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Design and implementation of small power switched reluctance generator-based wind energy conversion system

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Abstract: This paper presents the design and implementation of small power switched reluctance generator (SRG)-based wind energy conversion system supplying stand-alone DC load. A finite element analysis (FEA) model is developed for the existing machine geometry using MagNet 7.1.1 and solved to obtain parameters like flux linkage, inductance, and torque. The data obtained from the FEA model are utilized to develop an SRG machine model in the MATLAB/Simulink environment. The phase winding of the SRG is excited through asymmetric half bridge converter with dedicated buses for source and load to avoid absorbing a large current from the excitation battery. The performance of the system is analyzed for various values of torque input and dwell angle; the output of the SRG is supplied to the stand-alone DC load. A wind turbine with perfect maximum power point tracking algorithm is modelled to extract maximum power from the wind turbine and it is emulated by a DC motor. We implemented the SRG-based small power wind energy conversion system using a microcontroller. The results are examined.

Key words: Asymmetric half bridge converter, finite element analysis, maximum power point tracking, switched reluctance generator

1. Introduction

Switched reluctance generators (SRGs) show a simplified construction associated with the absence of permanent magnets or conductors in the rotor; they are low cost, easy to manufacture, and can operate at high speeds and in high temperature environments. Torque contributed by the SRG is independent of current direction, and therefore the unipolar converter itself is sufficient for the satisfactory operation of the machine. The machine and the power converter are very robust and the low inertia of the rotor allows the machine to respond to rapid load variations [1]. The phase winding of the SRG is electrically and magnetically independent from other windings, which makes the machine highly fault tolerant under open-coil fault and external faults [2].

The increasing use of fossil fuels results in air pollution and global warming; there is a need to concentrate on renewable energy sources to reduce these effects. Wind generation is one of the renewable energy power sources that help in reducing carbon dioxide in the atmosphere. The wind generator is one of the most important parts in wind generation systems and a permanent magnet generator is most commonly used. It requires high torque to run and cannot be used in harsh environments. Therefore, we focus our attention on SRG, which is

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characterized by a simple structure, toughness, and high efficiency; no starting torque is required for starting and it can be used in harsh environments [3].

This paper is organized as follows. Section 2 focuses on the SRG. Section 3 briefs the wind turbine modeling. Section 4 deals with the MATLAB/Simulink model of the converter and SRG. Section 5 provides the implementation of the SRG drive system.

2. SRG

The SRG is an electromechanical device that converts mechanical energy into electrical energy by properly synchronizing the phase current with the rotor position. To achieve generating mode, operation phase current pulses are applied during the period when the rotor leaves the aligned position; phase winding is excited by means of a DC source bus. During generation, the SRG produces negative torque that tends to oppose rotation, thereby extracting energy from the wind turbine [4]. The cross section of the SRG for the specifications given in the Table is shown in Figure 1.

Table. Specifications of SRM.

Rated power	1Hp (746w)
Rated speed	3000 RPM
Rated voltage	330 V, DC
Rated current	5 A
Winding gauge	24 SWG
No. of turns per pole	100 turns
Stator core stamping thickness	0.5 mm
Rotor core stamping thickness	0.5 mm
Shaft diameter	14 mm
Thickness of rotor yoke	5.8 mm
Height of rotor pole	10 mm
Air gap length	0.2 mm
Height of stator pole	9 mm
Thickness of stator yoke	11.5 mm
Stack length	80 mm
Stator pole arc	22 deg
Rotor pole arc	25 deg

One arm of the power converter, used to excite the phase winding of the SRG, is shown in Figure 2.

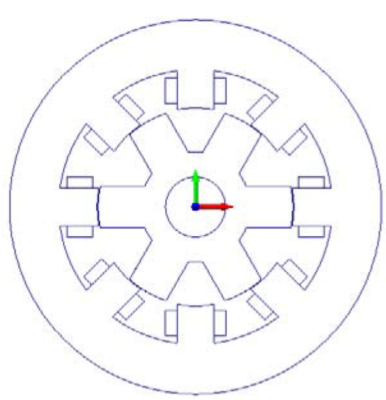

Figure 1. Core structure of the SRG.

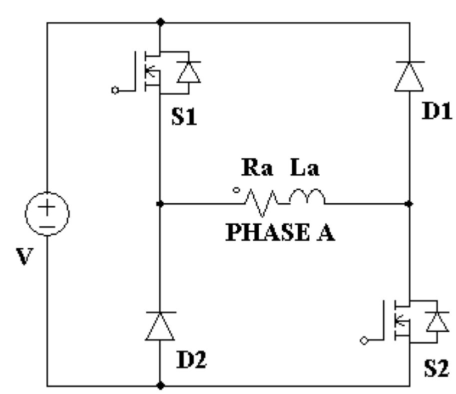

Figure 2. One arm of the power converter.

The dynamic equation of the phase voltage (v) is given as:

$$v = iR + \frac{d\lambda(i,\theta)}{dt} \tag{1}$$

where

v – DC source voltage;

λ– Flux linkage;

R – Resistance of the phase winding.

The flux linkage (λ) is a function of the current (i) and rotor position (θ), and therefore the voltage equation can be rewritten as [5]:

$$v = iR + L\frac{di}{dt} + i\omega\frac{dL}{d\theta} \tag{2}$$

Considering one phase of the converter, during the magnetization period both switches S_1 and S_2 connect the DC bus to the winding, and thus the phase current increases. The equation corresponding to excitation is described as follows:

$$v = i_{exc}R + L\frac{di_{exc}}{dt} - |e| \tag{3}$$

where

i_{exc} – Current during excitation;

L – Inductance, function of current (i) and position (θ);

e – Back emf.

During generation both switches, S_1 and S_2, are OFF; then the DC bus is connected in reverse polarity through diodes D_1 and D_2. Consequently, the phase current flows back to the DC bus and returns the generated power to it. The equation corresponding to generation is represented as follows:

$$-v = i_{gen}R + L\frac{di_{gen}}{dt} - |e| \tag{4}$$

where

i_{gen} – Current during generation.

A finite element analysis (FEA) model is developed for the existing machine geometry using MagNet 7.1.1 and solved to obtain the flux linkage, inductance, and torque parameters. The FEA model at the aligned position is shown in Figure 3.

The variation of flux linkage with respect to the current is shown in Figure 4.

It is evident from Figure 5 that the inductance is maximum at the aligned position. When the rotor leaves the aligned position, the inductance decreases and it is minimum at the unaligned position. The inductance profile of the machine is a periodic function of the rotor position, as seen in Figure 5.

The torque obtained from the FEA model for various values of the current and position is shown in Figure 6. It is negative from 0–30 degrees and positive from 30–60 degrees.

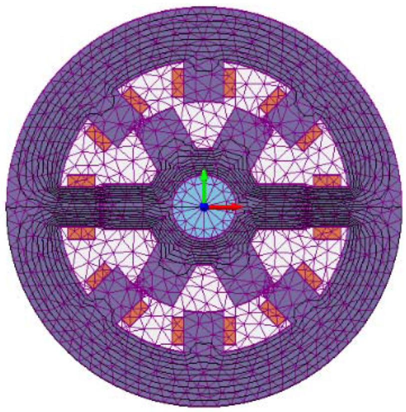

Figure 3. FEA model of SRG at the aligned position.

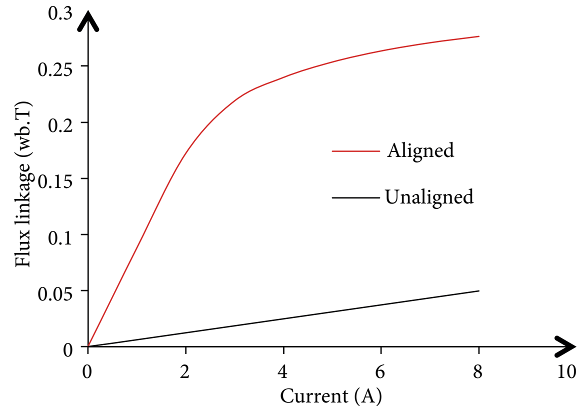

Figure 4. Flux linkage vs. current.

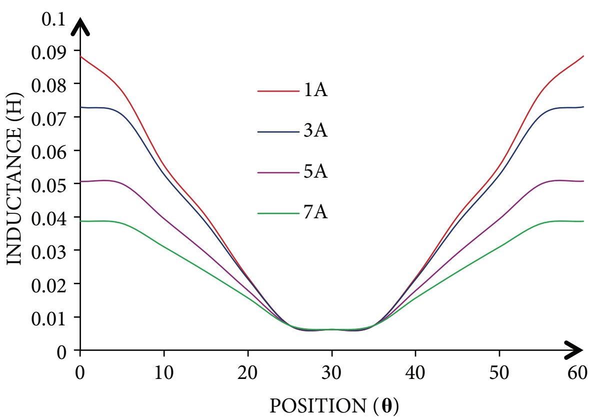

Figure 5. Inductance profile.

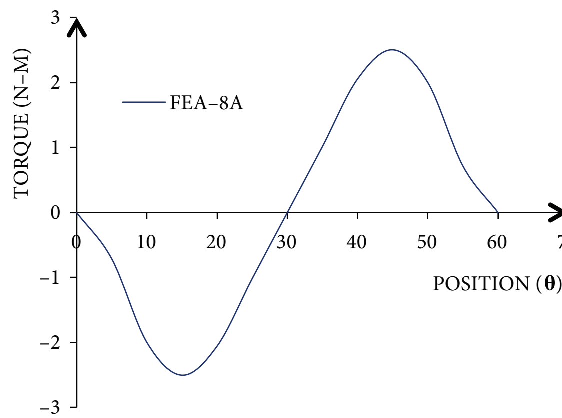

Figure 6. Torque characteristics.

3. Wind turbine modelling

The wind turbine is a machine for converting the kinetic energy in the wind into mechanical energy. The kinetic energy in a flow of air through a unit area perpendicular to the wind direction, per mass flow rate, and is computed as:

$$E = \frac{1}{2}v^2 \tag{5}$$

where

v – Wind speed (m/s).

For an air stream flowing through an area 'A', the mass flow rate is ρAv; therefore, the power in the wind is given as:

$$P_w = \frac{1}{2}\rho A v^3 (\text{watts or J/sec}) \tag{6}$$

where

ρ– Air density = 1.225 kg/m^3;

A – Area covered by blades, m^2.

The coefficient of performance (C_p) is defined as the fraction of energy extracted by the wind turbine of the total energy that would have flown through the area swept by the rotor if the turbine had not been there. The expression for C_p is described as:

$$C_p(\lambda,\beta) = \frac{P_{extracted}}{P_w} \tag{7}$$

Cp has a maximum theoretical value of 0.593,

where

$P_{extracted}$ – Power extracted by the wind turbine;

it is expressed as:

$$P_{extracted} = C_p(\lambda,\beta)\frac{1}{2}\rho A v^3 \tag{8}$$

where

$\lambda-$ tip speed ratio and it is given as $\lambda = \frac{\omega R}{v}$;

$\omega-$ rotor speed (rad/s);

R – rotor radius (blade length) (m);

B– pitch angle (degrees).

The rotor torque Tw is given as [6]:

$$T_w = \frac{\frac{1}{2}\pi C_p(\lambda,\beta)\rho R^2 v^3}{\omega} \tag{9}$$

The flow chart for the maximum power point tracking (MPPT) algorithm [7] to extract the maximum power from the wind turbine is shown in Figure 7.

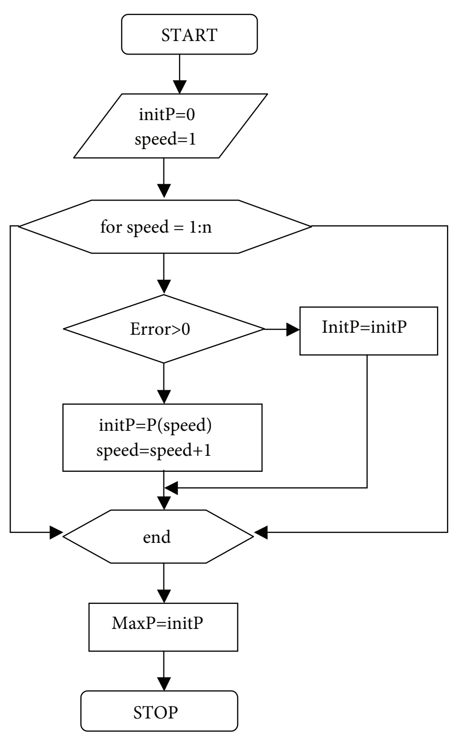

Figure 7. Flow chart for MPPT.

Coding is developed in MATLAB to obtain the response of the wind turbine with MPPT capability. The wind turbine characteristics for variable speed operation are shown in Figure 8. The wind turbine is modeled with cut-in velocity of 4 m/s and rated velocity of 12 m/s.

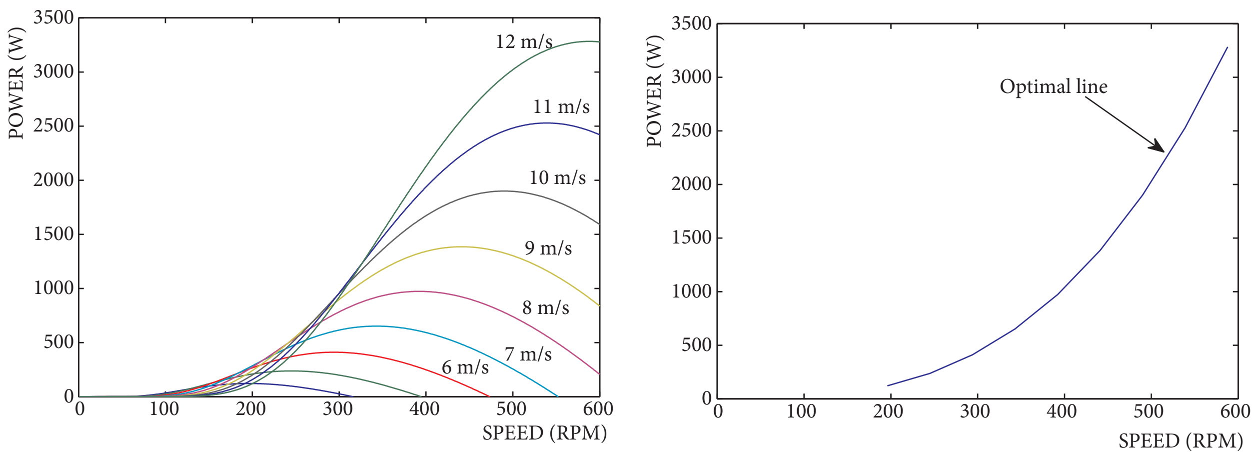

Figure 8. Wind turbine characteristics.

4. MATLAB/Simulink model of the converter and SRG

The converter used for the SRG is shown in Figure 9. An asymmetric half bridge converter with dedicated buses for source and load is used to avoid absorbing a large current from the excitation battery. To get to generator mode operation, winding is energized in the drooping inductance region of the inductance profile, where the variation of inductance with respect to the rotor position is negative ($dL/d\theta < 0$). The sign of the generated torque is negative, and thereby it extracts energy from the wind turbine.

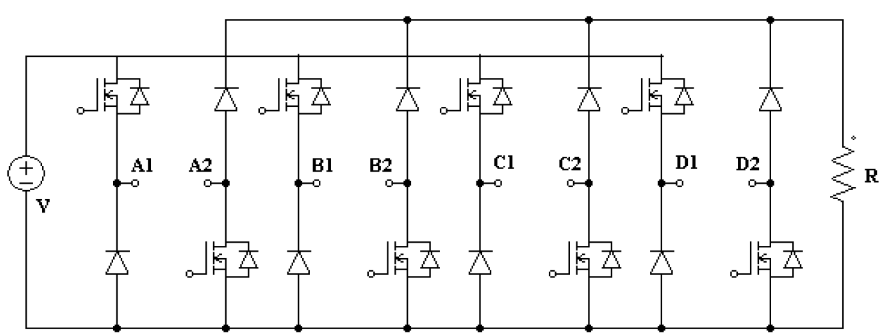

Figure 9. Asymmetric half bridge converter.

The MATLAB/Simulink model of SRG is shown in Figure 10. Phase windings of the SRG are excited in a sequential manner and the torques contributed by the individual phases are summed up to obtain the total torque (T) developed by the machine [8]. The dynamic equation is solved in the mechanical block to obtain speed and rotor position.

The operating variables of the SRG are the turn-on angle, turn-off angle, converter input voltage, and torque supplied to the generator. The responses of the SRG-based wind energy conversion system for wind velocity of 10 m/s and 12 m/s are shown in Figure 11 and Figure 12, respectively.

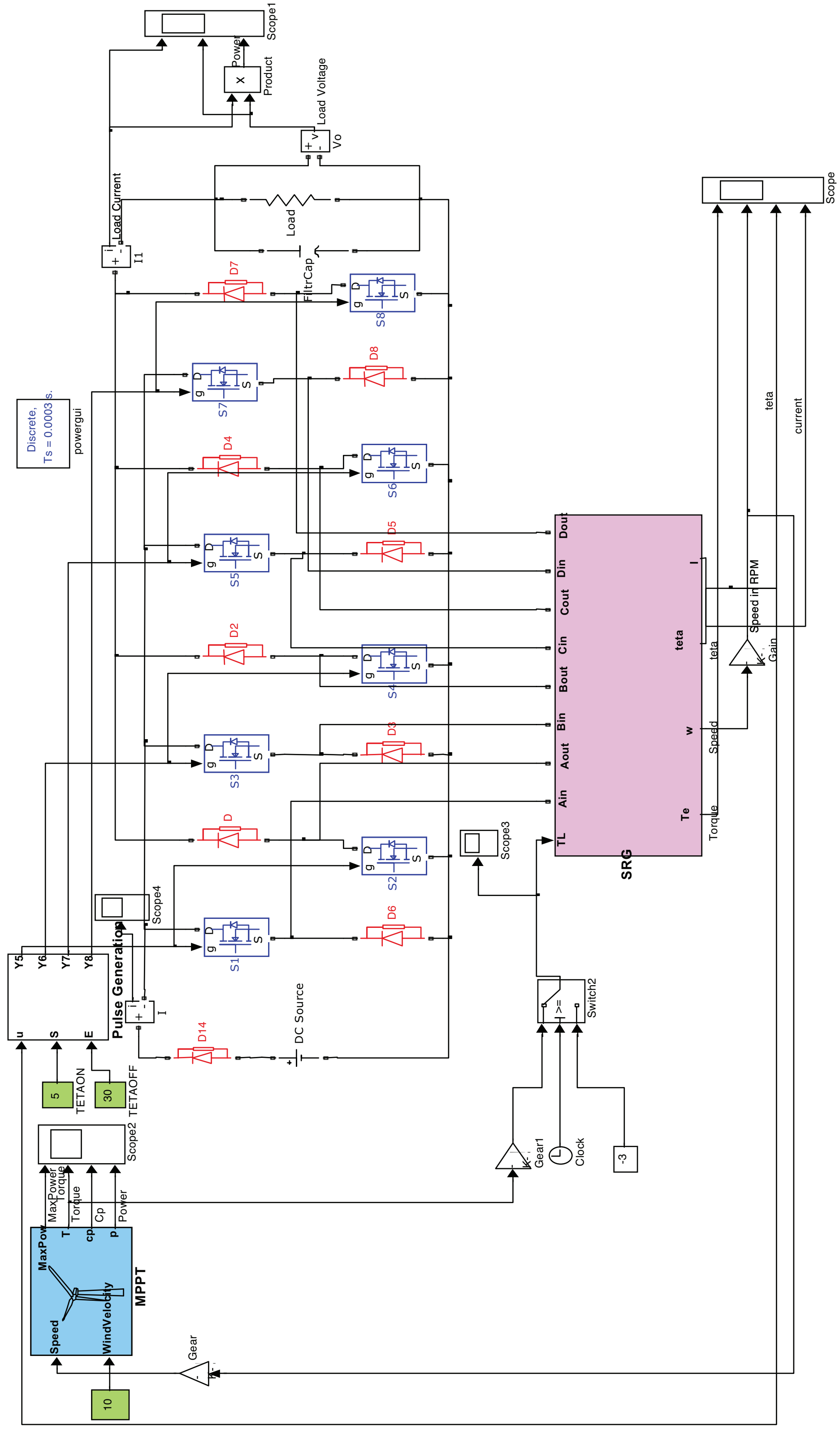

Figure 10. MATLAB/Simulink model of an SRG-based wind energy conversion system.

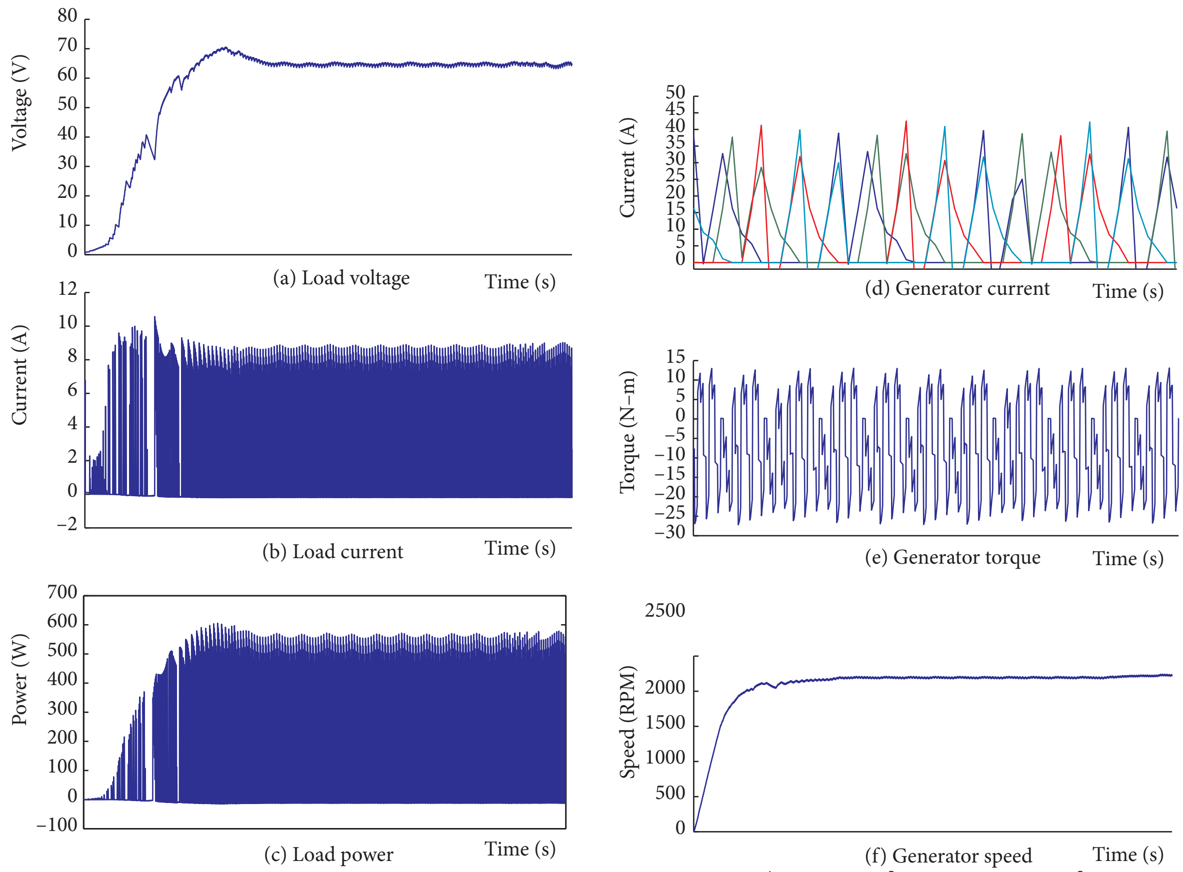

Figure 11. Response of the system for wind velocity of 10 m/s, $\theta_{on} = 5^\circ$, and $\theta_{off} = 30^\circ$.

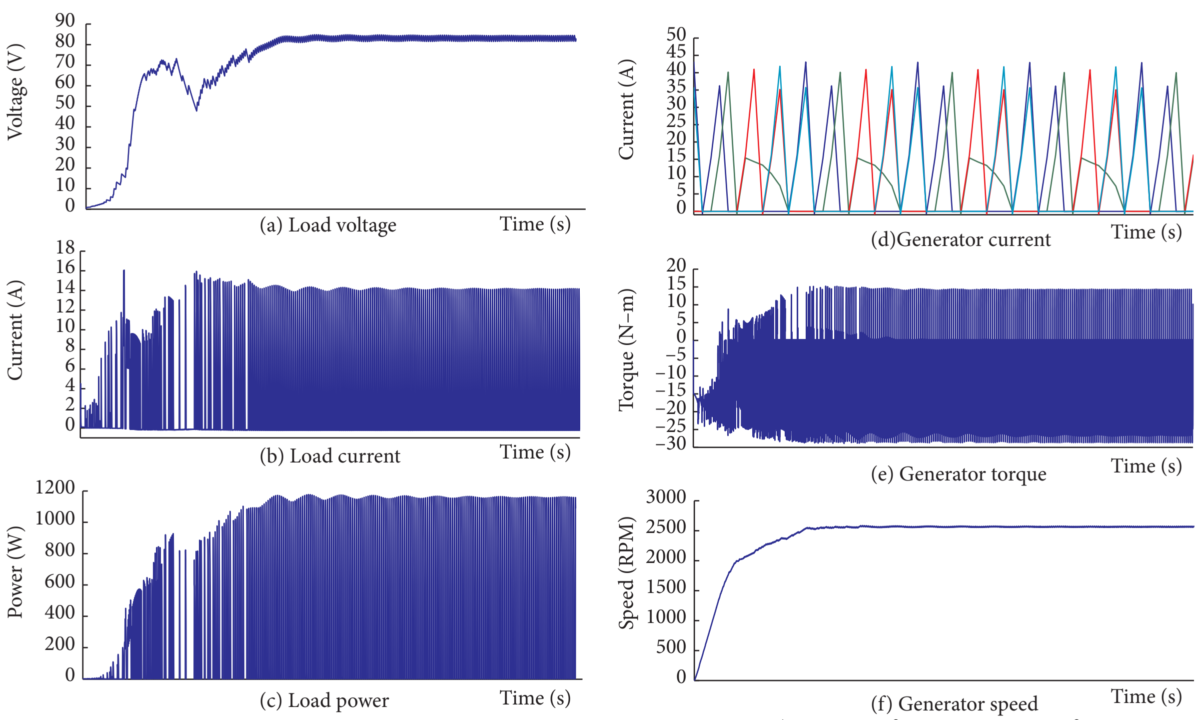

Figure 12. Response of the system for wind velocity of 12 m/s, $\theta_{on} = 5^\circ$, and $\theta_{off} = 27^\circ$.

5. Implementation of a small power switched reluctance wind energy conversion system

The complete block diagram of the SRG-based wind electric conversion system is shown in Figure 13.

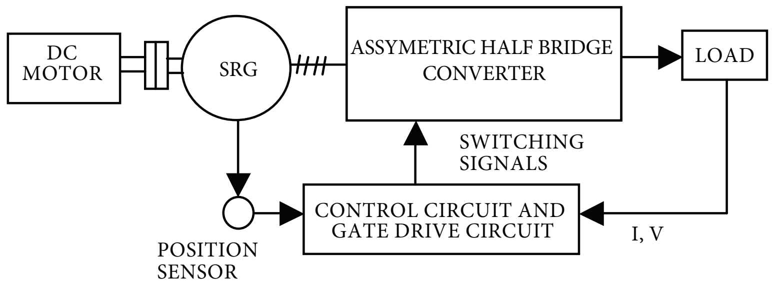

Figure 13. SRG-based wind electric conversion system.

The single phase AC is supplied to the rectifier unit. The rectifier unit converts AC input into DC output and it is supplied to the machine side converter through a filter and regulator. The DC output of the rectifier is controlled by means of an autotransformer. The machine side converter is an asymmetric half bridge converter topology consisting of eight MOSFET switches for the independent control of the phase winding [9].

Microcontroller ATMEGA-16 is used to obtain a switching signal and it is supplied to the asymmetric half bridge converter through a MOSFET driver circuit, as shown in Figure 14. The driver circuit consists of a rectifier, a regulator (7812), a filter, IR2110 driver, MCT2E Opto-isolator, and IRF 530 MOSFET switch.

The complete experimental set-up of the SRG-based wind electric conversion system in shown in Figure 15. The wind turbine is emulated by means of a 12 V DC motor coupled with SRG. The phase windings of the SRG are excited through an asymmetric half bridge converter.

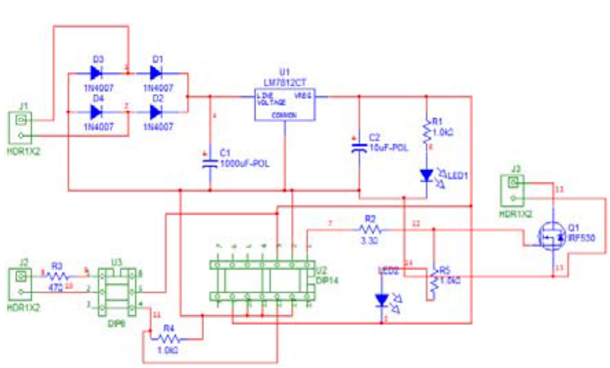

Figure 14. MOSFET driver.

Figure 15. Experimental set-up.

To obtain the position information of the rotor, IR sensor 1 and IR sensor 2 are used; the outputs of IR sensors are shown in Figure 16.

Position information obtained from IR sensors 1 and 2 is processed by a microcontroller and four switching signals are generated to excite the phase windings of the SRG in an independent manner. Switching signals for phase A, phase B, phase C, and phase D windings are shown in Figures 17 and 18.

The phase windings of the SRG are excited during the drooping inductance period and negative torque is developed to extract energy from the wind turbine emulated by a 12 V DC motor. The generated voltage of the SRG without filter is shown in Figure 19.

From Figure 19 it is clear that SRG output has more AC ripples and it is filtered by including a capacitor across the output terminals of the SRG. The response of the system with a capacitor is shown in Figure 20.

The experimental set-up is tested with low excitation voltage of magnitude 17.3 V DC for the converter of SRG to avoid damage to the switches present in the power converter and to limit the excess current from the mains. The magnitude of the generated voltage of the SRG is 70 V DC, as shown in Figure 20. From the results, it is apparent that the low power switched reluctance wind generation system gives satisfactory performance and SRG is an appropriate wind generator for a wind electric conversion system.

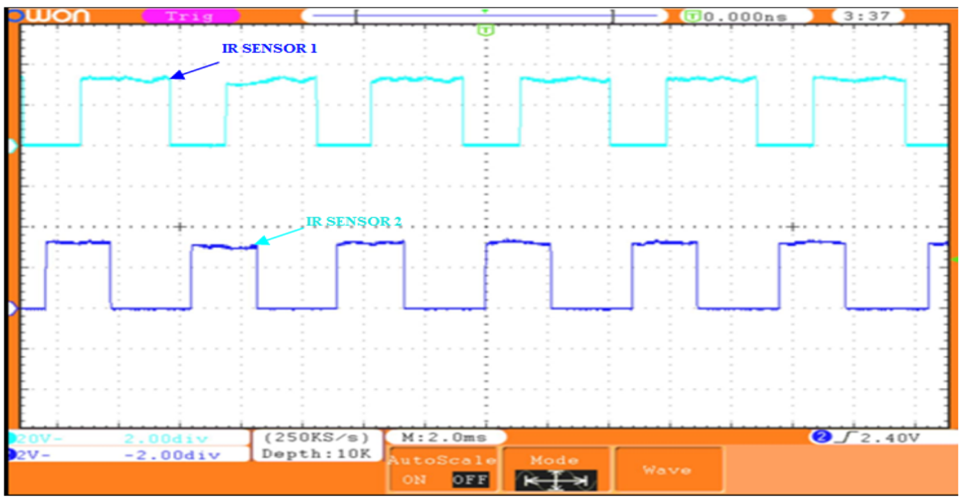

Figure 16. Position information of the rotor from IR sensor 1 and IR sensor 2.

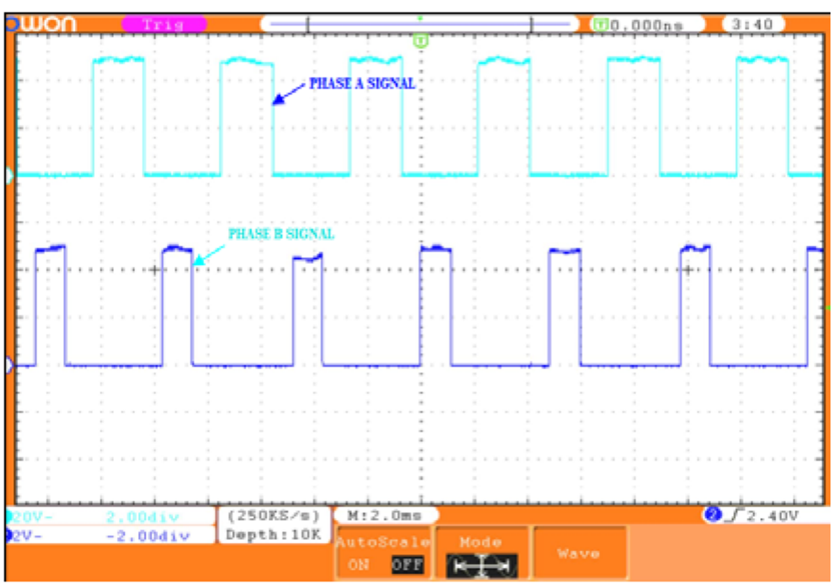

Figure 17. Switching signal for phase A and phase B windings.

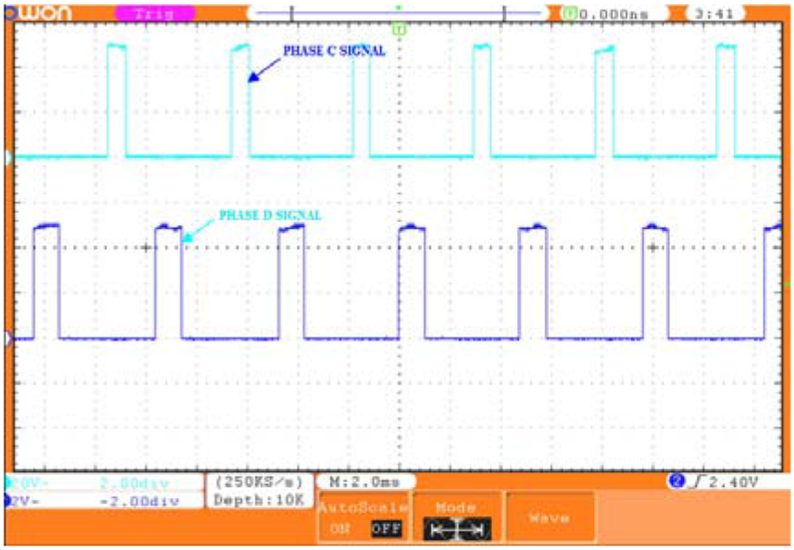

Figure 18. Switching signal for phase C and phase D windings.

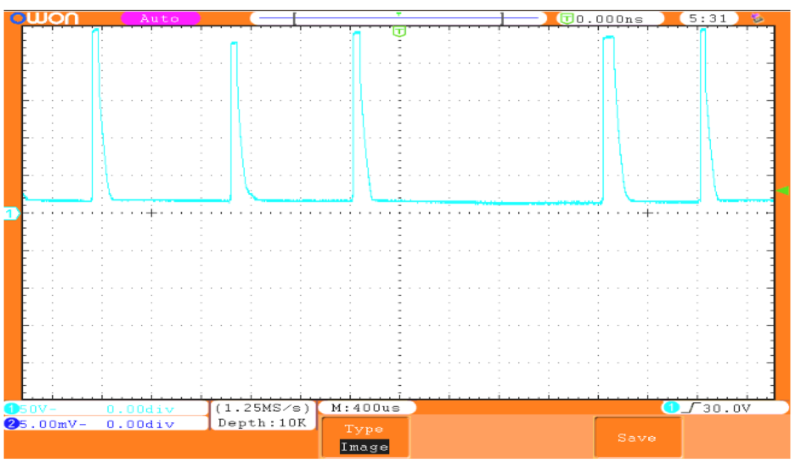

Figure 19. Generated voltage of SRG without filter.

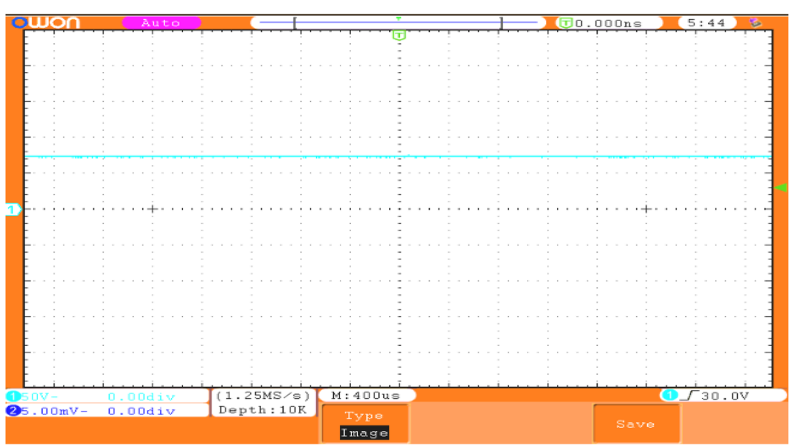

Figure 20. Generated voltage of SRG with filter.

6. Conclusion

The modeled small power switched reluctance wind energy conversion system supplies stand-alone DC load in the MATLAB/Simulink environment; the performance of the system is analyzed for various values of torque input and dwell angle. The phase winding of the SRG is excited through an asymmetric half bridge converter with dedicated buses for source and load to avoid absorbing a large current from the excitation battery. We modeled the wind turbine with a perfect MPPT algorithm to extract maximum power from the wind turbine, which was emulated by a 12 V DC motor. We implemented and tested a small power switched reluctance wind energy conversion system using a microcontroller. From the results it is apparent that the low power switched reluctance wind generation system gives satisfactory performance and SRG is an appropriate wind generator for a wind electric conversion system.

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