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Modelling, Simulation and Comparative Study between Switched Reluctance Generator 8x6 and Switched Reluctance Generator 12x8

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Abstract. This paper presents the modelling, simulation and comparative study between switched reluctance generator 8x6 and switched reluctance generator 12x8. During work, the structural properties of the rotor and stator laminates of these machines are exposed. This information was used to perform mathematical modelling for both topologies. Based on this modelling, a computer simulation model was developed in the Simulink/Matlab® environment where several tests were carried out. To ensure comparability between machines, the output power in both topologies was set to 735,5 VA. After analyzing the results obtained during the simulations, it was found that the topology of the switched reluctance generator 8x6 is more efficient than 12x8.

Keywords. Three-phase switched reluctance machine (12x8), Four phases switched reluctance machine, simulation (8x6), comparative study.

1. Introduction

The Switched Reluctance Machine (SRM) is possibly the simplest. This is because it does not use brushes and permanent magnets, and it also requires less ferromagnetic materials and copper [1] [2]. In addition, it is a robust machine with better performance at a variable speed [3]. Switched reluctance machines are also versatile, due to the fact that they can be driven as a motor or as a generator with simple drive modifications.

With increasing concern about the conscious consumption of energy resources, there is a growing scientific research using SRM in electrical cars [4] [5] and wind turbines [6] [7].

The aim of this work is to perform a comparative study between the switched reluctance generator 8x6 (SRG 8x6) and switched reluctance generator 12x8 (SRG 12x8) through computer simulations. An important focus on one specific application of these machines, by having a variable speed regime, is the field of wind energy [8].

2. The Structure of a Switched Reluctance Machine

A Switched reluctance machine consists of a stator with a winding field and a rotor, both with a salience pole. The torque is generated by the tendency of the rotor to move to a position where the inductance of the energized winding is maximized [7].

The switched reluctance generator 8x6 consists of 8 (eight) stator poles and 6 (six) rotor poles. Each pair of stator poles represents one phase in this machine, thus a four-phase machine. Figure 1 illustrates a 2D cross-section of an 8x6 SRM showing the coils in phase A.

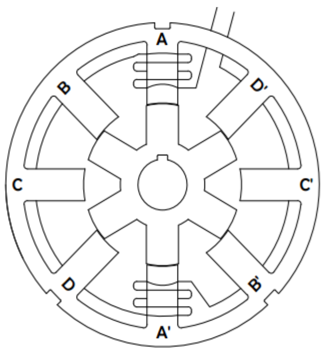

Fig. 1 Design of Switched Reluctance Generator 8x6

The switched reluctance generator 12x8 consists of 12 (twelve) stator poles and 8 (eight) rotor poles. In contrast to what happens in the 8x6 machine, where each pair of stator poles represents one phase, in this topology two pairs of poles represent one phase of this machine, ~~is~~ thus a three-phase machine. Figure 2 shows a 2D cross-section of a 12x8 MRV with the coils shown in phase A.

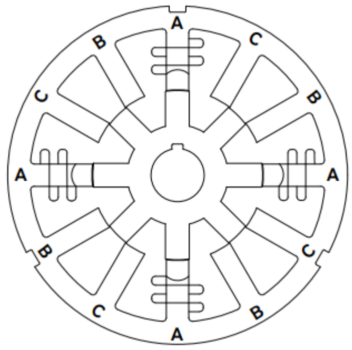

Fig. 2 Design of Switched Reluctance Generator 12x8

Figure 3 illustrates the design parameters of the rotor and stator laminates of the switched reluctance machines. Table I shows the values, with the respective abbreviations relating to the design of the rotor and stator blades for both machines [9].

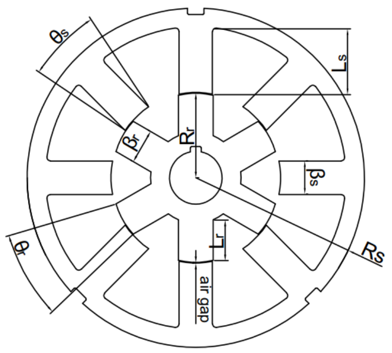

Fig. 3 Position of the project parameters

Table I. Rotor and stator laminates dimensions

Parameters	Symbol	8x6	12x8
Stator pole angles	θ s	22.50°	15.00°
Rotor pole angles	θ r	27.30°	16.10°
Stator poles width	β_s	13.77 mm	9.22mm
Rotor pole width	β_r	14.37 mm	9.82 mm
Air gap length	Air gap	0.03 mm	0.03 mm
Stator poles length	L_S	27.26 mm	25.49 mm
Rotor pole length	L_r	12.70 mm	14.48 mm
Stator radius	R_S	70.05 mm	70.05 mm
Rotor radius	R_r	35.00 mm	35.00 mm

Both topologies are designed for 0,9863HP (735.5 VA) output and 1200 rpm speed. The dimensions make it possible to perform the mathematical modelling of the machines.

3. Mathematical Model

The first step in performing the modelling is to calculate the inductance based on the dimensions of the rotor and stator blades, as shown in point 2 above.

The inductance (L) is defined by the flux linkage (λ) and the current flowing through the coil, as follows:

$$L = \frac{\lambda}{i} \tag{1}$$

The inductance values for SRM 8x6 and SRM 12x8 were calculated using *Finite Element Methods*. Figures 6 and 7 show the values of a self-inductance with respect to the rotor position and the current.

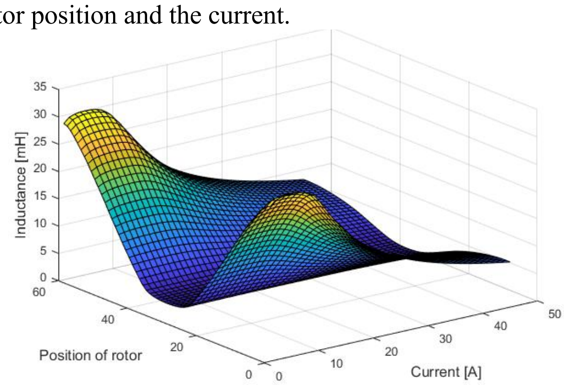

Fig. 4. The surface of a Self Inductance SRM 8x6

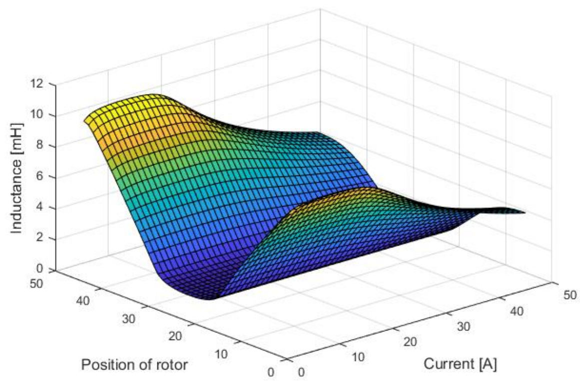

Fig. 5. The surface of a Self Inductance SRM 12x8

The voltage applied in one of the machine phases corresponds to the ohmic voltage drop, plus ~~of~~ the induced voltage in the inductance (e), we have:

$$v = R \cdot i + e \tag{2}$$

The induced voltage at the inductance (e) is defined by the change of the flux linkage (λ) as a function of time. The inductance (L) is related to the rotor position and the current. The voltage per phase corresponds to equation 3, as below:

$$v = R \cdot i + L\frac{\partial i}{\partial t} + i\frac{\partial L}{\partial t}\frac{\partial \theta}{\partial t} \tag{3}$$

The derivative of the rotor angle position (θ) as a function of time is the angular velocity (ω), therefore:

$$v = R \cdot i + L\frac{\partial i}{\partial t} + i\omega\frac{\partial L}{\partial t} \tag{4}$$

The machine, which is mathematically modelled, is a generator. Therefore, the equation of the mechanical forces contained in the SRG must be carried out as follows:

$$T_{emg} = T_{mec} + D\omega + J\frac{d\omega}{dt} \qquad (5)$$

Where:

D = coefficient of friction;
J = moment of inertia

The electromagnetic torque results from equation 6:

$$T_{emg} = \frac{1}{2} i^2 \frac{dL}{d\theta} \qquad (6)$$

To determine the voltages at the terminals (j) of the coils, we have:

$$v_j = R_j i_j + \frac{d\lambda_j}{dt} \qquad (7)$$

Equations 4 and 5 together represent the mechanical and electromagnetic behaviour of a three-phase switched reluctance generator (SRG 12x8).

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ T_g \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 & 0 & 0 & 0 & 0 \\ 0 & R_2 & 0 & 0 & 0 \\ 0 & 0 & R_3 & 0 & 0 \\ \frac{1}{2} i_1 \frac{\partial L_1}{\partial \theta} & \frac{1}{2} i_2 \frac{\partial L_2}{\partial \theta} & \frac{1}{2} i_3 \frac{\partial L_3}{\partial \theta} & D & 0 \\ 0 & 0 & 0 & -1 & 0 \end{bmatrix} x \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ \omega \\ \theta \end{bmatrix}$$

$$+ \begin{bmatrix} L_1 & 0 & 0 & 0 & i_1 \frac{\partial L_1}{\partial \theta} \\ 0 & L_2 & 0 & 0 & i_2 \frac{\partial L_2}{\partial \theta} \\ 0 & 0 & L_3 & 0 & i_3 \frac{\partial L_3}{\partial \theta} \\ 0 & 0 & 0 & -J & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} 0 \, x \begin{bmatrix} \dot{i}_1 \\ \dot{i}_2 \\ \dot{i}_3 \\ \dot{\omega} \\ \dot{\theta} \end{bmatrix} \qquad (9)$$

The mechanical and electromagnetic behaviour of the 8x6 SRG is similar to the 12x8 SRG. In the modelling 8x6 there is ~~a~~ one more phase compared to modelling 12x8.

4. Simulations

Computer simulations have become an important step in project execution. It minimizes errors during creation, saving time and resources.

The computer simulations are the solutions of the mathematical model, as stated before. The MATLAB®/SIMULINK environment was used to perform the simulations of both machines.

A. Converter Half Bridge

There are several converter configurations to trigger the SRM. The most commonly converter used for driving is the half-bridge converter [8] [9], reason why it was chose and used in this work.

Regarding the SRG 8x6 under study, tests were carried out with the machine, in which various angles and several driving windows were examinated. In this analysis, it was adopted the position of complete alignment with the zero angle. The SRG 8x6 has an inductance profile of 60°. It was found that for the best possible performance, this machine should be excited 0.8° before complete alignment up to 14.2°. Fig. 6 illustrates the half-bridge converter scheme for the SRG 8x6 drive.

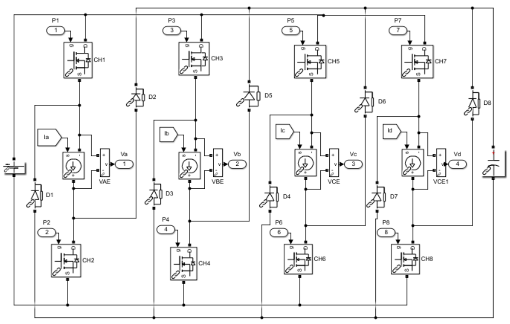

Fig. 6 Half-Bridge Converter for a Four-Phase 8x6 Switched Reluctance Generator

The SRG 12x8 has an inductance profile of 45°. It was concluded that for the best possible performance, this machine should be excited 2.7° before complete alignment up to 12.7°. Fig. 7 shows the scheme of the half-bridge converter for a SRG 8x6 drive.

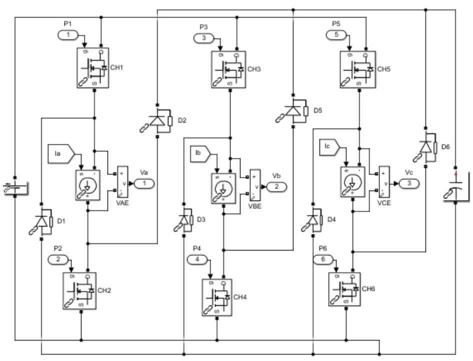

Fig. 7 Half-Bridge Converter for a Three-Phase 12x8 Switched Reluctance Generator

B. Blocks representing the switched reluctance generator

To perform machine simulations, a block was created in SIMULINK with an *S-Function* to represent the two topologies operation. Fig. 8 (a) represents the block for a SRG 12x8 and a (b) represents the block for the SRG 8x6.

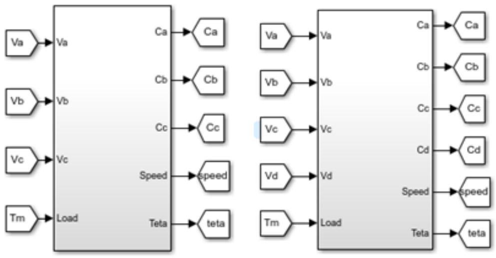

Fig. 8 (a) SRG 12x8 (b) SRG 8x6

5. Simulation Results

For the purpose of a consistent comparative study between these two machines (SRG 8x6 and SRG 12x8), the output power set by the initial design of the machines was at approximately 735.5 VA. The output power is defined by the difference between the output electrical power (load) and the input electrical power (source). Figure 9 reveals the output power rate of a SRG 8x6 and a SRG 12.8.

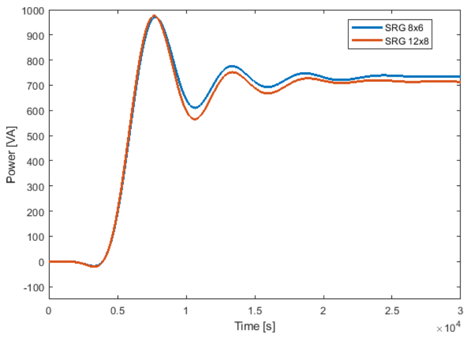

Fig. 9 – Output power.

Figure 10 delineates the instantaneous voltages in phase A regarding the SRGs. The SRG 8x6 has a higher instantaneous voltage with peak values of approximately 112 V, while SRG 12x8 has peak values of approx. 66 V.

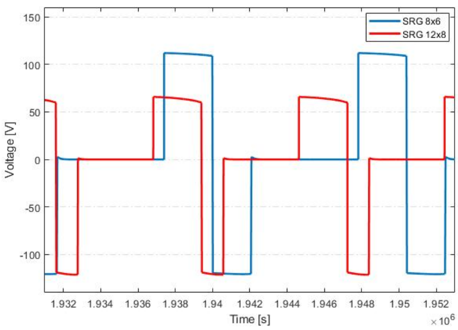

Fig. 10 Voltage in phase A.

In Figure 11, the mean voltages in phase A were verified in the SRG. While the average voltage is 4V for the SRG 8x6, 3.5 V was reached in the SRG 12x8.

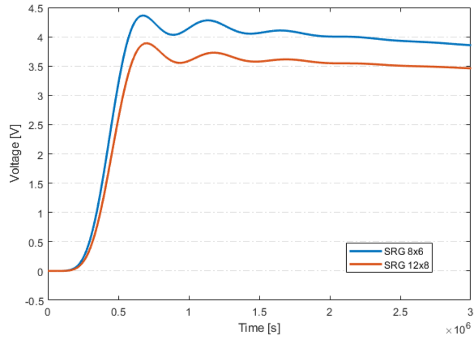

Fig. 11 Average voltage in phase A

The 12x8 SRG has a higher peak current ratings in comparison with the 8x6 SRG. In the SRG 12x8 the peak value is 32 A, while in the SRG 8x6 16 A (see Fig. 12).

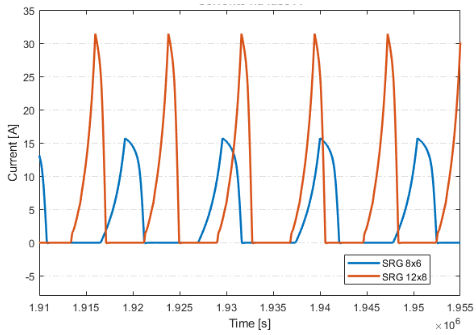

Fig. 12 – Current in phase A.

Figure 13 shows the average current in phase A. SRG 12x8 attain almost twice the current value of an 8x6 and has an average value of 7 A, while SRG 8x6 has an average current of 4A.

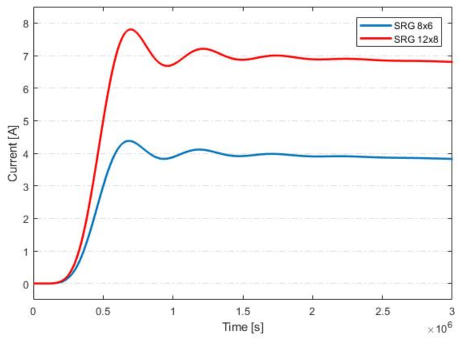

Fig. 13 - Average current in phase A.

Figure 14 exhibits the power at the source. The SRG 8x6 has an average value of 600 VA. At the same time, the SRG 12x8 has an average of 500 VA.

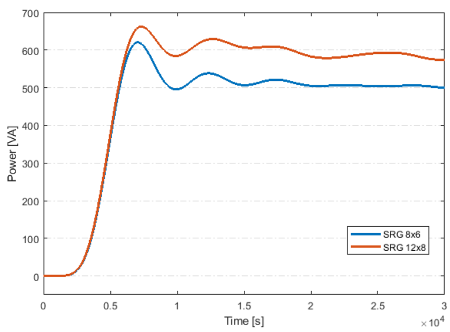

Fig. 14 – Power in the source

Figure 13 shows the mechanical performance. The SRG 8x6 has an average value of 600 Nm, while the SRG 12x8 states an average value of 700 Nm.

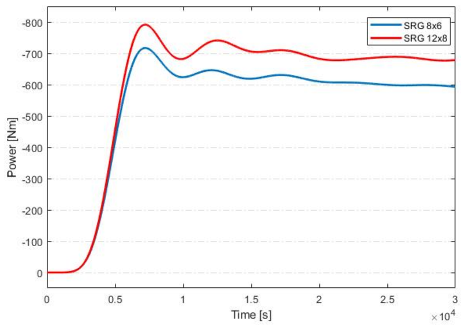

Fig. 15 - Mechanical Power

The performance of a machine (η) is defined as the ratio between output power and input power. With regard to the machine in this study, the switched reluctance generator, the output power is Pout, while the input power is composed by the source electrical power (Pein) and the mechanical power (Pmec). Thus:

$$\eta = \frac{Pout}{(Pein + Pmec)} \tag{10}$$

Analyzing Fig.16, the SRG 8x6 achieves values of 0.69 in performance while the SRG 12x8 has 0.59 in performance.

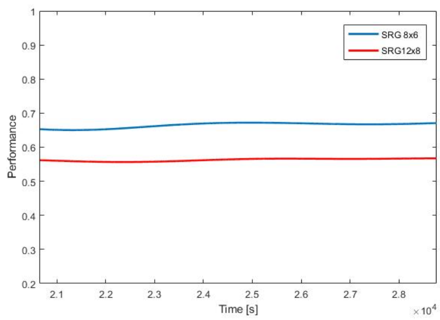

Fig. 16 – Performance

6. Conclusion

The experiments were conducted with several analyzes, such as the phase voltages and current in the coil, the power at the source and power at the load.

By the assessment of the results obtained with the simulations, it was found that the switched reluctance generator 12x8 needs more input power (source) and also more mechanical power to produce the same output power as the switched reluctance generator of 8x6.

It can be concluded that the switched reluctance generator 8x6 is more efficient with the same output power than the other topology (SRG 12x8). However, to drive this machine (SRG 8x6), it is necessary a converter with one more branch than in the SRG 12x8. Therefore, more IGBT and electronic components will be used.

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