Themed Section : Engineering and Technology
© 2018 IJSRSET | Volume 5 | Issue 3 | Print ISSN: 2395-1990 | Online ISSN : 2394-4099

# Design and Dynamic Analysis of Switched Reluctance Generator System

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## ABSTRACT

This paper discusses the design and dynamic analysis of Switched Reluctance Generator (SRG) system. A 1 Hp, 4 phase, 8/6, SRG machine is modelled in MATLAB/Simulink software, using the torque and flux linkage characteristics obtained from analytical model. Single Switch per Phase Converter (SSPC) with separate source bus and load bus in order to minimize the current drawn from the excitation battery which is used to energize the stator windings of the SRG. The transient response of SRG system is obtained at various load level and the results are reported. The feasibility check is performed on SRG to act as a Wind Generator (WG).

**Keywords:** Switched Reluctance Generator, Single Switch per Phase Converter, Wind Generator

## I. INTRODUCTION

SRM has several merits over conventional machines in both generating mode and motoring mode operations. It is a worth candidate for many industrial applications. Over a long period of time the research was focused on the motoring operation only. As the machine has got reversible power flow tendency, a few scholars took research on generating mode of SRM. This led to an idea that this machine will be good solution for worldwide increase in demand of electrical energy. The problems of the conventionally used generators has changed the researchers attention to the more simple and robust variable speed SRG which exhibits the qualities of a generator [1].

SRG as seen shows a very rugged construction associated with no permanent magnets or conductors in the rotor. The manufacturing of SRG is easy at low price and it possesses the capability of operating at high speed. The torque generated by SRG is not depending upon the current direction and therefore converter allows current in one direction itself enough to operate the machine. The machine accelerates at fast rate due to low inertia of the rotor as the machine and the power converter are very robust [2]. The machine can tolerate faults as the phase windings of SRG are both electrically and magnetically independent from other windings.

Increased use of fossil fuel leads to air contamination, increase in earth atmosphere temperature and there is a necessity to focus on non-conventional resources to minimize these problems. The power generated from wind is one of the available renewable energy power source which also helps in reduction of carbon dioxide emissions to the atmosphere. Generator operates with wind energy input is one of the major component in wind energy conversion system and permanent magnet generator is the widely used one. It needs more torque to run and not advisable to use in high temperature places. Therefore, we emphasize more on SRG as it is simple in structure, tough, highly efficient and easy to use in adverse environments [3]. This article is prepared with the following sections. Section 2 gives steps involved in the modelling of SRG machine. Section 3 briefs the power converter topology and section 4 presents the static and dynamic response of SRG system.

## II. SWITCHED RELUCTANCE GENERATOR

For achieving generator mode operation of the machine, windings are excited as the rotor is moving away from the stator poles, [4].

In generating mode, the SRG generates opposite torque which opposes the movement and extract energy from the prime mover [5]. A controller with rotary position sensor is augmented so that the feedback is utilized to integrate the pulses of stator current and position of the rotor. The cross-sectional view of SRG is shown in Figure 1 and theoretical graphs of various parameters/phase of SRG are shown in Figure 2.

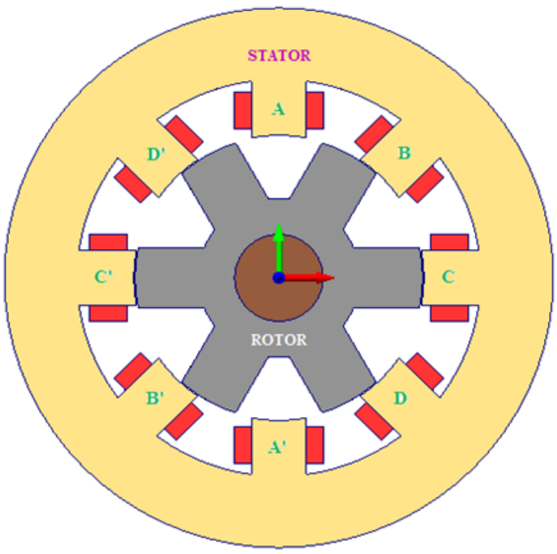



**Figure 1.** Cross-section of 8/6 SRG

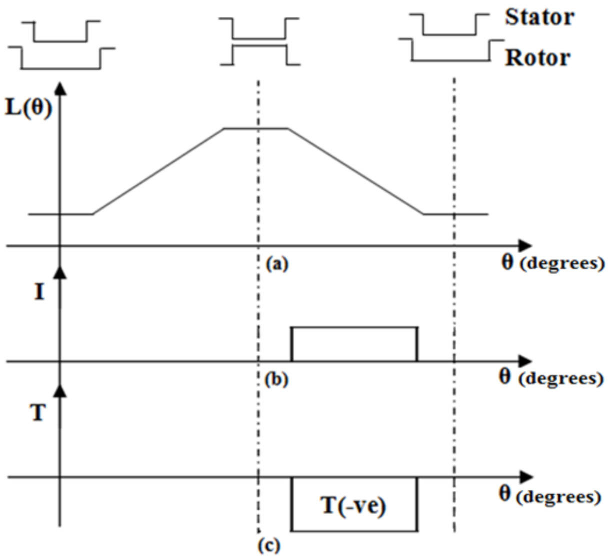



**Figure 2.** (a) Inductance profile (b) Current pulse (c) Torque

Torque is produced by the affinity of the rotor to settle at minimum reluctance position which favors spontaneous magnetization irrespective of current direction. Therefore, the machine contributes flux during excitation and it should be zero before the excitation of incoming phase [6].

Neglecting magnetic saturation, flux linkage is given as

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

The magnetic energy stored (We) or co-energy (Wc) changes with position of rotor to produce torque and it is expressed as

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

The electromagnetic torque is calculated using the equations given below

$$T_e = \left(\frac{\partial W_c(\theta, i)}{\partial \theta}\right)_{i=cons} \tag{3}$$

$$T_e = \frac{1}{2}i^2\frac{dL(\theta)}{d\theta} \tag{4}$$

Where, i = phase current

| | | |
|---|---|---|
| L | = | self-inductance |
| θ | = | position of rotor in radians |
| | = | variation of inductance with rotor position |

It is evident from equation (4) that the mode of operation of the machine is decided by the change in inductance with rotor position.

SRG is basically identified by a nonlinear operation due to saturation of magnetic field. A valid SRG model needs information regarding magnetic characteristics of the machine to determine its electrical and mechanical behaviors. The linked flux of a stator phase and developed torque, are a function of the excitation current (i) and the position of rotor (θ). For study purpose, amidst the availability of various numerical methods, FEA is the most often used method for study of electromagnetic field, [11]. This work employs MagNet 7.1.1 to develop FEA model.

Net torque developed in a SRG is a result of summation of torque produced in individual phases and is obtained as

$$T_{e(Total)} = \sum_{n=1}^{m} T_n(i,\theta) \qquad (5)$$

The dynamic mechanical analysis of the system is yields us with

$$T_e = T_L + B\omega + J\frac{d\omega}{dt} \qquad (6)$$

| | | |
|---|---|---|
| Where Te | = | electromagnetic torque (N-m) |
| TL | = | applied mechanical torque (N-m) |
| ω | = | angular speed (rad/sec) |
| J | = | moment of inertia (Kg/m2) |
| B | = | Viscous friction co-efficient (N-m/rad/sec) |

Angular speed is computed from equation (7) and it is expressed as

$$\omega = \frac{1}{J}\int (T - T_L - B\omega)dt \qquad (7)$$

Rotor position is obtained by integrating the angular speed and it is given as

$$\theta = \int \omega dt \qquad (8)$$

Equation (8) is elucidated to get speed information and rotor position and the corresponding model is shown in Figure 3.

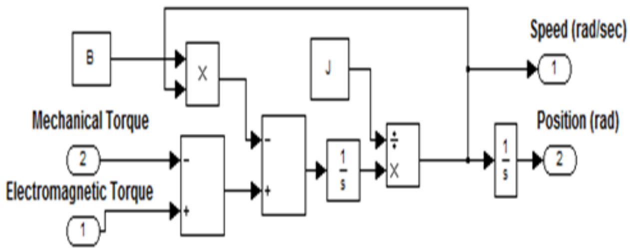



**Figure 3.** The dynamic model of machine

Equivalent electrical circuit of the stator windings SRG is shown in Figure 4.

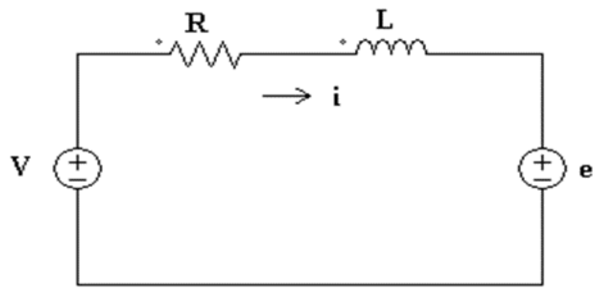



**Figure 4.** Electrical equivalent of the phase winding

On applying KVL, A differential equation is obtained which depends upon phase voltage v (t) given as

$$v = iR + \frac{d\psi(i,\theta)}{dt} \qquad (9)$$

| | | |
|---|---|---|
| Where v | | - DC source voltage |
| ψ | | - Flux linkage |
| R | | - Resistance of the phase winding |

The flux linkage ψ, depends on of phase current (i) and position of rotor (θ). The phase winding resistance R has to be considered for low speed operations.

The flux linkage (ψ) depends on current (i) and position of rotor (θ) [7], therefore the voltage equation can be rewritten as

$$v = iR + L\frac{di}{dt} + iw\frac{dL}{dq} \qquad (10)$$

The current is calculated from the voltage drop across the inductor and it is given as

$$V_L = L\frac{di}{dt} \qquad (11)$$

The incremental inductance is modelled as controlled current source. The sub system, which implements the current calculation, is shown in Figure 5.

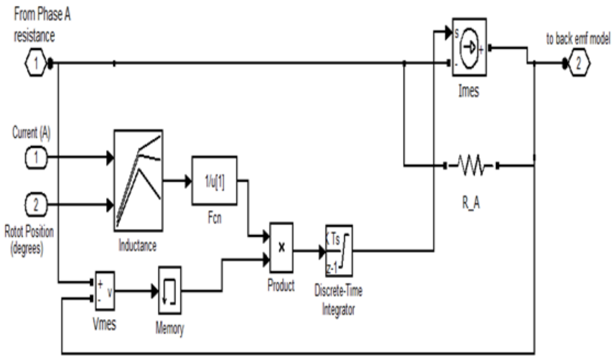



**Figure 5.** The model for the incremental inductance

The controlled voltage source is used to represent the back emf. The subsystem for back emf computation is presented in Figure 6.

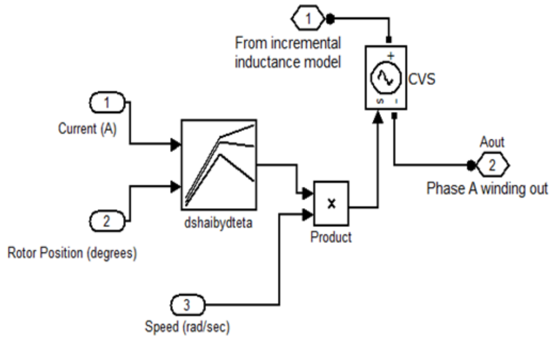



**Figure 6.** The back EMF model

The MATLAB/Simulink model of the terminal voltage expression is shown in Figure 7.

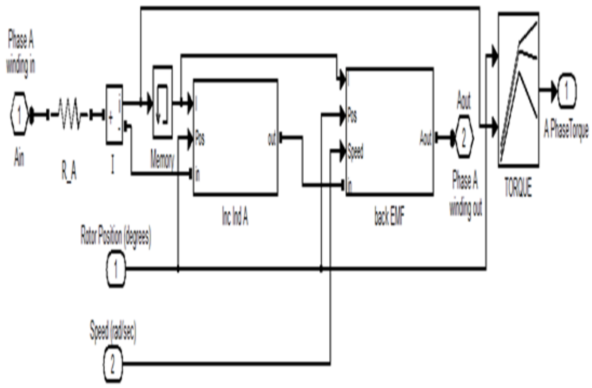



**Figure 7.** Simulink model of the phase voltage equation

The complete simulation model of SRG in the MATLAB/Simulink environment is shown in Figure 8. Stator windings of SRG are energized in a sequential fashion and the torque developed by the individual phases are integrated to obtain the total torque (T) produced by the machine [8]. Dynamic mechanical analysis yields a equation, which is solved in the mechanical block to obtain speed and position of rotor.

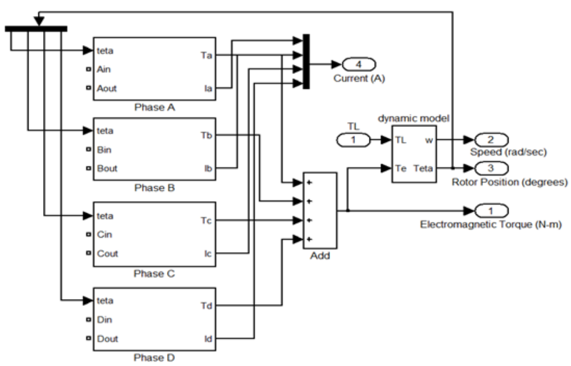



**Figure 8.** MATLAB/Simulink model of SRG

## III. SINGLE SWITCH PER PHASE CONVERTER

Switched reluctance machines belong to a group which are obviously called as electronically commutated machine. It means that they are not able to operate on a rigid grid with a constant voltage and frequency, but they need the cooperation of converters. Therefore, it is very important to investigate how a converter topology influences the performances of this machine operation, [9]. The excitation period shown in Fig. 9 is between the θon and θoff, during which the phase winding is excited from a DC source or from a capacitor. Then there is a generation period, between θoff and θext, during which the electrical energy is generated and delivered to the load, [10]. Therefore, the values of θon, θoff and θext are very important variables affecting the output parameters of SRG.

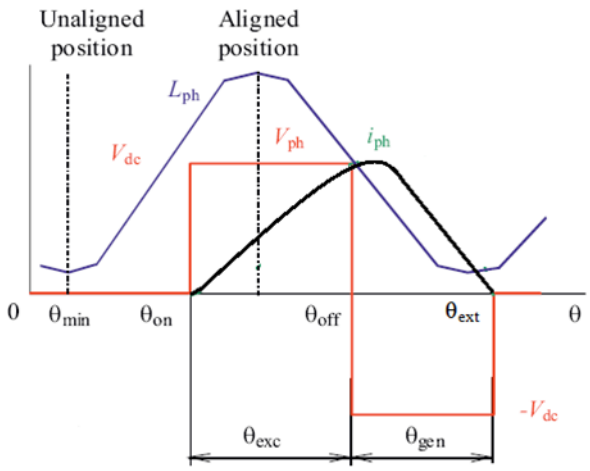



**Figure 9.** θon, θoff and θext variables of SRG

In order to reduce the number of devices, single switch per phase converter is used. Dedicated buses are made available for the source and load which are used to prevent absorption of high magnitude of current from the battery which is used for excitation. This converter allows feeding of the load from the grid even when SRG is not running. This is good for an unstable renewable complementary power source like wind power. Fig. 10 illustrates a circuit configuration of the single switch per phase converter.

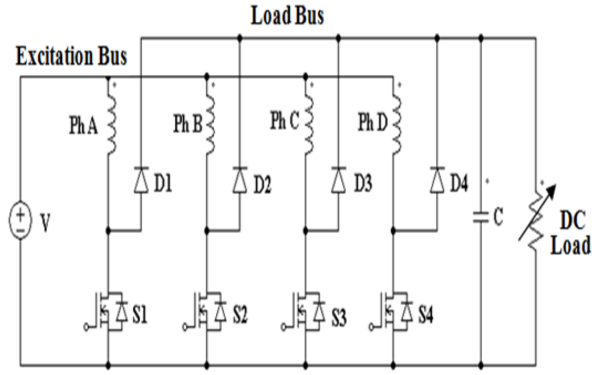



**Figure 10.** Single switch per phase converter for SRG

During excitation period of a phase, switch S1 connects the DC excitation bus to the winding to increase the phase current. During generation, the switch S1 is OFF. The energy in the winding is delivered to the load through the diode D1. It is clear from the circuit that the applied voltage is in series with the electromotive force.

## IV. ANALYSIS OF SRG SYSTEM

SRG system normally comprises of three main components: SR machine, converter and controller. SRG and single switch per phase converter discussed in the previous section are integrated together toobtain SRG system. The complete block diagram of SRG system is shown in Fig. 11.

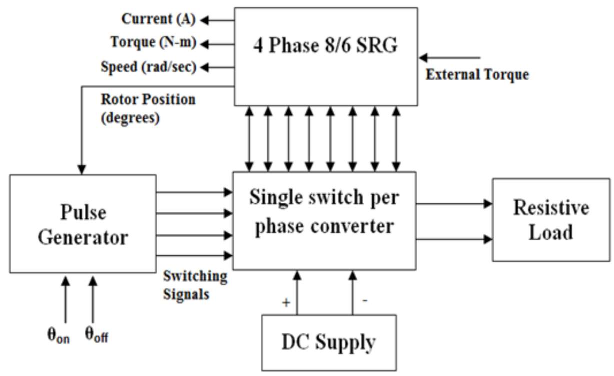



**Figure 11.** Block diagram of SRG System

The stator windings of SRG are energized using SSPC topology powered by DC supply. The required external torque for SRG is supplied manually to analyze the performance of SRG. For SRG based Wind Energy Conversion System (WECS), the torque is supplied by the wind turbine. The output of SRG is supplied to the stand alone load. The MATLAB/Simulink model of SRG system is shown in Fig. 12.

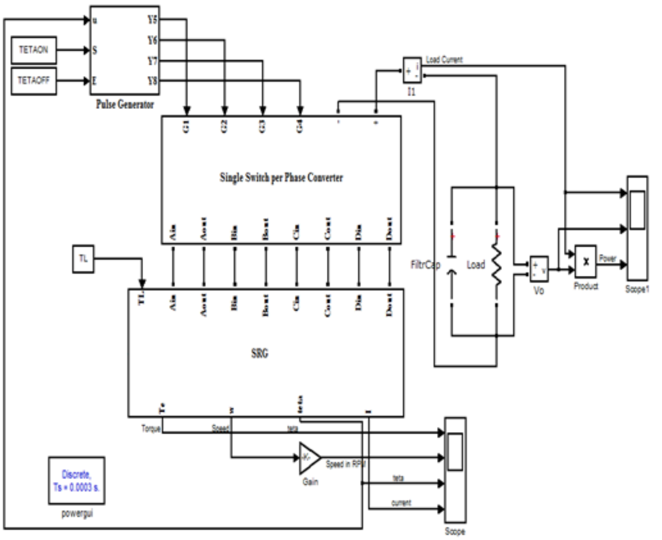
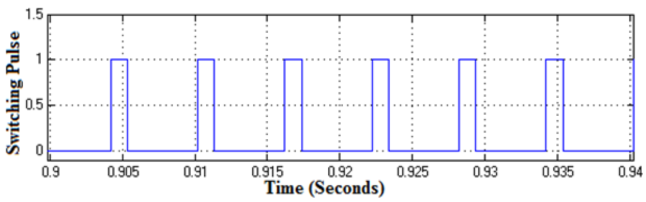


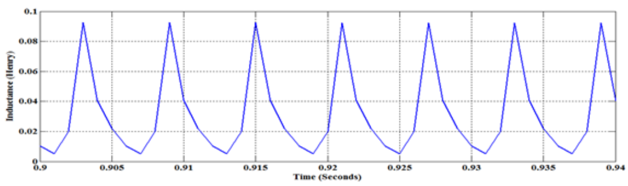

**Figure 12.** MATLAB/Simulink model of SRG system

The θon, θoff, converter input voltage and torque supplied to the generator are the operating variables of SRG. The steady state response of SRG drive system for the turn-on angle of 15° and turn-off angle of 27° are shown in Fig. 13.

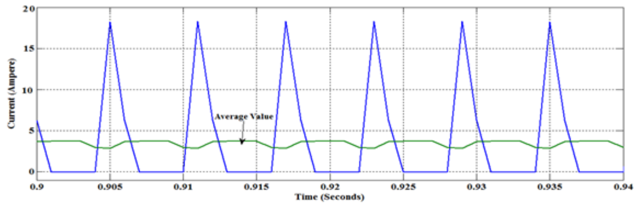
From Fig. 13 (b & c) it is clear that phase current is aligned with the decreasing inductance slope and SRG contributes negative torque as shown in Fig. 13 (d). Therefore, the placement of turn-on angle is very important for the operation of SRG. The speed of SRG is shown in Fig. 13 (e).



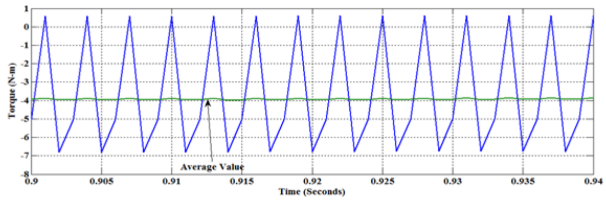

(a) Switching Pulse



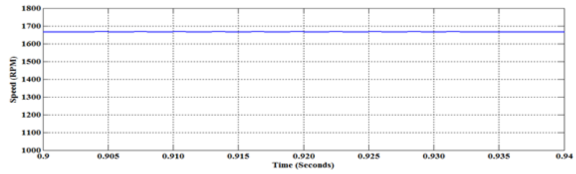

(b) Phase Inductance




(c) Phase Current



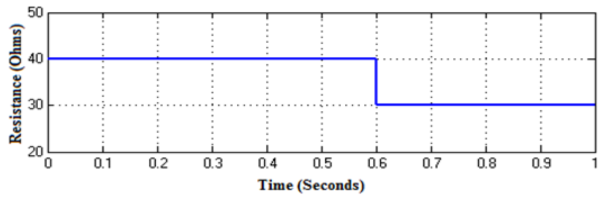

(d) Torque



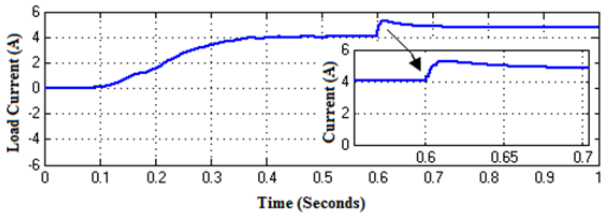

(e) Speed

**Figure 13.** Steady state response of SRG drive system for turn-on angle of 15°, turn-off angle of 27°

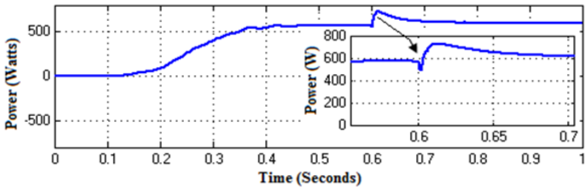
Output power of SRG is supplied to the stand alone resistive load. The transient response of SRG system is analyzed by changing the load resistance from 40Ω to 30Ω. The corresponding change in load current and power consumed by the load are shown in Fig. 14.




(a) Load Resistance




(b) Load Current




(c) Load Power

Fig. 14: Transient response of SRG system for the change in RL from 40 Ω to 30Ω

When load is increased, there is an increase in load current, decrease in terminal voltage and in turn increase in output power. The rated current of SRG is 5A and the machine is loaded till 4.77 A to calculate the efficiency and it is given below.

Mechanical power input

$$P_{in} = T_L \frac{2pN}{60} \qquad (12)$$

For TL = 4N-m and speed N = 1660RPM
Pin = 694.98 watts

Electrical power output $P_{out} = V_L I_L$ (13)

The measured current and voltage are IL=4.77A, VL=125V
Pout = 596.25 watts
Percentage efficiency =85.79%

From the response of SRG system, it is clear that the switched reluctance machine gives reasonable performance in the generating mode of operation.

## V. CONCLUSION

A 1 Hp, 4 phase, 8/6, machine model of SRG is developed in the MATLAB/Simulink software using the torque and flux linkage characteristics obtained from analytical model. To minimize the current drawn from the excitation battery, Single switch per phase converter has dedicated buses for source and load. This converter allows the grid to feed the load even when SRG not in operation. This is suitable for unstable renewable complementary power source like wind power. Therefore, it is found that single switch per phase converter is suitable for SRG operation. Finally, single switch per phase converter is integrated with SRG machine model and analyzed the performance of SRG system. The generating mode operation is achieved by exciting the phase winding when the rotor leaves aligned position. From the results it is clear that, phase current is aligned with the decreasing inductance region and SRG produces negative torque to extract power from the prime mover. The transient response of SRG system is analyzed by changing the load resistance from 40Ω to 30Ω and the results are reported. From the steady state and transient response of SRG system, it is found that SRG gives satisfactory performance as a generator and found suitable to act as a wind generator.

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