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Analysis of Double Salient Reluctance Machine Using Total Surface Gap Area

*Enesi, A. Y[1], Ejiogu, E. C[2], Anih, L. U[3]
[1]Electrical Engineering Department, Federal University of Technology, PMB 65 Minna Niger State, Nigeria
[2,3]Department of Electrical Engineering, University of Nigeria, Nsukka
*Corresponding author email:enesi.asizehi@futminna.edu.ng, +2348035671462

ABSTRACT
In this paper, we analyze the stator-rotor design of a double salient reluctance machine using total surface gap area. The high number of poles in a 4-phase reluctance machine makes it suitable for the analysis. An expression is derived for the total surface gap area which includes the sum of the area of the air-gap (between the inner stator radius and the outer rotor radius), the area between the gaps of the stator poles and the area between the gaps of the rotor poles. The rated torque and the rated power output are expressed through the total surface gap area and the geometrical parameters. The total surface gap area is used to predict the torque ripple and the average torque developed by the machine for different pole arcs, air gaps, number of poles, number of phases and frequencies which are investigated by MATLAB simulation. The stator and the rotor of the machine are drawn by ANSYS software for the purpose of visualization.

Keywords: *Double salient reluctance machine, MATLAB, Stator and rotor poles, Torque ripple, Total surface gap area.*

1 INTRODUCTION

A double salient reluctance machine has reduced air gap and hence enhances direct-axis inductance. The mathematical equation for the total surface gap area, the output torque and the output power are expressed in terms of geometrical parameters which can be applied to any machine with a number of phase. In this paper, the geometrical parameters of a 4-phase double salient reluctance machine are analyzed through its total surface gap area for the purpose of studying the effect of power output, air gap, frequencies, number of stator and rotor poles, number of phases and pole arcs on the machine rated torque. The stator and the rotor pole are both salient (El-Kharashi & Hassanien, 2012). The total surface gap area can be used as a measure of torque ripple. Increasing the number of poles decreases the total surface area thereby decreasing the torque ripple. The total surface gap area can also be used as a measure of an average torque. Tapering of the stator or rotor poles (pole shape) has significant effect on the total surface gap area which may consequently increases or decreases the average torque (C. Neagoe, 1997) and (R. E. Centre and G. Rural, 2014). Therefore it becomes a necessity to study the effect of geometrical parameters of the machine through the total surface gap area. If the wire diameter and the number of turns for stator windings are calculated, the stator poles are now wound and each phase is connected to power electronic switches. The machine is known as the switched reluctance machine (Liyan, 2013), (Wadnerkar, 2008) ,(N. B. Kavita, 2014) and (E. Darie, E. Darie, 2006). The machine is rugged, cheap in construction, tolerance, with variable speed and high efficiency as in (Liptak, 2004) and (R. Krishnan, 1988). The major drawback of the machine is the torque ripples developed due to the machine double saliency. The torque ripple causes vibrations and acoustic noise as explained in (Y. Ozogulu, 1999), (G. Shahgholian, 2015) and (Kakilli, 2011). The three main parts of electric machine are the stator, the rotor and the air gap. The air gap is used as an energy conversion medium. The stator and rotor are made of magnetic core of steel laminations which reduce eddy current losses. Each stator pole has concentrated windings and there is absence of windings or coils on the rotor.

Diametrically opposite windings are connected together as a pair or in a group to form the phases of the machine. Switched reluctance motor is connected to dc through an inverter which supplies current to the stator winding. Torque is produced by the tendency of a pair of rotor poles moving towards the region of maximum inductance. Its application can be found in electric vehicle, aircraft, servo-drive, energy conversion device and for industrial drives (M. A. Aboungem, 2014).

2 METHODOLOGY

The geometrical dimensions of the double salient reluctance machine are given in Table 1.

TABLE 1: PARAMETERS OF THE MACHINE

Parameter	Description	Value
T	Torque	95.5 N-m
R_{ir}	Inner stator radius	75 mm
R_{sh}	Shaft radius	21 mm
R_{rp}	Outer rotor radius	74.5 mm
R_{os}	Outer stator radius	155 mm
W_{sy}	Stator yoke width	28.8 mm
W_{ry}	Rotor yoke width	18 mm
L_{st}	Stack length	200 mm
β_s	Stator pole arc	22 degr
β_r	Rotor pole arc	24 degr
P_s	Number of stator poles	8
P_r	Number of rotor poles	6
h_{sp}	Stator pole height	51.2mm
h_{rp}	Rotor pole height	35.5mm
g	Air gap length	0.5 mm

The values in Table 1 are obtained through the design procedures in accordance to the National Electrical Manufacturer Association (NEMA) and International Electrotechnical commission (IEC).

The cross-section of 4-phase 8/6 double salient reluctance machine is shown in Figure 1.

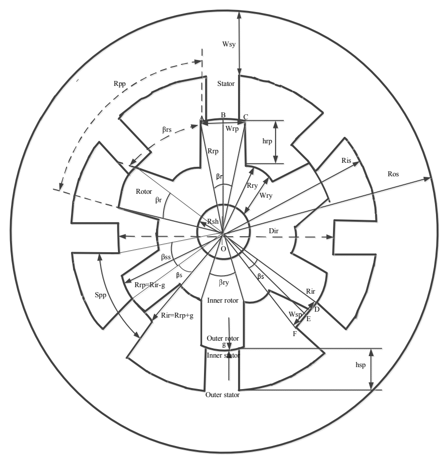

Figure 1: Cross-section of 4-phase 8/6 double salient reluctance machine.

The following equations are obtained from Figure 1

2.1 GEOMETRIC DIMENSIONS (in mm)

The outer rotor radius is given as:

$$R_{rp} = \frac{D_{ir}}{2} - g \qquad (2.1)$$

The inner stator yoke radius can be expressed as:

$$R_{is} = \frac{D_{ir}}{2} + h_{sp} \qquad (2.2)$$

The inner rotor radius is given as:

$$R_{ry} = R_{rp} - h_{rp} \tag{2.3}$$

The outer stator radius is given as:

$$R_{os} = R_{ir} + h_{sp} + W_{sy} \tag{2.4}$$

The stator yoke width can be expressed as:

$$W_{sy} = R_{os} - h_{sp} - R_{ir} \tag{2.5}$$

The rotor yoke width is given as:

$$W_{ry} = R_{rp} - h_{rp} - R_{sh} \tag{2.6}$$

The stator pole width is given as

$$W_{sp} = (2R_{rp} + 2g)\sin(\frac{B_s}{2} \times \frac{\pi}{180}) \tag{2.7}$$

The rotor pole with is given by:

$$W_{rp} = 2R_{rp}\sin(\frac{B_r}{2} \times \frac{\pi}{180}) \tag{2.8}$$

The difference between the sum of the stator yoke width, the stator pole height, the air gap length, the rotor pole height, the rotor yoke width, the shaft radius and the outer stator radius equal to zero

$$R_{os} - (W_{sy} + h_{sp} + g + h_{rp} + W_{ry} + R_{sh}) = 0 \tag{2.9}$$

2.2 TOTAL SURFACE GAP AREA

The total surface gap area can be derived from Figure 1 as follows:

Area of the uniform air gap when both stator and rotor poles are aligned is given by:

$$A_{ga} = \pi R_{ir}^{2} - \pi R_{rp}^{2}$$

$$= \pi(R_{ir} - R_{rp})(R_{ir} + R_{rp})$$

$$= \pi g(R_{ir} + R_{rp}) \tag{2.10}$$

The surface area of the rotor pole is approximately $SA_{rp} = W_{rp}h_{rp}$ and that of the stator is $SA_{sp} = W_{sp}h_{sp}$ (2.11)

The surface area between the outer rotor radius and the inner rotor radius is given by;

$$A_{rpy} = \pi(R_{rp}^{s} - R_{ry}^{2})$$

$$= \pi(R_{rp} - R_{ry})(R_{rp} + R_{ry})$$

$$= \pi h_{rp}(R_{rp} + R_{ry}) \tag{2.12}$$

The total surface area of the rotor interpolar gap is given by:

$$A_{\text{int}\,rp} = \pi h_{rp}(R_{rp} + R_{ry}) - P_r W_{rp} h_{rp} \tag{2.13}$$

The surface gap area between the inner stator yoke radius and the outer stator radius is given by:

$$A_{spy} = \pi h_{sp}(R_{is} + R_{ir}) \tag{2.14}$$

The total surface area of the stator interpolar gap is given by:

$$A_{\text{int}\,sp} = \pi h_{sp}(R_{is} + R_{ir}) - P_s W_{sp} h_{sp} \tag{2.15}$$

The total surface gap area is the sum of the equations (2.10), (2.13) and (2.15)

$$A_{gT} = A_{ga} + A_{\text{int}\,rp} + A_{\text{int}\,sp} \tag{2.16}$$

The total surface gap area is expressed in terms of geometrical parameters is given by

$$A_{gT} = (\pi g(R_{ir} + R_{rp})) + (\pi h_{rp}(R_{rp} + R_{ry}) - P_r W_{rp} h_{rp}) + (\pi h_{sp}(R_{is} + R_{ir}) - P_s W_{sp} h_{sp}) \tag{2.17}$$

Note that A_{gT} $is\,in\,(mm^2)$

The total surface gap area is independent of frequency. A change in frequency does not change the total surface gap area except during the construction of the machine.

$$T\omega = P_{out},\ \frac{P_s}{q} = P\ and\ N_s = \frac{60f}{P} = \frac{60fq}{P_s}\ \text{and}$$

$$\frac{2\pi N_s}{60}T = P_{out}\ so\,that\ N_s = \frac{60P_{out}}{2\pi T} = \frac{60fq}{P_s}$$

where P is the number of poles that determine the base speed in rev/min

Therefore, $P_s = \dfrac{2\pi fqT}{P_{out}}$ (2.18)

Substitute the alue of P from equation (2.18) into equation (2.17)

$$A_{gT} = \pi(h_{rp}(R_{rp} + R_{ry}) + h_{sp}(R_{is} + R_{ir}) + g(R_{ir} + R_{rp})) - (P_r W_{rp} h_{rp} + (\frac{2\pi fqT}{P_{out}}) W_{sp} h_{sp}) \quad (2.19)$$

The output torque can now be expressed from equation (2.20)

$$T = \frac{(\pi(h_{rp}(R_{rp} + R_{ry}) + h_{sp}(R_{is} + R_{ir}) + g(R_{ir} + R_{rp})) - P_r W_{rp} h_{rp} - A_{gT})P_{out}}{2\pi fqW_{sp}h_{sp}}(N-m) \quad (2.20)$$

The rated power can be made as subject of formula from equation (2.20) to obtain

$$P_{out} = \frac{T2\pi fqW_{sp}h_{sp}}{(\pi(h_{rp}(R_{rp} + R_{ry}) + h_{sp}(R_{is} + R_{ir}) + g(R_{ir} + R_{rp})) - P_r W_{rp} h_{rp} - A_{gT})}(watts) \quad (2.21)$$

2.3 Expression of Angular velocity and synchronous speed in terms of geometrical parameters

The angular velocity in radian per second can be expressed as

$$\omega = \frac{P_{out}}{T} = \frac{2\pi fqW_{sp}h_{sp}}{(\pi(h_{rp}(R_{rp} + R_{ry}) + h_{sp}(R_{is} + R_{ir}) + g(R_{ir} + R_{rp})) - P_r W_{rp} h_{rp} - A_{gT})} \quad (2.22)$$

$in\,(rad/s)$

In the absence of slip, the synchronous speed is equal to the rotor speed $(N_s = N_r)$. The angular velocity is given by:

$$\omega = \frac{2\pi N_s}{60} \quad (2.23)$$

Making N_s as the subject of formula from equation (2.23), we obtain:

$$N_s = \frac{P_{out}}{T} = \frac{60\pi fqW_{sp}h_{sp}}{2\pi(\pi(h_{rp}(R_{rp} + R_{ry}) + h_{sp}(R_{is} + R_{ir}) + g(R_{ir} + R_{rp})) - P_r W_{rp} h_{rp} - A_{gT})} \quad (2.24)$$

Simplified equation (2.24), we obtain:

$$N_s = \frac{P_{out}}{T} = \frac{30fqW_{sp}h_{sp}}{(\pi(h_{rp}(R_{rp} + R_{ry}) + h_{sp}(R_{is} + R_{ir}) + g(R_{ir} + R_{rp})) - P_r W_{rp} h_{rp} - A_{gT})} \quad (2.25)$$

3 RESULTS AND DISCUSSSION

The rated torque and power output versus the total surface gap area are shown in Figure 2. The output torque is inversely proportional to the total surface gap area while the output power increases as the total surface gap area increases.

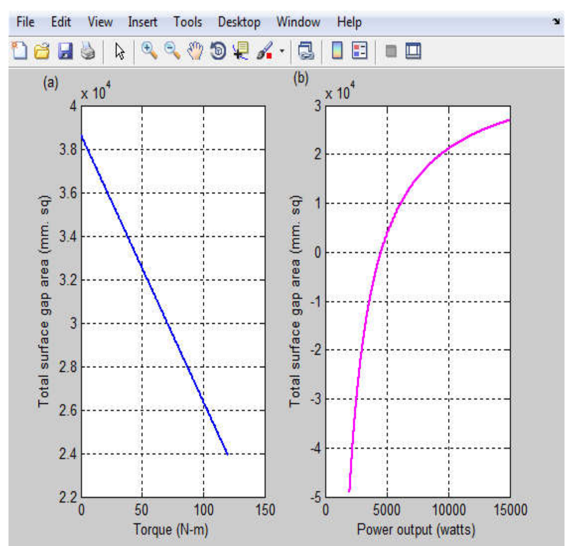

Figure 2: Total surface gap area versus the torque and power output characteristic

In Figure 3, the pole arcs are inversely proportional to the total surface gap area. The higher the pole arcs the smaller the rated torque and the smaller the pole arcs the larger the rated torque. These conditions are fulfilled at any chosen total surface gap area. The area under the straight line graph for higher rotor pole arcs are smaller than that of the lower pole arcs. More torque ripples are generated from machine with lower pole arcs.

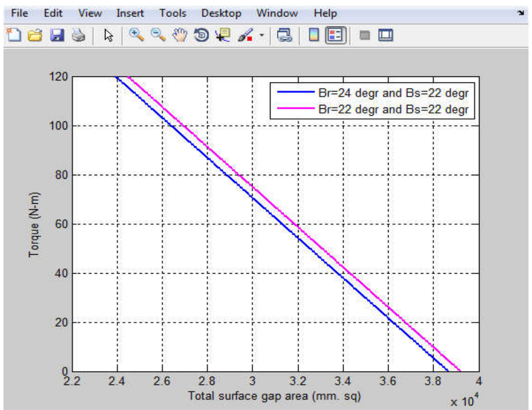

Figure 3: Effect of pole arcs on the torque versus total surface gap area characteristic

The higher the air gap, the higher is the rated torque and vice versa. This is shown in Figure 4. The area enclosed by the smaller air gap length is lower than that of the higher air gap length and consequently, less torque ripples are generated from the small air gap length.

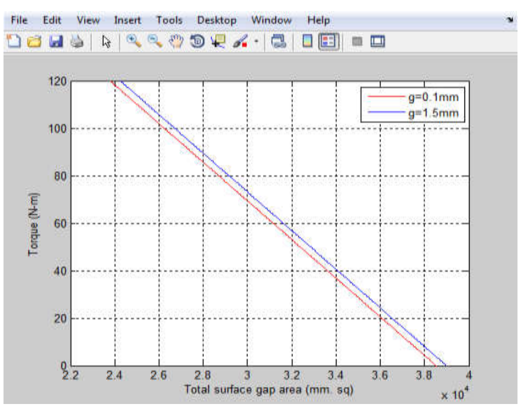

Figure 4: Effect of air gap length on the torque versus total surface gap area charactersitic.

In Figure 5 shows that the rated torque of a 3-phase double salient reluctance machine is slightly greater than that of the 4-phase. The area under the straight line of 3-phase is larger than that of the 4-phase. We can now predict that machines with higher number of phases have reduced torque ripple than those of the lower phases.

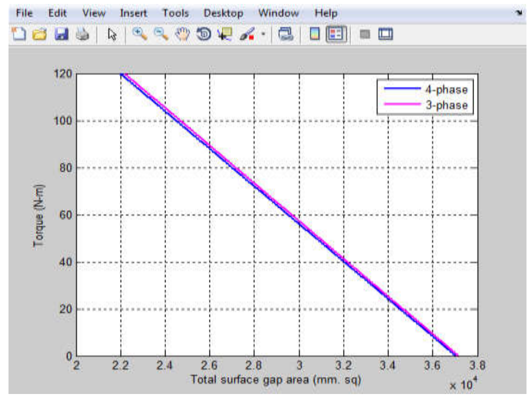

Figure 5: Effect of number of phases on the torque versus total surface gap area characteristic

Figure 6 shows that the larger the number of poles, the lower is the rated torque output of the machine. The area under the graph for a lower number of poles is larger than that for the larger number of poles and therefore, more torque ripples are generated from the machines designed with few numbers of stator and rotor poles.

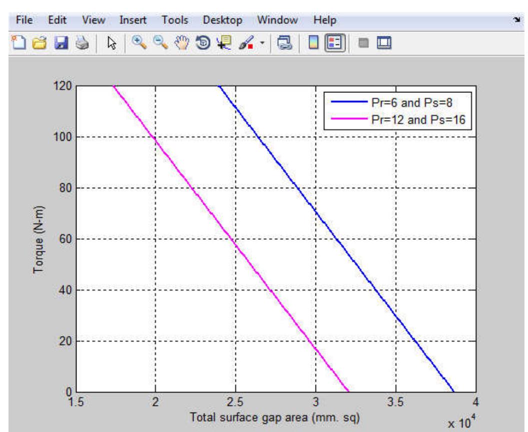

Figure 6: Effect of number of poles on the Torque versus Total surface gap area characteristic

The rated torque at low frequency is higher than those at higher frequency. This is shown in Figure 7. The area under the graph at 50Hz is larger than that of the 60Hz. Therefore more torque ripple is generated from machine with low frequency. We can now predict that more torque ripples are generated from the machines imported from countries whose frequencies are higher than 50Hz as used in our country Nigeria. If such machine should be manufactured in Nigeria, the rated torque shall be made higher than that of the imported once.

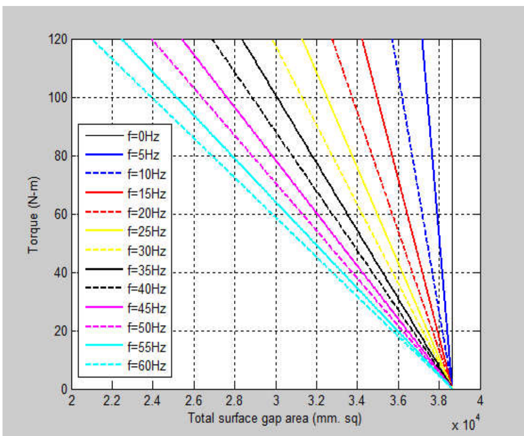

Figure 7: Effect of frequency on the torque versus total surface gap area characteristic

The rotor, stator and stator-rotor models from ANSYS are shown in Figure 8, Figure 9 and Figure 10 respectively.

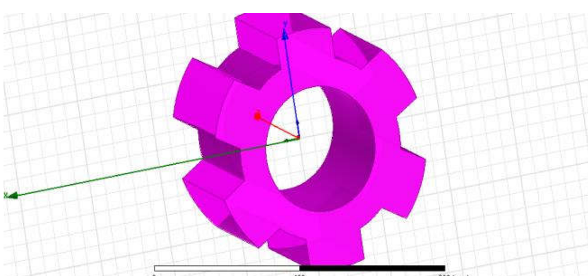

Figure 8: Rotor model

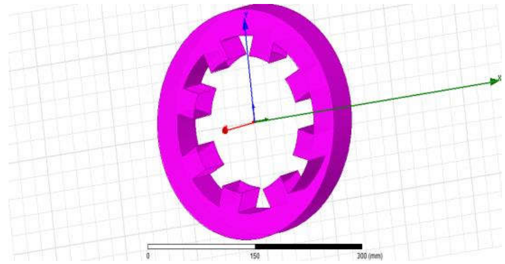

Figure 9: Stator model

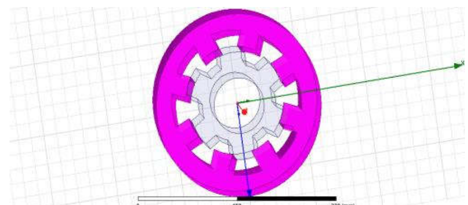

Figure 10: Stator and Rotor model

CONCLUSION

Mathematical equations for the total surface gap area, rated torque and output power in terms of geometrical parameters are derived. The total surface gap area by MATLAB simulation is used to predict the effect of the number of poles, stator and rotor pole arcs, frequencies, number of phases, air gap length on the rated output torque of a double salient reluctance machine. Double salient reluctance machine of high number of poles, high number of phases, large stator and rotor pole arcs, high frequency and small air gap length develop low torque ripple. Machine with large surface gap area produces high torque ripple and delivers low average torque while that of the small surface gap area produces low torque ripple and delivers high average torque. These informations are necessary for the good machine design. The rotor, stator and stator-rotor are drawn with ANSYS software.

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