} \right)^2 \left( \frac{V_{in}}{k_c k_s} \right) \left( \frac{D_{in}}{(D_{in})^2} \right)$$  (11)

where, $k_c$ is the winding factor, and $k_c$ and $k_s$ are Carter factor and saturation factor, respectively. Here, the selected factors are $k_c = 1.03$, $k_s = 1.2$. Based on the finite element analysis, the
desired electromagnetic-torque and torque-ripples of the SRG and FM-SRG structures for different volumetric amounts are summarized in Table III.

| Performance | Reference SRG ($V_{fm} = 0\%$) | Structure A | Structure B ($V_{fm} = 30\%$) | Structure C ($V_{fm} = 40\%$) | Structure D ($V_{fm} = 58\%$) |
|-------------|--------------------------------|-------------|-------------------------------|-------------------------------|-------------------------------|
| Average torque (Nm) | 12.23 | 12.28 | 13.70 | 13.16 |
| Experimental (Nm) | 12.17 | - | - | - |
| Torque ripples (%) | 9.7 | 11 | 17 | 17.9 |

IV. STRUCTURE AND PERFORMANCE EVALUATIONS

The arrangement of the ferrite magnets and the design of rotor flux segments/barriers of an FM-SRG is explained in the previous sections. Figure 5 shows the distribution of the magnetic field ($B$) with the change in volume of ferrite magnets using the FEM simulation. Figure 5(a) show the magnetic flux distribution without magnet i.e., the initial reference SRG ($V_{fm} = 0\%$). Similarly, Figs. 5(b), (c) and (d), shows the distribution of magnetic flux in the presence of ferrite magnet with $V_{fm} = 30\%, 40\%, \text{and} 58\%$, respectively. Since with the increase in the volume of the magnet, the core length is also reduced to maintain the same rating of the machine as that of reference SRG, it is observed from Figs. 5(a), (b), (c) and (d), that the magnitude of flux density distributions in nearly constant. The performance index of the two machines i.e., FM-SRG and SRG of the same ratings, are mainly compared using the data obtained through FEM simulations.

Both the machines are of 2.7−hp, and has identical stator. The experimental validation of the performance is done only for the designed SRG. The prototype of the SRG, as indicated in Figs. 6(a) and 6(b) are provided as per the stator and rotor core specifications. From Table III, it can be observed that the average torque as estimated by FEA is 12.23 Nm, and average torque as obtained from the designed prototype of initial reference SRG is 12.17 Nm. Hence, it can be concluded that experimental and FEA results are very close to each other. This also validates results as obtained from FEA. Except for the placement of ferrite magnets of different volumes in the rotor flux barrier, the design of FM-SRG is similar to that of SRG without ferrite magnets. In the analysis for FM-SRG with a fixed volume of ferrite magnet, the machine volumes are changed suitably to ensure the same rating of the machine. Therefore, from Figs. 8, 9 and Table III, it is observed that the performance of FM-SRG with ferrite magnet volume of $V_{fm} = 30\%$ is similar to that of reference SRG. Here, the machine volume of reference SRG is 1.65M (mm)$^3$, and that of FM-SRG (Structure A, i.e., $V_{fm} = 30\%$) is about 1.27M (mm)$^3$.

Figure 7, shows the estimated losses of the machine with the increasing volume of the machine. It is required to get the operational efficiency of the generator with different volumes. Fig. 7(a) shows the plot corresponding to the stator yoke, rotor core, and stator teeth losses. It is observed that these losses increase linearly with an increase in the volume of the machine. The electromagnetic performance of initial reference SRG improves with minimizing the inductance of the q-axis, $L_q$, and maximizing the inductance of d − axis, $L_d$. This also increases the power factor of the machine, which is defined as the ratio of $(L_d/L_q−1)$ to $(L_d/L_q+1)$. It is seen that by increasing the volume of the generator axially, as indicated in Fig. 8(a), the inductances $L_d$ and $L_q$ is increased, but the increase of $L_d$ is comparative more as compared to $L_q$ i.e., the ratio of $(L_d/L_q−1)$...
to \((L_d/L_q+1)\) tends to increase, but torque ripple also tends to increase. Thus, the design selects a suitable axially volume, which gives better performance between these two contradictory objectives. Hence, the design choice made for reference SRG is with a volume of \(1.65 \text{M (mm)}^3\), as shown in Fig. 8(a). In this Figure, the red-colour curve represents the d-and q-axes inductances as estimated using FEA at the axial designed volume, and the dashed line is the one obtained experimentally from the fabricated reference SRG.

![Fig. 7. (a) Summarized stator yoke, rotor and teeth losses. (b) Entire core and resistive losses](image)

Similarly, the variation of the flux along the d− and q axes with the change of axial volume is shown in Fig. 8(b). It is observed that as the volume of the generator is reduced, the values of \(\lambda_d\) and \(\lambda_q\) reduces (see Fig. 8(b)). In Fig. 8(b), the red-colored curve represents the d− and q−axes as obtained using FEA, and the dashed line curve is experimentally obtained flux values. It can be observed that the result obtained through the experiment is very close to the one obtained through FEA. It is observed that by increasing the volume of the FM-SRG axially, as indicated in Fig. 8(a), for \(V_{fm} = 30\%\), the inductances \(L_d\) and \(L_q\) is increased, but the increase of \(L_d\) is significantly more as compared to \(L_q\) i.e., the ratio of \((L_d/L_q-1)\) to \((L_d/L_q+1)\) tends to increase significantly, but at the same time torque ripple also tends to increase. Therefore, the design selects a suitable axially volume, which gives better performance between these two conflicting objectives. Hence, the design choice made for FMSRG is with a volume of \(1.27 \text{M (mm)}^3\), as shown in Fig. 9(a). In this Figure, the red-colored curve represents the d− and q−axes as obtained using FEA. From Fig. 9(b), it is clear that \(\lambda_d\) and \(\lambda_q\) become almost constant due to saturation. It is observed that for FM-SRG, the q− axis flux gradually increases as the current increase. In Fig. 9(a), it is seen that by increasing the volume of the FM-SRG axially, at \(V_{fm} = 40\%\), the inductances \(L_d\) and \(L_q\) is increased, but the increase of \(L_d\) is far more as compared to \(L_q\) i.e., the ratio of \((L_d/L_q-1)\) to \((L_d/L_q+1)\) is significantly large, but at the same time torque ripple also tends to increase. Hence, the design choice is made for FM-SRG with a volume of nearly \(1.2 M \text{ (mm)}^3\), as shown in Fig. 10(a). Similarly, the variation of the flux along the d− and q axes with the change of axial volume is shown in Fig. 10(b), for \(V_{fm} = \)
It is observed that as the volume of the FM-SRG is reduced, the values of $\lambda_d$ and $\lambda_q$ reduce (see Fig. 10(b)). In Fig. 10(b), the d–and q-axes group of flux curves are obtained using FEA.

Figs. 8(c), 9(c) and 10(c) represents the plot of electromagnetic torque of SRG with and without ferrite magnet. The plot represents the electromagnetic torque at different power angle i.e., $\gamma=90^\circ, 110^\circ, 130^\circ, \text{and } 150^\circ$. From Fig. 8(c), it is observed that the electromagnetic torque of reference SRG increases with the increase in the volume of the machine. Similarly, from Figs. 9(c) and 10(c) comparing the torque magnitudes, it can be seen that the torque of the machine with ferrite magnet is higher than the machine without ferrite magnet but, as the percentage volume of ferrite magnet is increased, the ripple torque also increases. Moreover, from the plots, it can be observed that as the volume of the machine increases, there is a slight increase in the ripple torque for the FM-SRG. The observation about the variation of d– and q-axes inductances and flux linkage for the FMSRG with $V_{fm}=58\%$ are shown in Figs. 11(a) and 11(b), respectively. These curves are obtained for different volume i.e., $1.02M \text{ mm}^3$, $1.27M \text{ mm}^3$, $1.65M \text{ mm}^3$, and $2.04M \text{ mm}^3$. In Fig. 10(a), it is seen that by increasing the volume of the FMSRG axially, at $V_{fm}=58\%$, the inductances $L_d$ and $L_q$ is increased, but the increase of $L_d$ is lightly more as compared to $L_q$ i.e., the ratio of $(L_d/L_q-1)$ to $(L_d/L_q+1)$ is slightly
more, but at the same time torque ripple also tends to increase significantly. Hence, the overall performance of the machine reduces. Similarly, the corresponding variation of the flux is shown in Fig. 11(a).

Fig. 12 represents the decrease in machine volume versus the increase of percentage volume of ferrite magnet while keeping the rating of the machine as 2.7-hp. It is observed that as the volume of ferrite magnet increases, the volume of the machine decrease.

V. CONCLUSION AND DISCUSSION

The paper presents the effect on the performance index for the synchronous reluctance generator (SRG) by placing the low-cost ferrite magnet in the rotor air barrier with suitable location and orientation. The orientation is chosen such a way as to reduce the q-axis flux. It is observed that as the percentage volume of the ferrite magnet ($V_{fm}$) increases in the air barrier, there is an increase in the performance index of SRG, but this observation is observed till the $V_{fm} = 30\%$. For $V_{fm} > 30\%$, the performance index decrease, as there is a significant increase in the ripple torque. Hence, it can be said that till $V_{fm} \leq 30\%$, there is an improvement in power factor, compactness, and the operational efficiency of FM-SRG.

Moreover, the paper also analyses the variation of the d-axes and q-axes flux linkage and inductances while varying the $V_{fm}$. It also links this variation to the improved performance of the machine. Moreover, using the prototype of the reference SRG developed in the laboratory, the experimental validation of the SRG result obtained through finite element analysis is provided in the present work.

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