Determination of Switching Angle from Inductance Profile of Converter Fed Switched Reluctance Generator in Wind Energy Conversion System

B Mohamed Arafath Rajack ¹, S Ganesh², S Sarojini Mary ³ and JS Richard Jimreeves ⁴

¹,²Assistant Professor, SRM TRP Engineering College, Department of Electrical and Electronics Engineering, Trichy, Tamilnadu, India.
³Associate Professor, M.I.E.T Engineering College, Department of Electrical and Electronics Engineering, Trichy, Tamilnadu, India.
⁴Assistant Professor, SRM EASWARI Engineering College, Department of Information Technology, Chennai, Tamilnadu, India.

rarafath@gmail.com, gauti.ganeshs@gmail.com, sarojinisamikannu@gmail.com, richardjimreevesec@gmail.com

Abstract. Now a day’s Switched Reluctance Generator (SRG) had been used in renewable energy applications. The main aim is to detect the angle of switching in 1kW 8/6 SRG in Wind Energy Conversion System (WECS) for various structures of rotor and stator. The Generator is turned on by the classic converter. The switching angle is determined by analyzing the inductance profile of each structure. The generator is analyzed using Infolytica MagNet software. The Shaft is driven at a constant speed. The air gap length is 0.5 mm for all structures. The material taken for analysis is cold rolled steel. The dimensions of the generator depend upon the B-H curve of the material used. With B-H curve the total ampere turns of the generator can be evaluated. SRG is excited by voltage source for starting and after some times the switch will turn off the voltage source. Once SRG turned on during decreasing profile of inductance curve, the power generated will be transferred to the load or grid.

Keywords: Wind Energy Conversion System, Switched Reluctance Machine, Switched Reluctance Generator, Step Recovery Diode

1 INTRODUCTION

SRG functions in power delivering mode, as the windings are excited and the salient poles of the rotating part are away from their aligned position owing to the rotating conductor. The material required for Switched Reluctance Machine (SRM) is cheap and robust. In addition range of speed is wide. SRG is a dual salient pole with no winding, as winding is absent in rotor. Operation principle is that whenever stator coils are excited, the rotor tends to attain a low reluctance position. The working of SRG in Wind mill is drawn in Figure1. There is a great demand for SRD in Market.
The rotor pole angle ($\beta_r$) is chosen to be greater than the stator pole arc angle ($\beta_s$). The stator pole angle ($\beta_s$) should be greater than the stroke angle. In WECS SRG is turned on by a classic converter. The Torque is directly equated to the square of the phase current. The harvested energy could be tied to grid for energy support.

In [1] performance comparison was done between 12/8 SRG and 12/16 SRG by FEA and simulation model. In [2] performance comparison was done between SRG and PMSG. The design is optimized in accordance with gear ratio in EV. In [3] the generator is plugged in with micro-grid, which fits in wind deficient areas. In [4] a reliable control is achieved in line with inverter. In [5] a low power SRD is designed and analyzed. In [6] a novel method for exciting SRG is evaluated in accordance with step up converter. In [7] a 8/6 SRG was designed and analyzed by its dynamic characteristics for wind Energy application. In [8] an optimization control of SRG in low and mid speed range is designed. In [9] SRG is analyzed for various air gaps in WECS. In [10] the mechanical parameters of 12/8 Switched Reluctance Micro wind generator was analyzed by Transient Magnetic field analysis. In [11] an optimization concept was proposed to increase efficiency map based on design of experiments. In [12] the factors affecting the efficiency of 6/4 SRG was analyzed and studied. In [13] a novel method of MPPT based on i-v characteristics is analyzed in WECS application using SRG. In [14] a 12/8 SRG designed is optimized by controlling on time and off time for various wind speed. In [15] the optimized inductance profile is compared with rotor parameters which match its inductance curve. The aim of this paper is to detect the switching angle of SRG based on inductance profile of 8/6 SRG.

2 Design of Switched Reluctance Generator

The Torque can be calculated from the angular speed and power

$$T = P/\omega$$  \hspace{1cm}(1)

Practically, the outer diameter of the stator is given as [16-20],

$$D_o = (\text{Frame Size} - 3) \times 2$$ \hspace{1cm}(2)

The stator pole angle ($\beta_s$) should be greater than the stroke angle.

The magnetic circuit equation can be given as,

$$AT = 2*(H_s * l_s + H_r * l_r) + \frac{B_A}{P_a} + (H_y * l_y) + (H_{rc} * l_{rc})$$ \hspace{1cm}(3)
To evaluate the efficiency, the input mechanical power($P_m$), output electrical power($P_o$) and exciting electrical power($P_e$) is estimated. the input mechanical power is

$$P_m = T_{avg} \omega$$  \hspace{1cm} (4)

Where $\omega$ is angular velocity and $T_{avg}$ is average instantaneous torque

The exciting electrical power and output power is estimated as follows

$$P_e = \frac{1}{T} \int_{T_0}^{t} V_{dc} \cdot I_{in} \cdot dt$$  \hspace{1cm} (5)

$$P_o = \frac{1}{T} \int_{T_0}^{t} I_o^2 \cdot R_L \cdot dt$$  \hspace{1cm} (6)

The efficiency of the SRG can be calculated by,

$$\eta = \frac{P_o}{P_e + P_m}$$  \hspace{1cm} (7)

Based on the switching angle deduced from the inductance profile, the different topology of SRG is analyzed and designed.

3 Proposed Methodology

3.1 Classic Converter

Choice of power controller switching circuits for SRM depends upon applications. When switch is on during decreasing inductance profile, SRM will be in generating mode. The basic requirement is that each phase of SRM should conduct independent of other phase and the converter has the ability to freewheel. Classic converter contains dual switch and diode for individual phase. When both switches in a phase turned off, the energy gets dissipated to the source via the two diodes. Two switches are required in each phase leading to switching loss and increase in cost. Circuit is shown in Figure 2. Voltage source will be switched off after the generator starts rotating.
3.2 Structures of SRG

General structure is weighed with curved rotor structure and curved rotor structure with pole shoe. The various structures of stator and rotor is illustrated in Figure 3 (a), Figure 3 (b) and Figure 3 (c).

4 Static Characteristics of SRG

Static parameter of SRG is obtained by exciting the coil of one phase at a time to get the inductance profile of that phase. From static characteristics we can get turn on time (θ_{on}) and turn off time (θ_{off}) for motor and generator. The torque obtained from the static characteristic is analyzed to ensure the absence of dead zone. Dead zone makes SRG difficult to start, as the torque goes below zero. The flux linkage
waveform with respect to rotor position for one pair of coil for various structure of SRG is shown in Figure 4 (a), Figure 4 (b) and Figure 4 (c).

5 Result Analysis

5.1 Determination of Switching Angle

To excite the generator, the switches are to be turned on in decreasing inductance profile and turned off in increasing inductance profile. The switching angles for general structures, curved rotor structure and curved rotor structure with pole shoe is illustrated in Table 1.
Table 1. Turn On and Turn Off Angles

| Coil pair | θ<sub>on</sub> (deg) | θ<sub>off</sub> (deg) | θ<sub>on</sub> (deg) | θ<sub>off</sub> (deg) | θ<sub>on</sub> (deg) | θ<sub>off</sub> (deg) |
|-----------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| 3-Coil 7  | 25                  | 44                  | 85                  | 23.5                | 44                  | 83.5                |
| 2-Coil 6  | 39                  | 58                  | 99                  | 39                  | 59                  | 99                  |
| 1-Coil 5  | 55                  | 74                  | 115                 | 53.5                | 74                  | 113.5               |
| 4-Coil 8  | 9                   | 28                  | 69                  | 9                   | 29                  | 69                  |

5.2 Calculation of Generator Efficiency

Based on the switching angle deduced from the inductance profile, the different topology of SRG is analyzed and designed. The comparison of different structures is illustrated in Table 2.

Table 2. Efficiency comparison of SRG

| Structure of SRG                  | T<sub>avg</sub> (Nm) | P<sub>in</sub> (W) | P<sub>o</sub> (W) | P<sub>t</sub> (W) | % efficiency of SRG | θ<sub>on</sub> (deg) | θ<sub>off</sub> (deg) |
|-----------------------------------|----------------------|-------------------|-----------------|------------------|---------------------|---------------------|---------------------|
| General structure                 | 6                    | 988.4             | 848             | 140.4            | 85.7                | 19                  | 41                  |
| Curved rotor structure            | 6                    | 991.6             | 848             | 143.6            | 85.51               | 20.5                | 39.5                |
| Curved rotor structure with pole shoe | 5.5                 | 914.54            | 848             | 66.54            | 92.72               | 21.5                | 38.5                |

6 CONCLUSIONS

From Table 4, it is observed that the Curved rotor structure with pole shoe promises better efficiency than the other two for a constant speed. The difference in on time and off time is due to the nature of inductance profile. However for curved rotor structure and general structure, the average output torque is increased. The better efficiency of curved rotor structure with pole shoe is due to the fact that curved ends ensure better flux linkage resulting in minimizing leakage flux. The pole shoe also ensures better flux linkage and offers mechanical support to the coil. From Figure 4 the profile of the curve is smooth and wide, which shows its wide range of operating speed and torque. From Table 4 the efficiency is also considerably higher than the other two structures, this can be infer from the fact the wide range of operating speed ensures better efficacy map.

Acknowledgment

This research was supported by the Electrical and Electronics Engineering department that was provided SRM TRP Engineering College, Trichy, Tamilnadu, India.
References

[1] Dranca MA and Radulescu MM 2018 Comparative Design Analysis of Three-Phase Switched Reluctance Generators for Micro-Wind Power Applications International Conference on Electrical Machines (ICEM) pp 597-601.

[2] Kawata N and Chiba A 2018 Design of Switched Reluctance Generator for Competitive Energy Efficiency in the Latest Hybrid Electric Vehicle IEEE Energy Conversion Congress and Exposition (ECCE) pp 6461-6467.

[3] Liaw C–M Lu M-Z and Jhou P-H Wind Switched-reluctance Generator based Microgrid with Integrated Plug-in Energy Support Mechanism IEEE Transactions on Power Electronics doi: 10.1109/TPEL.2020.3029528.

[4] Veerakumar Nirmalkumar, Total Harmonic Distortion Reduction for n-level Cascaded H-Bridge Boost Inverter Using Hybrid Method, International Review on Modelling and Simulations Vol. 6 No.3 2013

[5] Ptakh G Bobrov and Shapovalov V 2020 Test Results of Prototype of Low-power Switched Reluctance Electric Drive with Integrated Design International Ural Conference on Electrical Power Engineering (UralCon) pp 431-435.

[6] Sivaraman, P “A New Method of Maximum Power Point Tracking for Maximizing the Power Generation from a SPV Plant” Journal of scientific and Industrial Research Vol.74, No.3 pp.411 - 415 AUG 2015.

[7] E. Ramprasath, P. Manojkumar, P. Veena “Analysis of Direct Current Motor in LabVIEW”, World Academy of Science, Engineering and Technology, 2015

[8] Dheepanchakkravarthy, A., Venkatraman, K., Selvan, M.P., Moorthi, S. and Venkatakirthiga, M. Capability Evaluation of Four-leg DSTATCOM for Compensating Multifarious Loads Australian Journal of Electrical and Electronics Engineering 13 04 229 - 243 OCT 2017

[9] Viajante GP 2018 Study and Dynamic Performance Analysis of a Switched Reluctance Generator 8/6 for Wind Energy Application IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe pp 1-6.

[10] Yueying Z Chuantian Y and Chengwen Z 2018 Multi-Objective Optimization of Switched Reluctance Generator for Electric Vehicles International Conference on Electrical Machines and Systems (ICEMS) pp 1903-1907.

[11] Mohamed Arafath Rajack B Mohamed Abdul Rahman Naveen TA Prabaharan M 2019 Analysis of Switched Reluctance Generator for Wind Energy Conversion systems (WECS) for various air gaps. International Journal Of Information And Computing Science (IJICS) 1-9.

[12] Dranca MA and Radulescu MM 2016 Dynamic behaviour of a three-phase low-speed switched reluctance micro-wind generator International Conference on Applied and Theoretical Electricity
(ICATE) pp 1-5.

[13] Bhuvaneswari, S., et al. “Performance Analysis of Radial Flux and Axial Flux Permanent Magnet Generators for Low-Speed Wind Turbine Applications.” International Journal of Applied Electromagnetics and Mechanics, 2020, pp. 1–19. Crossref, doi:10.3233/jae-190150.

[14] Senthil kumar J, Charles Raja S, Dipti S, Venkatesh P 2018 Hybrid Renewable Energy based Distribution System for Seasonal Load Variations International Journal of Energy Research 42 3 1066 - 1087 2018.

[15] Alagu, M, Ponnusamy, P, Pandarinathan, S, Mohamed Ali, JS. Performance improvement of solar PV power conversion system through low duty cycle DC-DC converter. Int J Circ Theor Appl. 2020; 1–16. https://doi.org/10.1002/cta.2918.

[16] Wang W 2017 Control system of switched reluctance generator. IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus) pp 1064-1069.

[17] Yang X and Ohyama K 2016 Design method of rotor core shape for improving efficiency of switched reluctance generator IEEE Industrial Electronics and Applications Conference (IEACon) pp 191-196.

[18] Ganesh S and Kanimozhi R 2018 Meta-heuristic technique for network reconfiguration in distribution system with photovoltaic and D-STATCOM IET J. Gener. Transm. Distrib. Vol 12 pp 4524–4535.

[19] Ganesh S, Vengatesan V, Richard Jimreieves JS, and Ramasubramanian B 2020 Simultaneous network reconfiguration and PMU placement in the radial distribution system. Advances in Mathematics: Scientific Journal Vol 9 pp 8143–8151.

[20] Ganesh S, Ram Prakash G, Michline Rupa JA 2021 Optimal Placement of Green Power Generation in the Radial Distribution System Using Harmony Search Algorithm. In: Peter J., Fernandes S., Alavi A. (eds) Intelligence in Big Data Technologies—Beyond the Hype. Advances in Intelligent Systems and Computing, 1167 (2021). Springer, Singapore. https://doi.org/10.1007/978-981-15-5285-4_23.

[21] Ganesh S, Velayudham T, Kanimozhi R 2020 Numerical method for islanding the location of ground fault in the material based distribution system Materials Today Proceedings https://doi.org/10.1016/j.matpr.2020.02.723.

[22] Ganesh S, Kanimozhi R 2018 Multi Objective Approach For Capacitor Placement based on Load Balancing Index in Radial Distribution System. J. Comp. Theo. Nanosci Vol 653 pp 368–375.