Implementation of Wind Powered Switched Reluctance Generator System

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Abstract- This paper reports implementation of Battery Energy Storage System (BESS) for Switched Reluctance Generator (SRG) based wind power generation system supplying stand alone load. MATLAB/Simulink model of the SRG machine is developed using the characteristics acquired by solving the Finite Element Analysis (FEA) model of the machine used for implementation. Wind turbine is incorporated with Maximum Power Point Tracking (MPPT) control technique and to mitigate the problem of wind power fluctuation a BESS for a wind powered SRG with Isolated Bi-directional DC-DC Converter (IBDC) is proposed. The response of BESS is evaluated using MATLAB/Simulink computing tool and the results are reported. For experimental purpose, the wind turbine is emulated by a 12V DC motor. The BESS for wind powered SRG is analyzed and implemented using microcontroller to validate the simulation results.

Keywords-Switched Reluctance Generator, Single Switch per Phase Converter, Battery Energy Storage System, Isolated Bi-directional DC-DC Converter.

1. Introduction

Electric power generated by the renewable energy sources is unsteady in nature and produces adverse effects in the utility system due to stochastic nature of the wind speed [20]. It is most obvious to use BESS to ensure un-interruptible power flow to the load. The most important element of the renewable energy system is the energy storage element which is used to improve the energy quality and system dynamic properties. Generally, a chemical battery or a ultra-capacitor is used as energy storage element. To charge and discharge the storage element, a bi-directional DC-DC converter is used and galvanic isolation is provided by a high frequency transformer [24]. The high frequency operation is preferred to reduce the transformer size and weight. Bi-directional DC-DC converters are classified into non-isolated and isolated types. Non-isolated Bi-directional DC-DC (NBDC) converters are simpler than Isolated Bi-directional DC-DC converters (IBDC) and achieve better efficiency. However, galvanic isolation is required for high voltage and high power transfer applications and mandated by different standards. In this paper, IBDC converter is considered for the design of BESS.

The construction of SRG is very simple and robust due to the presence of windings only in the stator. It can be loaded to its maximum thermal capacity and can operate at high speeds [1]. A simple concentrated winding with independent control makes the machine highly fault tolerant [2].

A noval control technique for changing the conduction angle of the SRG, effective charging of battery bank with low dc ripple is proposed by Sandeep Narla et al [3].

Nadia Mei Lin Tan et al reported design and performance of an IBDC by accounting the magnetic saturation due to dc-bias currents at high voltage [4]. Yuang-Shung Lee et al proposed a soft switching based switched capacitor BDC structure to reduce the current ripple, switching loss and to increase the converter efficiency and the power density [5].

The problems associated with unstable nature of renewable energy sources and fluctuation of load demands are overcome by integrating high energy density storage battery and high power density storage ultra-capacitor Haihua Zhou et al [6]. Hao Qian et al presented a high efficiency grid-connected battery energy storage system. A 1 kW proto type is designed and implemented by the authors for validating the proposed system [7].

This paper is organized as follows. Section 2 focuses on the Switched Reluctance Generator. While Section 3 briefs the wind turbine modelling, Section 4 deals with simulation model of the converter and SRG. Section 5 gives BESS using IBDC. Section 6 explains the implementation of wind power conversion system using SRG with BESS.

2. Switched Reluctance Generator

Switched reluctance machine has got the reversible operation characteristics and to achieve generating mode operation, it is necessary to energize the stator coil during drooping inductance period of the inductance profile [8]. During generation, the switched reluctance generator produces negative torque that tends to oppose the rotation, thereby extracting energy from the prime mover [9,10].

A well designed controller is necessary to match the phase current pulses with the rotor position. The cut view of SRG rated 1 Hp, 4 phases, 8 stator poles and 6 rotor poles is shown in Figure 1 and ideal waveforms corresponding to one phase of SRG are shown in Figure 2.

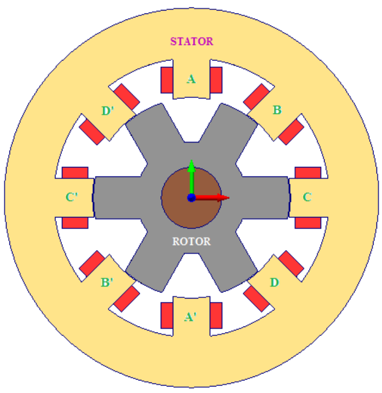


Fig. 1. Core structure of 8/6 SRG

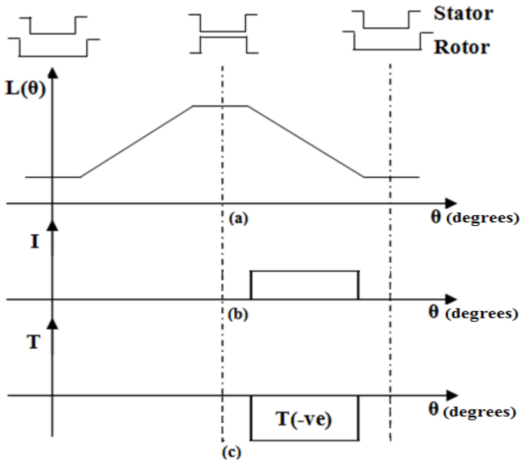


Fig. 2. (a) Inductance variation (b) Positive current c) Negative torque

Torque is produced through magnetic anisotropy i.e. by the tendency of the magnetic flux lines to complete its path where minimum reluctance occurs and it is independent of the direction of current flow [18]. Therefore, the flux must be established in each cycle and returned to zero before the excitation of next phase [11]. In the absence of magnetic saturation, flux linkage is expressed as

$$\psi = L(\theta).i \tag{1}$$

The flux linked to a coil (ψ) depends on current (i) and rotor position (θ), and therefore the voltage supplied to the winding is written as [12]

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

where

L – Inductance, depends on current (i) and position (θ);

$$i\omega\frac{dL}{d\theta} = e = counter\ emf$$

The stored magnetic energy (W_e) or co-energy (W_c) varies with rotor position to produce torque and it is given as

$$W_e = W_c = \frac{1}{2}L(\theta).i^2 \tag{3}$$

The instantaneous torque is calculated using the equations given below

$$T_e = \left(\frac{\partial W_c(\theta,i)}{\partial\theta}\right)_{i=cons} \tag{4}$$

$$T_e = \frac{1}{2}i^2\frac{dL(\theta)}{d\theta} \tag{5}$$

where	i	=	phase current
	L	=	self-inductance dependent on the rotor position and phase current
	θ	=	rotor position in radians
	$dL/d\theta$	=	slope of the inductance variation

It is clear from equation (5) that the polarity of the current is not relevant for torque production. $dL/d\theta$ is positive for motor operation, and negative for generation.

The total torque of SRG is the summation of torque of all the phases and it is given as

$$T_{e(Total)} = \sum_{n=1}^{m} T_n(i,\theta) \tag{6}$$

SRG has got nonlinear characteristics due to magnetic saturation. To analyze the electrical and mechanical performance of the SRG model, it needs knowledge of the magnetic characteristics of the machine [13]. It is obtained by solving the FEA model developed for the specifications given in Table 1.

3. SRG Based Wind Energy Conversion System

When SRG is preferred for wind energy applications, the focus is to maximize the power generation as much as possible for the given speed range [14,25]. Therefore, model of wind turbine is developed by incorporating MPPT algorithm [15, 21, 22, 23, 26]. The power contributed by the wind turbine for different wind velocity with optimal line is shown in Figure 3. The WT is modeled, considering the cut-in velocity of 4 m/s and the rated velocity of 12 m/s.

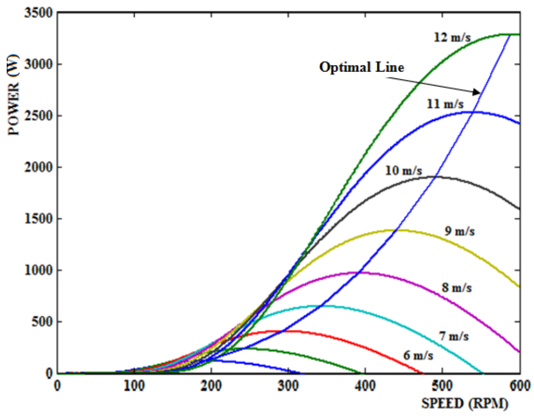


Fig. 3. Wind Turbine characteristics

The torque contributed by the wind turbine is coupled with SRG system through the gear arrangement to obtain SRG based wind energy conversion system [17,19]. The MATLAB/Simulink model of wind power conversion system using SRG is illustrated in Figure 4.

SRG output varies with wind speed and it is regulated using buck regulator before supplying it to the stand alone load. The response of wind power conversion system using SRG for the wind profile with three different wind velocities varying in steps at the interval of 0.5 seconds is shown in Figure 5.

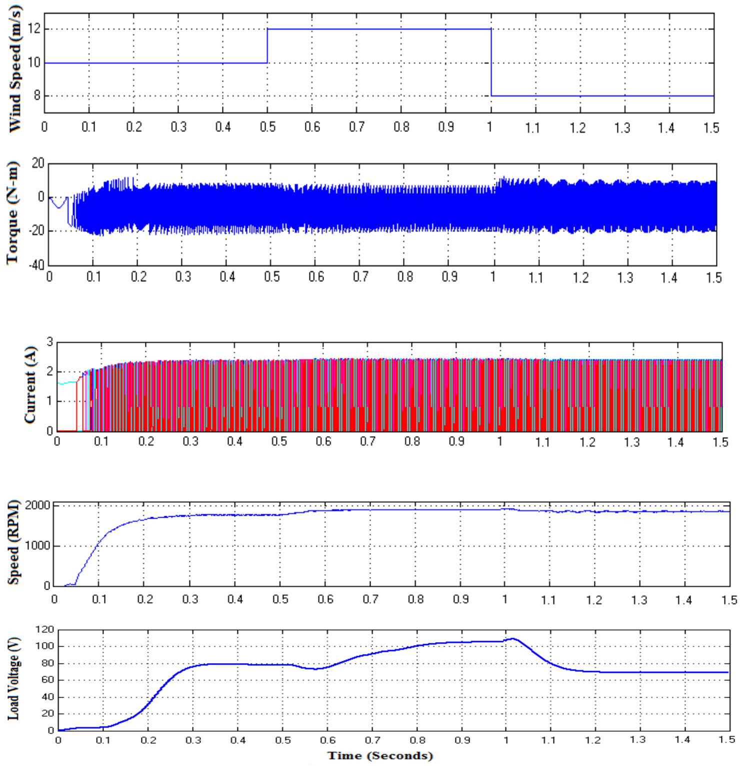


Fig.5. Response of wind powered SRG system

From the response it is clear that for the change in wind velocity from 10 m/s to 12 m/s, at time=0.5 second, the speed of SRG is increased. As a result, generated voltage, current and power are increased. For the decrease in wind velocity from 12 m/s to 8 m/s at time=1 second, SRG speed is decreased.

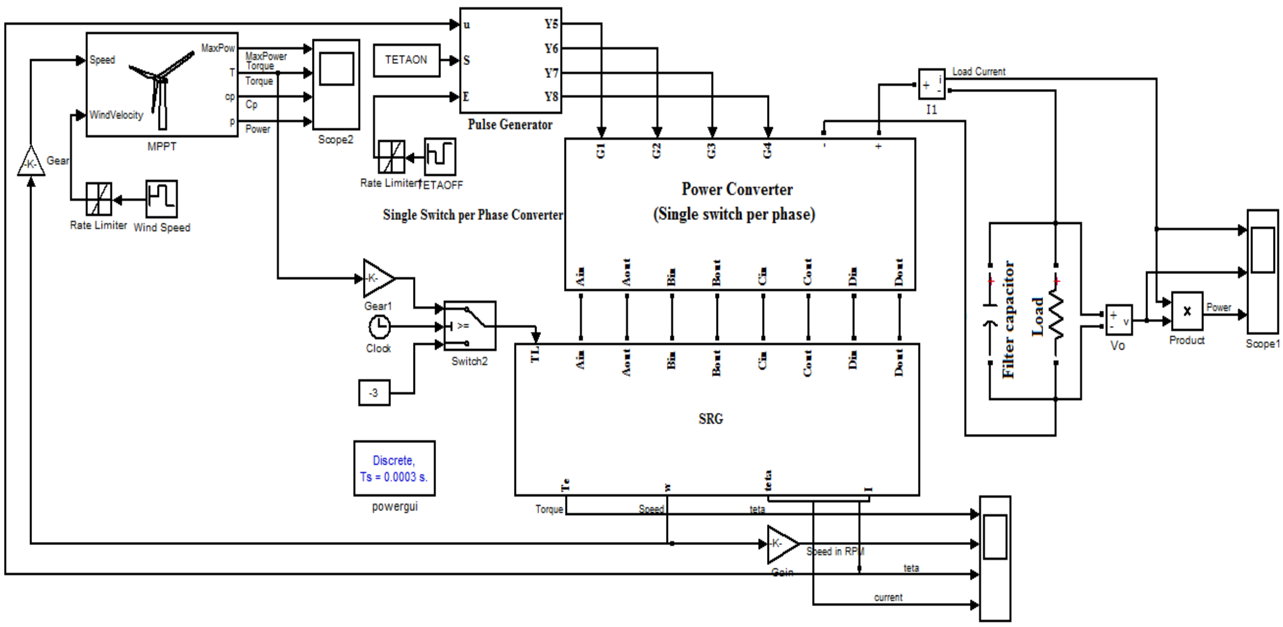


Fig. 4. MATLAB/Simulink model of wind powered SRG system

4. BESS for Wind Powered SRG

The IBDC along with battery bank is integrated with wind powered SRG for developing BESS. The MATLAB/Simulink model of the BESS for wind powered SRG system supplying stand alone load is shown in Figure 6. For the ease of analysis SRG is considered as constant voltage source. During charging mode of operation, converter 1 alone is gated and acts as an inverter and converter 2 acts as a rectifier. The direction of power flow is from converter 1 to converter 2 and the battery bank will get charged.

In the discharging mode of operation, converter 1 acts as a rectifier and the converter 2 acts as an inverter. The direction of power flow is from converter 2 to converter 1 and battery bank will get discharged, i.e supplies power to the stand alone load. The switching pattern for converters 1 and 2 is shown in Table 2.

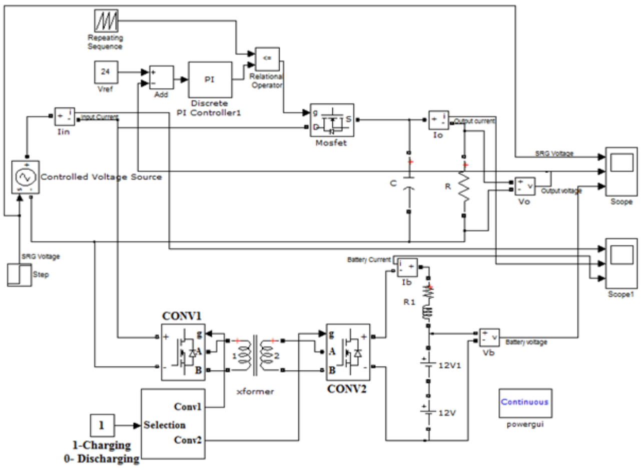


Fig. 6. MATLAB/Simulink model of the BESS for wind powered SRG

To supply constant voltage to load, the voltage is regulated to 24V using voltage control loop. It consists of comparator, PI controller, PWM generator and MOSFET switch. Load voltage is measured and compared with the reference voltage of 24V and error is supplied as input to the PI controller. PI controller output is considered as reference signal and it is compared with the carrier signal to generate PWM signal. MOSFET switch is triggered using PWM signal and the output voltage is regulated to 24V. The response of BESS, during charging mode of operation is shown in Figure 7.

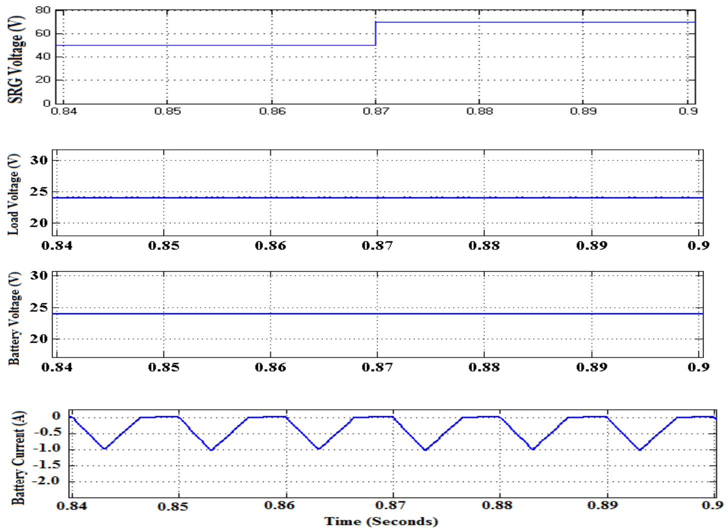


Fig. 7. Response of SRG with BESS during charging

From the response it is clear that, in the charging mode of operation battery current is negative and battery voltage will get increased to its maximum value. The response of SRG with BESS, during discharging mode of operation is shown in Figure 8. In the dis-charging mode of operation, battery delivers power to the load and battery current is positive.

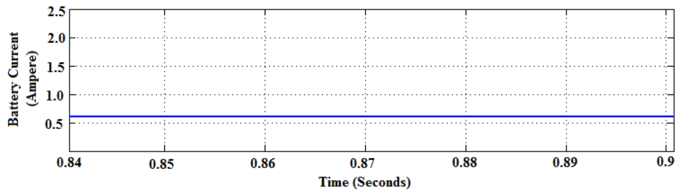


Fig.8. Response of SRG with BESS during dis-charging

5. Implementation of BESS for SRG based Wind Power Conversion System

The complete block diagram of the battery energy storage system for switched reluctance generator based wind power generation system supplying stand alone load is shown in Figure 9. The wind turbine supplies mechanical energy required for SRG. The simulation model of wind turbine is developed and connected to SRG for analysis, where as for the experimental set up wind turbine is emulated by a 12V DC Motor powered by an external DC power supply.

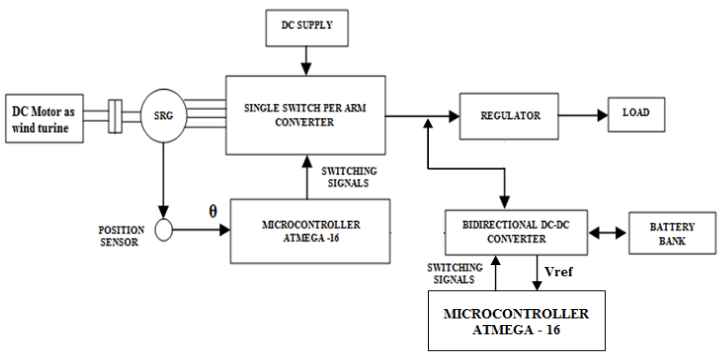


Fig. 9. Block diagram of the BESS for wind powered SRG

The speed of the DC motor is varied by varying the voltage applied to it and it is directly coupled with SRG. For the wind velocity of 10 m/s, the DC motor is supplied with 10V and SRG coupled with it rotates at a speed of 1750 RPM. For the wind velocity of 12 m/s, the DC motor is supplied with 12V and SRG coupled with it rotates at a speed of 1850 RPM.

A 4 phase, 8/6 SRG is used for experimental set-up and its phase windings are excited by single switch per phase converter topology, consisting of four MOSFET (IRF 540) switches. The power converter is supplied by DC power. The DC power required for power converter is obtained by converting single phase AC into DC using rectifier and it is supplied to the power converter through filter. The DC output of the rectifier i.e excitation voltage is controlled by means of auto-transformer.

To get satisfactory closed loop operation of the switched reluctance generator and to produce torque in correct direction, the rotor position information is mandatory and it is sensed by IR sensor which is mounted at rear end of the machine as shown in Figure 10.

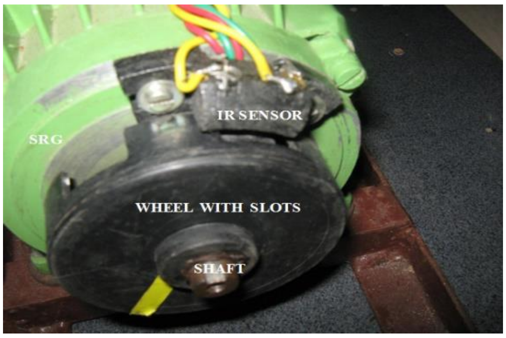


Fig.10. IR Sensor mounting

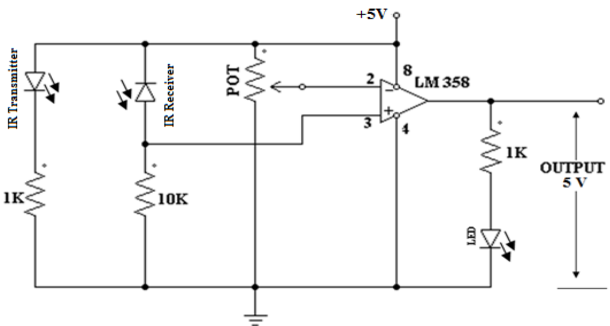


Fig. 11. Signal conditioning circuit for IR sensor

Position information obtained from IR sensor is processed using signal conditioning circuit, before feeding it to the microcontroller. The signal conditioning circuit includes IR sensor as shown in Figure 11. To obtain the rotor position information of SRG, IR sensor1 and 2 are used and the outputs of IR sensors are shown in Figure 12.

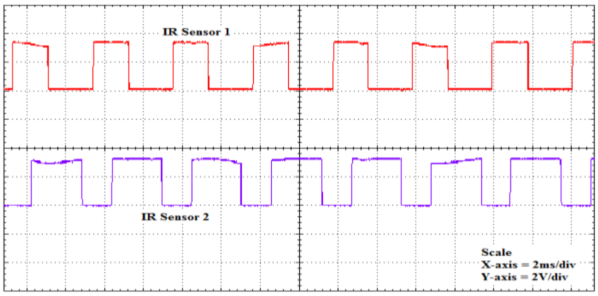


Fig. 12. Rotor position information of SRG from IR sensor1 and IR sensor 2

Output of IR sensor1 and IR sensor2 are applied to ATmega-16 microcontroller to generate switching signals for energizing the phase windings of SRG. Four switching signals are derived based on IR sensor signals for the speed of 1850 RPM as shown in Figure 13.

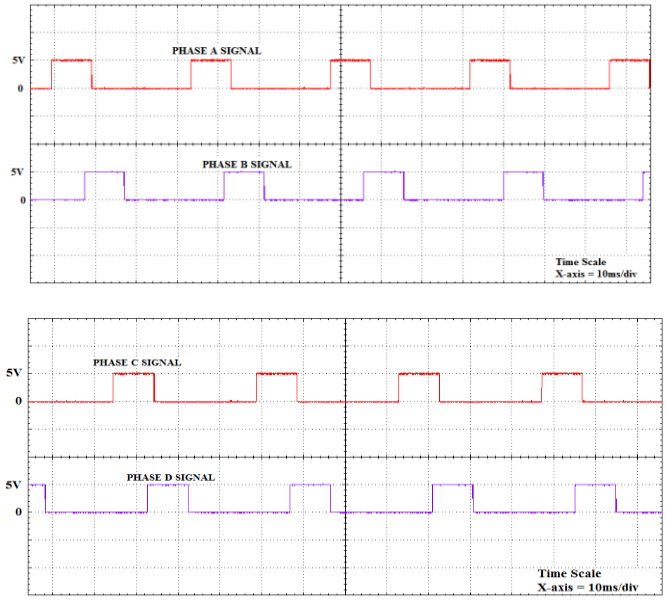


Fig. 13. Switching signal for phase A, Phase B, Phase C and Phase D windings

Sequential excitation of the phase windings causes continuous rotation and the switching pattern for energizing the stator windings of SRG is given in Table 3. Switching signal generated using microcontroller ATmega-16 drives the single switch per phase converter through MOSFET driver circuit and it is shown in Figure 14. Driver circuit consists of bridge rectifier, filter, PC 817 DIP 4pin general purpose photocoupler and IRF 540 MOSFET switch. Photocoupler provides I/O isolation for microcontroller unit and suppresses the noise in the switching circuits.

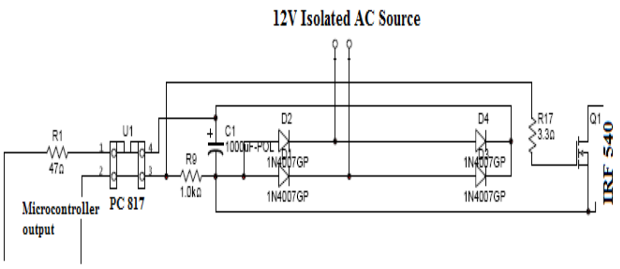


Fig.14. Driver circuit for MOSFET

The opto-coupler used is PC817 which is also known as the interface circuit is mainly used for two purposes: amplification and isolation. The isolation is provided between the control circuit and power switches. Current amplification is required because the microcontroller supplies less than 10 mA which is insufficient for the power circuit as it requires greater than 50 mA. Hence amplification process should be carried out by the interface circuit. The features of PC817 include voltage isolation between input and output.

The complete experimental set-up of SRG based BESS for wind power generation system supplying stand alone load is shown in Figure 15. Wind turbine is emulated by means of 12 V DC motor and it is coupled with SRG. Phase windings of SRG are excited through single switch per phase converter. Output of SRG is also connected to the battery bank through IBDC for achieving bi-directional energy transfer.

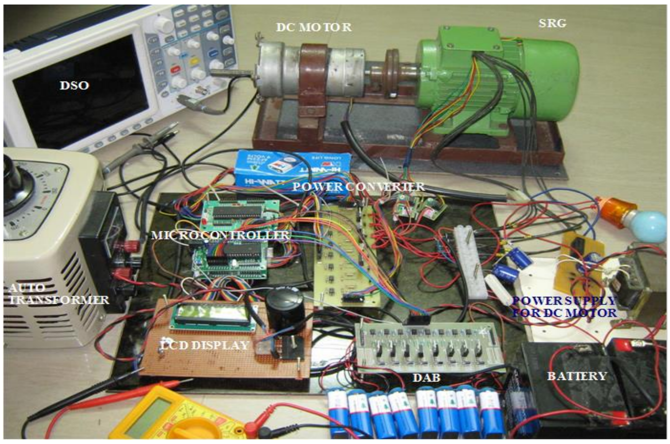
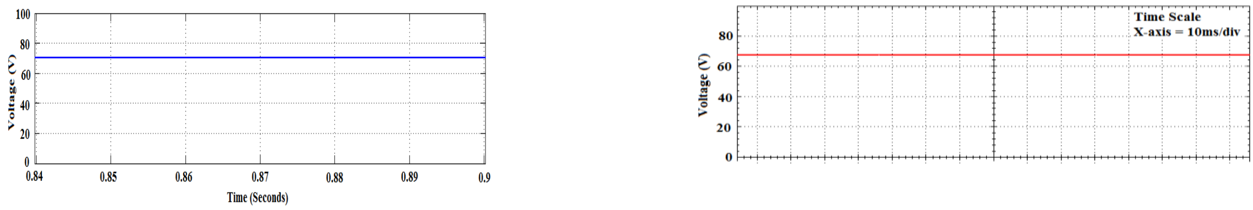
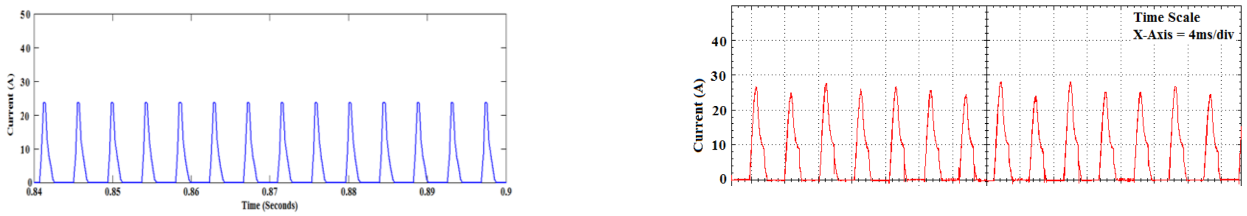


Fig.15. Experimental set-up

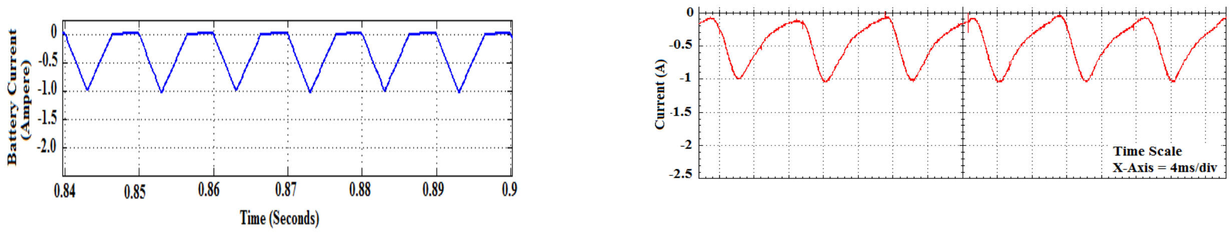
SRG output is also connected to battery bank through IBDC which allows bi-directional energy transfer. During dis-charging mode of operation, the inductor in series with the battery bank is charged by triggering the switches in the same arm and discharged using opposite pair of switches. Response obtained from an experimental set-up is used to validate the simulation results and are shown in Figure16.



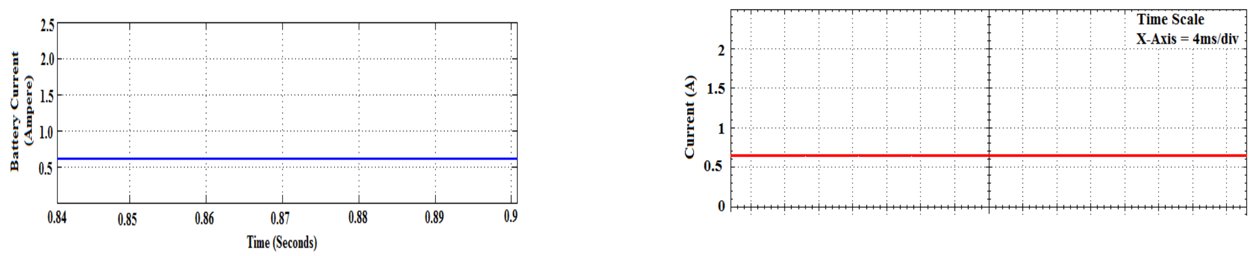
(a) Generated voltage



(b) Phase A current



(c) Battery current during charging



(d) Battery Current during dis-charging

Simulation Results **Experimental Results**

Fig. 16. Comparison of simulation and experimental results

From the comparison, it is found that there is a close match between the experimental and simulation results. The BESS using IBDC for the wind powered SRG gives satisfactory performance in the charging and dis-charging modes.

6. Conclusion

A small power switched reluctance wind energy conversion system supplying stand alone DC load is modelled in the MATLAB/Simulink environment. The wind turbine with HCS MPPT control technique is developed and equation of the optimal line in the wind turbine characteristics to obtain optimum power for different rotor speed is obtained using curve fitting technique. The response of SRG based wind energy conversion system with three different wind speeds is analyzed and the results are reported. The BESS is developed for wind powered SRG using IBDC converter and the performance is analyzed in charging and discharging mode. Further, a microcontroller based BESS for a wind powered SRG system is implemented and validated with simulation results. From the results, it is apparent that the low power switched reluctance wind generation system gives satisfactory performance and therefore, SRG is appropriate wind generator for a small wind electric conversion system.

Table 1 Specifications of SRM

Rated Power	1Hp (746w)
Rated Speed	3000 RPM
Rated Voltage	330 V,DC
Rated Current	5 A
No. of turns per pole	100 turns
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
Stack length	80 mm
Stator pole arc	22 deg
Rotor pole arc	25 deg

Table 2 Switching Pattern for DAB

Converter Number	Converter 2				Converter 1			
Switch Number	Q8	Q7	Q6	Q5	Q4	Q3	Q2	Q1
Charging Mode	0	0	0	0	1	0	0	1
	0	0	0	0	0	1	1	0
Dis-charging Mode	1	1	0	0	0	0	0	0
	1	0	0	1	0	0	0	0
	0	0	1	1	0	0	0	0
	0	1	1	0	0	0	0	0

Table 3 Switching pattern for phase winding excitation

IR Sensor 1	IR Sensor 2	Phase windings			
		D	C	B	A
0	0	1	0	0	0
0	1	0	0	0	1
1	1	0	0	1	0
1	0	0	1	0	0

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