Double-stator switched reluctance generator

Ashkan Karimi Koohpar, Jawad Faiz

Double-stator switched reluctance generator (DSSRG) is a switched reluctance machine consisting of two stators and one rotor, it is potentially compact, low cost, efficient, high output power and power density. This paper presents design and simulation procedure for a DSSRG. Finite element analysis is applied to design and optimize DSSRG geometry by improving its back electromotive force, DSSRG drive is built to simulate operation and analyze performance. Eventually, the results are compared with the single stator switched reluctance generator with the same volume.

Keywords – Double stator, geometry design, optimization, reluctance machine, switched reluctance generator.

Introduction

Switched reluctance machine (SRM) offers some advantages over conventional alternating current (AC) machines in generating and motoring modes. They are appropriate candidate for many industrial applications [1]. Doubly-fed induction machines, however, suffer from relatively low efficiency issue. Permanent magnet (PM) machines normally use expensive rare earth PMs in the rotor. Synchronous machine requires direct current (DC) excitation, slip rings and brushes, and needs some arrangements for its starting and synchronizing. To address these drawbacks, a switched reluctance generator (SRG) utilizing a rotor core with no PM has been recommended in [2]. The switching nature of the SRG operation makes it compatible with every application that requires variable-speed operation. In the case of aerospace and automotive applications, variable-speed operation is suitable for compatibility with the engine that drives the SRG [3]. Further, SRMs with multiphase excitation are more robust and have greater potential for fault tolerance compared with other synchronous machines. Many researchers to further performance improvements have proposed novel SRM configurations. A bipolar SRM with short flux path achieves a high efficiency, better power quality and low torque pulsation under single-phase and multi-phase excitation [4]. A two-phase SRM has been presented in [5] with E-core structure to reduce the lamination material and hence iron loss. To enhance the torque in the SRMs, higher number of rotor poles than that of stator poles have been introduced in [6]. A double-stator SRM composing of two stators and one rotor has been presented in [7], [8], [9], to enhance the power density and reduce torque ripple. Furthermore, multiphase SRMs in terms of sensor-less control and fault-tolerance control has been presented in [10].

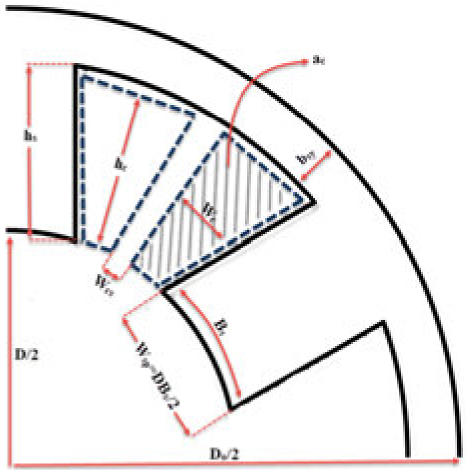


Fig. 1. Geometry parameters of the motor.

This paper addresses a new design for SRM coupled to a diesel generator. The machine is radial type consisting of 2 stators (inner/outer) with 12 poles and 6 poles. Fig. 1 shows the geometrical parameters pf the machine. Performance of this machine will be compared with a convention single stator SRG to validate the merit of the proposed SRG.

The paper is organized as follows. The Double-stator switched reluctance generator (DSSRG) fundamentals are described in the section 2. Section 3 fully investigates the DSSRG performance by simulations of various perspectives. Electro-magnetic simulations are carried out while loss analysis and thermal evaluations are also presented. Furthermore, a DSSRM drive model is built to simulate the DSSRG with control. Section 4 compares the simulation results with the experimental results to validate the simulation results. Finally, section 5 concludes the paper.

Principle of switched reluctance generator design

A 5 kW and 3000 rpm SRM is considered here. Power, P_d, and developed torque, T, versus outer stator and rotor diameter, yokes, teeth and cross-section of slot are calculated as follows [11]:

$$P_d = KBA_sD^2LN_r \quad (1)$$

$$T = K(BA_s)D^2L \quad (2)$$

where B is the aligned magnetic flux density, A_s is the electric loading, D is the bore diameter, L is the stack length of the stator pole, N_r is the rotor speed in length of the stator pole, N_r is the rotor speed in revolutions per minute (rpm). If the L is kept as a multiple or submultiples of rotor bore diameter, the output power equation is as follows:

$$p_d \propto k_2.D^3 \quad (3)$$

In general, at the rated operating point, the range of k_2 is (0.65, 0.75). The teeth arc given by [11]:

$$\frac{B_s}{\tau} \in (0.3,0.45) \quad (4)$$

Therefore, the other design parameters are as follows:

$$W_{sp} = D\sin(\frac{B_s}{2}) \quad (5)$$

$$b_{sy} \in (0.5W_{sp}, W_{sp}) \quad (6)$$

$$W_c = \frac{\pi}{2P_s} - \frac{1}{2}\left(\frac{D.B_s}{2} + W_{cs}\right) \quad (7)$$

$$h_c = \frac{a_c}{W_c}.\frac{T_{ph}}{2} \quad (8)$$

$$h_s \in (h_c, 1.4h_c) \quad (9)$$

where W_{sp} is the pole width, b_{sy} is the back iron thickness, W_c is the average of coil width, h_c and h_s is the slot length and teeth length, respectively, T_{ph} is the number of coil turns and D_o is the outer diameter of the machine.

Mathematical model of SRG

The mathematical model of the SRM (Fig. 1) is obtained through the electrical analysis of the power electronic converter illustrated in Fig. 2. Neglecting the mutual inductance between the phases, the phase voltage u_k is as follows:

$$u_k = R_k i_k + \left(L_k(\theta_k, i_k) + i_k\frac{dL_k(\theta_k, i_k)}{di_k}\right)\frac{di_k}{dt} + v i_k\frac{dL_k(\theta_k, i_k)}{di_k} \quad (10)$$

where R_k is the internal electrical resistance, i_k the electrical current, $L_k(\theta_k,i_k)$ is the magnetic flux-linkage, θ_k is the electrical position of the phase and $\omega=d\theta_k/dt$ is the rotor speed revolution in rad/s.

According to the notation indicated in Fig. 2, the capacitor voltage U_c is:

$$i_c = C\frac{dU_c}{dt} \quad (11)$$

where i_c is the current of the capacitor and C is its capacitance. The total electrical current flowing from the generator to the capacitor and load resistance R_L can be calculated as follows:

$$i_T = \sum_{k=1}^{3} i_k \quad (12)$$

The i_c is associated with the total electrical current of the generator and load current i_L:

$$i_c = i_T - i_L \quad (13)$$

The converter bus voltage U_{bus} is equal to U_c. Depending on the states of electronic switches, the voltage at each phase terminals is as follows:

$$u_k = \begin{cases} -U_{bus} - 2U_s, & S_{1,k} \text{ and } S_{2,k} \text{ Closed} \\ -U_{bus} - 2U_D, & S_{1,k} \text{ and } S_{2,k} \text{ Open} \\ -U_D - U_s, & S_{1,k} \text{ Open and } S_{2,k} \text{ Closed} \end{cases} \quad (14)$$

where U_s and U_D are, respectively, the voltage drops of each electronic switch and free-wheeling diode.

The generator developed torque T_{gen}, is:

$$T_{gen}(t) = \sum_{k=1}^{q} T_{em,k}(\theta_k, i_k) \quad (15)$$

where $T_{em,k}$ is the electromechanical Torque contributed by phase k.

During each process of energy transfer between the elements of the DSSRG, the mean electric power P_e is evaluated as follows:

$$P_e = \frac{1}{\Delta t}\int_{t_0}^{t_1} ui\,dt = \frac{W_e}{\Delta t} \quad (16)$$

where W_e is the transferred electric energy during the time interval $\Delta t = t_1 - t_0$.

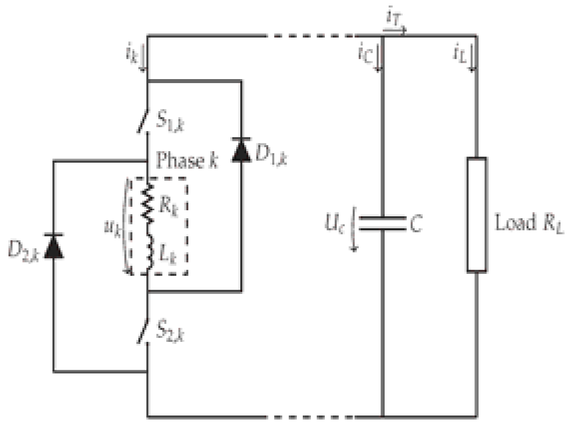


Fig. 2. Single-phase current.

At a given constant speed, the mean value of the mechanical power P_{mec} extracted from the rotor can be estimated from T_{gen} as follows:

$$P_{mec} = T_{gen}\omega \tag{17}$$

with the mean value of the generated electric power P_{gen} and input mechanical power P_{mec}, the electro- mechanical conversion efficiency η_e is calculated as follows:

$$\eta_e = \frac{P_{gen}}{P_{mec}} \tag{18}$$

The mathematical model is formulated as function of electrical position of the phase. The latter represents a value between the two opposing unaligned positions of the phase. As the rotor moves, the electrical position describes a periodic profile. The relation between the electrical position of one phase θ_k and the mechanical position of the rotor θ_{mec} is as follows:

$$\theta_k = -S_t + \left(\frac{\theta_{mec} - k_{offset} - S_t}{2S_t} - \left\lfloor\frac{\theta_{mec} - k_{offset} - S_t}{2S_t}\right\rfloor\right) 2S_t \tag{19}$$

where S_t is the displacement described by the rotor part between the aligned and the unaligned positions and k_{offset} is the angle between the same electrical positions of two consecutive phases.

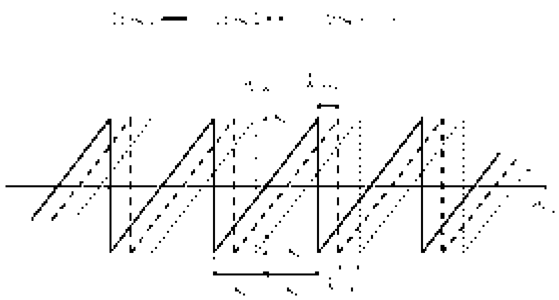


Fig. 3. Electrical position as function of mechanical position [12].

Fig. 3 represents Eqn. (19).

Designing and simulating proposed SRG

The proposed SRG based on the 12/8 SRM with the same outer diameter, but the second stator includes 6 poles and rotor stands between the two shifted stator structures as shown in Fig. 1. The parameters are estimated from Eqns. (5-9). Hence, Table I shows the design results for the basic model of the proposed machine. The proposed DSSRG 12/8/6 illustrated in Fig. 4. The design results of the basic model are validated using FEA. Fig. 5 illustrates the magnetic flux distribution of the proposed DSSRG using FEA. As know, the SRG is excited before align position and the switch is off when it passes the half of flux reduction section and the current maximum over the overlap position. To make an agreement between DSSRG and SRG and create a real comparison, the outer diameter of stators was assumed to be the same.

Simulation results

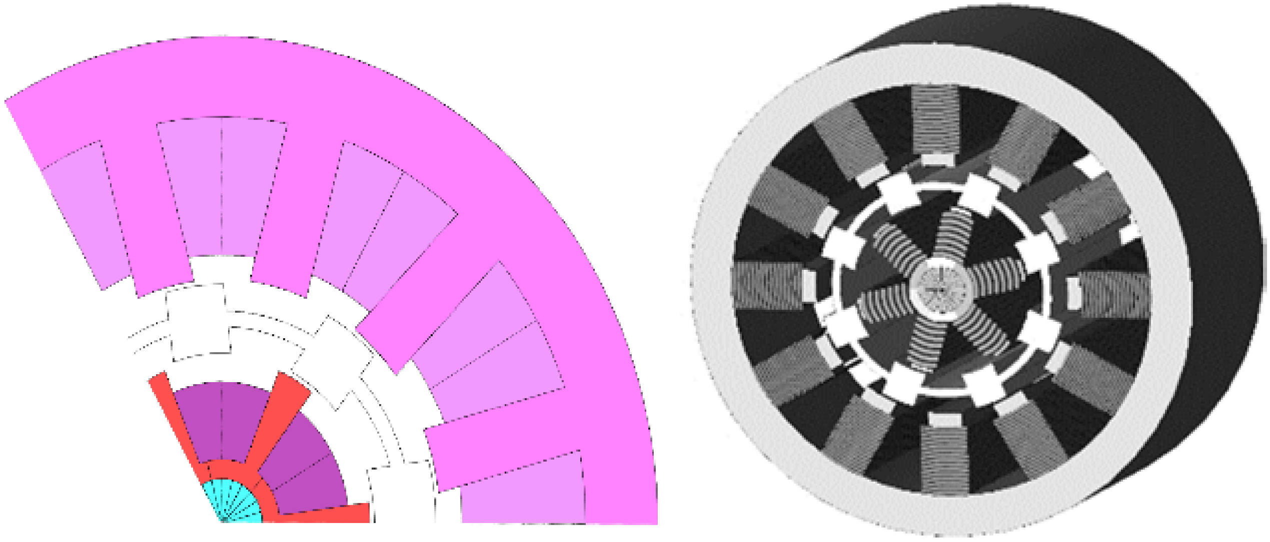
To validate the designing and simulating the DSSRG, it is compared with a single stator SRG and the current waveforms have been shown in Fig. 6. The current starts to increase when the switches of specified phase are off, indicating that the back-emf of coils is larger than supply voltage.

In this mode, generation continues until the back-emf drops to a lower than DC link voltage. However, the back-emf should be calculated to create a smooth current waveform and prevent voltage ripple in the output terminal. In this case, back-emf calculated from

Table 1

Design result for basic model

	Sym	SRG	DSSRG	unit
Outer Stator				
Outer diameter	D_o	151	151	mm
Pole arc	B_{s1}	30	30	deg
Yoke thickness	b_{sy1}	12.5	12.5	mm
Number of turns	T_{ph1}	16	16	Q
Inner Stator				
Outer diameter	D_2	x	23.86	mm
Pole arc	B_{s2}	x	19.44	deg
Yoke thickness	b_{sy2}	x	3	mm
Number of turns	T_{ph2}	x	16	Q
Rotor				
Outer diameter	D_1	48	30.38	mm
Pole arc	B_r	31	31	deg
Yoke thickness	b_{ry}	12.5	2.53	mm
Shaft diameter	D_{sh}	13.85	9.64	mm
Stack length	L_{stack}	70	70	mm



(a) (b)

Fig. 4. Proposed DSSRG, (a) 2D design, (b) 3D design.

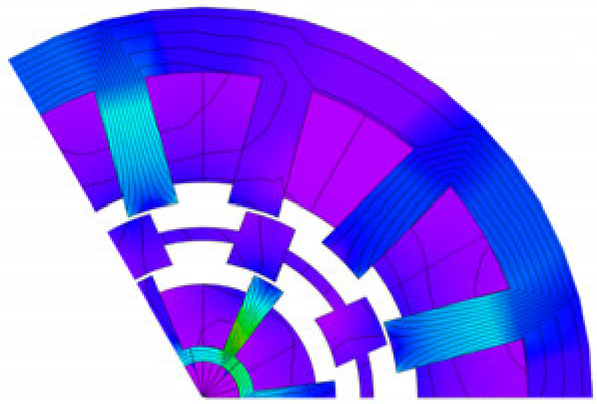


Fig. 5. Magnetic flux distribution of proposed machine obtained by FEA.

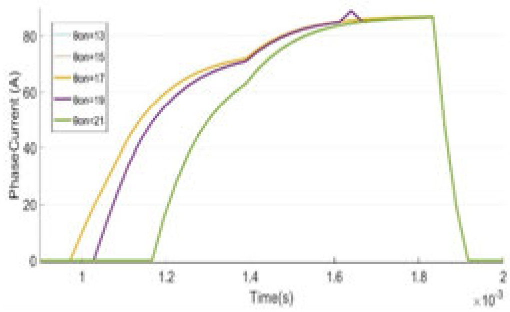


Fig. 6. Current/time waveform of one phase vs turn on angle at θ_{off}=25°.

each stator and DC-link voltage 300 VDC to create 453.7 VDC back-emf on single phase; generating current and supplying the load or voltage source. To optimize the current waveform turn-on and turn-off angles as shown in Fig. 6 and Fig. 7 respectively.

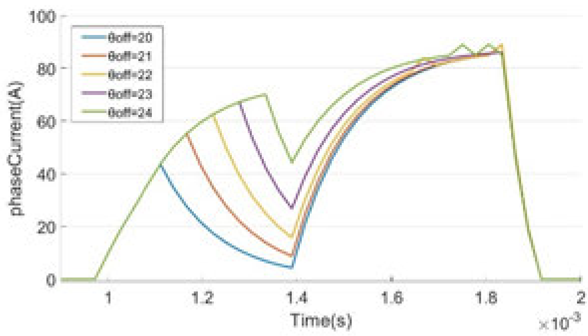


Fig. 7. Current/time waveform of one phase vs turn off angle at θ_{on}=18°

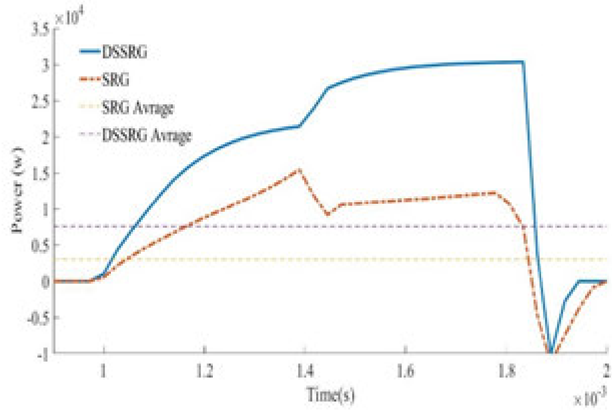


Fig. 8. Electrical output power/time of DSSRG vs SRG, at θ_{off}=25°, θ_{on}=18°.

The output power of the DSSRG illustrates in Fig. 8. Fig. 9 compares the current waveforms and voltages of coils in the DSSRG and SRG as the designed results.

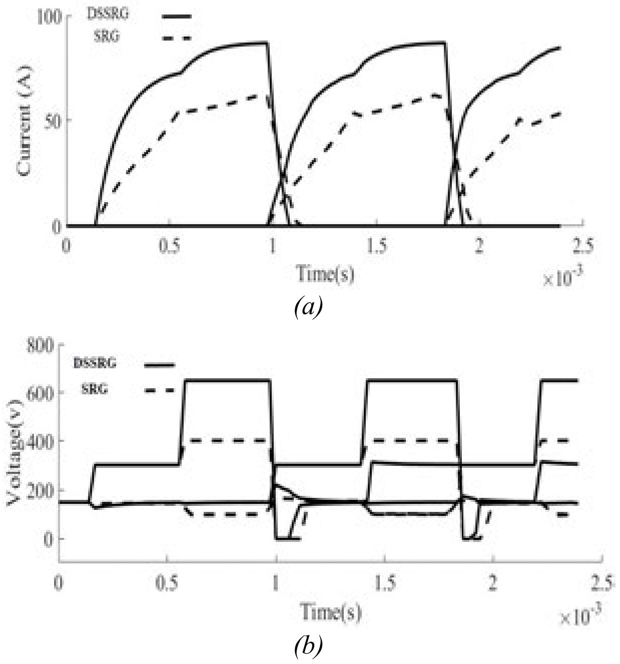


Fig. 9. FEA results of DSSRG and SRG (a) current wave form (b) applied voltage of coils.

Conclusion

DSSRG is an SRG consisting of double-stator with one stator shift one stroke. It is potentially a compact, low cost, high output power which facilities to control the output power and voltage. The paper presented a detailed design and simulations for a scaled DSSRG prototype. The output power of DSSRG improves by 47.25%. Current and voltage of DSSRG and single-stator SRG were simulated and compared.

This paper is reported in the 14-th International Conference on Applied Electromagnetics – ΠΕC 2019, Niš, Serbia

REFERENCES

[1] Susitra, D., Annie E., Jebaseeli, E., Paramasivam, S. Switched reluctance generator-modeling, design, simulation, analysis and control a comprehensive review. International Journal of Computer Applications, Volume 1, 2010, pages 10-16.

[2] Shin, H. U., and Kyo-Beum L. Optimal design of a 1 kW switched reluctance generator for wind power systems using a genetic algorithm. IET Electric Power Application*s* Volume 10, 2016, pages 807-817.

[2] David, A. Switched reluctance generators and their control. IEEE Trans. on Industrial Electronics, Volume 49, 2002, pages 3-14.

[4] Myers, R. H., Montgomery, D. C., Anderson-Cook, C. M. Response surface methodology: process and product optimization using designed experiments. John Wiley & Sons, 2016.

[4] Edrington, C.S., Krishnamurthy, M., Fahimi, B. Bipolar switched reluctance machines: a novel solution for automotive applications. IEEE Trans. Veh. Technol, Volume 25, 2005, pages. 795–808.

[5] Lee, C., Krishnan, R., Lobo, N. S. Novel two-phase switched reluctance machine using common-pole E-core structure: concept, analysis, and experimental verification. IEEE Trans. Ind. Appl., Volume 45, 2009, pages 3630–3637.

[6] Desai, P. C., Krishnamurthy, M., Schofield, N., et al. Novel switched reluctance machine configuration with higher number of rotor poles than stator poles: concept of implementation. IEEE Trans. Ind. Electron., Volume 57, 2010, pages 649–659.

[7] Abbasian, M., Moallem, M., Fahimi, B. Double-stator switched reluctance machines (DSSRM): fundamentals and magnetic force analysis. IEEE Trans. Energy Convers. Volume 25, 2010, pages 589–597.

[8] Wang, W., Lin, C., Fahimi, B. Comparative analysis of double stator switched reluctance machine and permanent magnet synchronous machine. IEEE Int. Symp. on Industrial Electronics (ISlE), Hangzhou, China, 2012, pp. 617–622

[9] Lin, C., Wang, W., Fahimi, B. Optimal design of double stator switched reluctance machine (DSSRM). IEEE Int. Symp. on Industrial Electronics (ISlE), Hangzhou, China, 2012, pp. 719–724

[10] Wang, W., Fahimi, B. Fault resilient strategies for position sensorless methods of switched reluctance motors under single and multiphase fault, IEEE J. Emerg. Sel. Top. Power Electron., Volume 2, 2014, pages 190–220.

[11] Krishnan, R. Switched reluctance motor drives: modeling, simulation, analysis, design, and applications. CRC Press, 2001.

[12] Mendes, R., Maria C., Sílvio M. Maximum Power Point Tracking for a Point Absorber Device with a Tubular Linear Switched Reluctance Generator. Energies, Volume 11, 2018, 2192.

Prof. Dr. Jawad Faiz *- received the Ph.D. degree in electrical engineering from the University of Newcastle upon Tyne, UK in 1988. He became an Assistant Professor in 1988, an Associate Professor in 1992, and a Full Professor in 1998 at the University of Tabri, Iranz. Since February 1999, he has been working as a Professor in the School of Electrical and Computer Engineering, College of Engineering, University of Tehran, Iran. He is also the director of Center of Excellence on Applied Electromagnetic Systems since 2003. He was the Dean of the Faculty of Engineering, at University of Tabriz for 7 years and vice dean of College of Engineering in the University of Tehran for 7 years. Professor Faiz is an IEEE Senior Member,*

Member of Iran Academy of Sciences and Member of Euro-Med. Academy of Art and Sciences. He received a number of International and National awards. His current research includes design of electrical machines, fault diagnosis of electrical machines and analysis of transformers performance

tel. +98 21 61114223 e-mail: jfaiz@ut.ac.ir

***Ashkan Karimi Koohpar** – received the B.Sc. degree in electrical engineering from Arak University of Technology, Arak, Iran in 2016. He is now doing M.Sc. in School of Electrical and Computer Engineering, College of Engineering, University of Tehran, Iran. His current research includes design of electrical machines, particularly switched reluctance machines.*

tel. +98 21 61119715

e-mail: email: karimikoohparashkan@gmail.com

Received on: 30.06.2019