

## **Modeling and Control of a Permanent Magnet Synchronous Generator Wind Turbine with Energy Storage**

**K. Uday Kumar Reddy<sup>1</sup>, M. Ramasekhara Reddy<sup>2</sup>, Dr. M. Vijaya Kumar<sup>3</sup>**

<sup>1</sup>(M. Tech, Department of Electrical & Electronics Engg, JNTUACE, Pulivendula, A.P, India.)

<sup>2</sup>(Assistant Professor, Department of Electrical & Electronics Engg, JNTUACE, Pulivendula, A.P, India.)

<sup>3</sup>(Professor, Department of Electrical & Electronics Engg, JNTUACE, Anantapur, A.P, India.)

### **ABSTRACT**

Wind energy is an important renewable source which is used for power generation for a stand-alone as well as grid connected applications. In many remote areas, loads are usually connected away from the grid. In such cases, isolated wind energy systems can be considered as an effective way to provide continuous power to electrical loads. The power conversion unit features a wind-turbine-driven PMSG, a diode rectifier, a buck converter, a battery bank, a feed-back controller, and a dc/ac inverter. In this paper, an isolated wind energy conversion system is implemented using a variable speed permanent magnet synchronous generator (PMSG) with PWM rectifier and a battery for storing the excess amount of wind energy. To change the duty cycle of the converter, a controller of DC-DC buck converter with MOSFET as a switching component is designed using P, PI and PID controller to provide the efficient choice for the selection of the controller. The proposed scheme is implemented in MATLAB using Simulink & the simulation results show that the output voltage of the converter can be controlled according to the value of duty cycle and the excess power is stored in battery to provide balance between the generator and the load.

**Keywords:** Wind energy conversion system, battery bank, Permanent magnet synchronous generator, isolated system.

### **1. Introduction**

Renewable sources of energy mainly including wind power offer a feasible solution to distributed power generation for isolated communities where grids are unavailable. At present scenario wind power has emerged as the most viable source of electric power is economically competitive with the non-renewable sources of energy. In such cases, isolated wind energy systems can be considered as an effective way to provide continuous power to electrical loads. One of the most promising applications of renewable energy generation lies in the development of power supply systems for remote villages that lack an economically feasible means of connecting to the main electrical grid. For the type of loads located far from a utility grid, one practical

approach to self-sufficient power generation involves using a wind-turbine with a storage mechanism to create a stand-alone system. If wind conditions are favorable, these stand-alone wind energy systems usually can provide communities with electricity at the lowest cost. Stand-alone wind energy systems often include batteries, because the available wind does not always produce the required quantities of power. If wind power exceeds the load demand, the surplus energy can be stored in storage systems like batteries [1-3]. Multiple types of generators are being used with wind turbines. Small wind turbines are equipped with DC generators of up to a fractional kilowatt in capacity [6]. The major types of AC generators that are possible candidates in wind turbine systems are as follows:

- Squirrel-Cage rotor Induction Generator (SCIG),
- Wound-Rotor Induction Generator (WRIG),
- Doubly-Fed Induction Generator (DFIG)
- Synchronous Generator (With external field excitation),
- Permanent Magnet Synchronous Generator (PMSG).

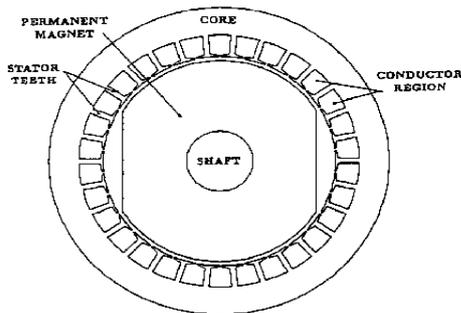
An induction generator (IG) has been extensively used in commercial wind turbine units. Asynchronous operation of induction generators is considered an advantage for application in wind turbine systems, because it provides some degree of flexibility when the wind speed is fluctuating or variable [5-6]. The induction generator based on Squirrel-Cage rotor (SCIG) is a very popular machine because of its low cost, mechanical simplicity, robust structure, and resistance against disturbance and vibration. The induction generator based on wound rotor is the doubly fed induction generator (DFIG), which is a kind of induction machine in which both the stator windings and the rotor windings are connected to the source [7-8].

Another type of generator that has been proposed for wind turbines in several research articles is synchronous generator. This type of generator has the capability of direct connection (direct-drive) to wind turbines, with no gearbox [12]. This advantage is favorable with respect to lifetime and maintenance. Synchronous machines can use either electrically excited or permanent magnet (PM) rotor. The PM and electrically-excited synchronous generators differ from the induction generator in that the magnetization is provided by a Permanent

Magnet pole system or a dc supply on the rotor, featuring providing self-excitation property. Self-excitation allows operation at high power factors and high efficiencies for the PMSG [13]. A comparison between the variable speed wind turbine and the constant speed wind turbine shows that variable speed reduce mechanical stresses, gusts of wind can be absorbed, dynamically compensate for torque and power pulsations caused by back pressure of the tower. This backpressure causes noticeable torque pulsations at a rate equal to the turbine rotor speed times the number of rotor blades [3-8].

## 2. Permanent Magnet Generator

Figure 1 shows the cross-section of a typical Permanent Magnet Generator (PMG). The loss free excitation provided by permanent magnet therefore increases in relative value as the machine size is decreased.



**Fig.1** Cross-section of typical conventional Permanent Magnet Generator

The main features of the permanent magnet synchronous machine are as follows:

1. Robust, compact and less weight.
2. Copper loss due to the current flow which is the largest loss in case of induction machine is approximately half that of induction motor.
3. High efficiency in case of permanent magnet synchronous machine compared to induction machine.

The merits of permanent-magnet synchronous machines [6-8] over electrically excited machines [14] can be as follows:

1. No additional power supply for the magnet field excitation,
2. No sliding contacts, so it requires less maintenance.
3. Higher reliability due to the absence of mechanical components like slip rings.
4. No field winding, no field copper loss.

The demerits of PMSM are as follows:

1. The power factor of operation cannot be controlled due to the absence of the field winding,
2. Demagnetization of PM at high temperature.

In recent years, the use of PMs is more attractive than before [14], because the performance of PMs is improving and the cost of PM is decreasing. The permanent magnet synchronous machines can be majorly applied in direct-drive traction motors. Due to

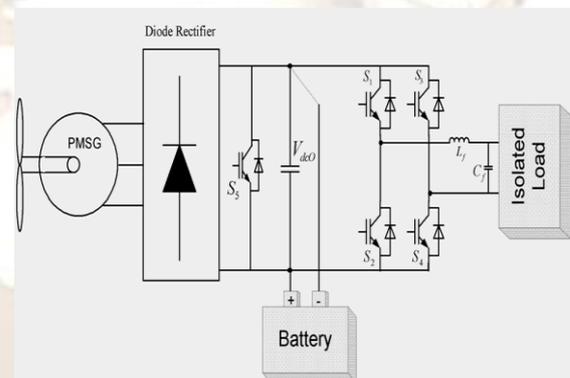
the natural laws of electromagnetic scaling, there is an excitation penalty involved in small PM machines.

As the geometrical size is decreased, the cross-sectional area available for copper conductor decreases with the square of the linear dimensions. The need for the magneto-motive force decreases with the linear dimension, being primarily determined by the length of the air-gap [14]. During the high temperatures, the current may be sufficient enough to demagnetize the magnets providing excitation.

## 3. Topologies for isolated operation of a variable speed wind driven PMSG

Variable speed use is good for extracting more prime mover power as in wind turbine or for providing optimum efficiency for the prime mover by increasing its speed with power. Variable speed also allows for a more flexible generator system. For wind turbines, a battery may be added to store the extra wind energy that is not momentarily needed for the existing loads or local power grids [10-11].

At variable speed, the DC link voltage is maintained constant by exchanging power with the storage device, battery as shown in Fig. 2.



**Fig.2** PMSG with PWM rectifier with battery for storing the extra wind energy

## 4. Modeling of proposed system

### 4.1. Modeling of System

This section includes modeling of supply system (PMSG), load, controller etc. The relevant mathematical analysis is illustrated as follows.

### 4.2. Modeling of Permanent Magnet Synchronous Machine.

The permanent magnet synchronous machine block operates in generating or motoring modes. The operating mode is dictated by the sign of the mechanical power (positive for generating, negative for motoring). The electrical part of the machine is represented by a sixth-order state-space model [15]. The model takes into account the dynamics of the stator and damper windings.

The equivalent frame (d-q frame) is used for developing the equations for the model of the PMSG. The following equations are used to express the

model of the PMSG as:

$$V_d = R_s i_d + p\phi_d - w_r \phi_q \quad (1)$$

$$V_q = R_s i_q + p\phi_q + w_r \phi_d \quad (2)$$

$$V'_{fd} = R'_{fd} i'_{fd} + p\phi'_{fd} \quad (3)$$

$$V'_{kd} = R'_{kd} i'_{kd} + p\phi'_{kd} \quad (4)$$

$$V'_{kq1} = R'_{kq1} i'_{kq1} + p\phi'_{kq1} \quad (5)$$

$$V'_{kq2} = R'_{kq2} i'_{kq2} + p\phi'_{kq2} \quad (6)$$

$$\phi_d = L_d i_d + L_{md} (i'_{fd} + i'_{kd}) \quad (7)$$

$$\phi_q = L_q i_q + L_{mq} i'_{kq} \quad (8)$$

$$\phi'_{fd} = L'_{fd} i'_{fd} + L_{md} (i_d + i'_{kd}) \quad (9)$$

$$\phi'_{kd} = L'_{kd} i'_{kd} + L_{md} (i_d + i'_{fd}) \quad (10)$$

$$\phi'_{kq2} = L'_{kq2} i'_{kq2} + L_{mq} i_q \quad (11)$$

Where the subscripts used are defined as: d, q: d and q axis quantity, r, s: Rotor and stator quantity, l, m: Leakage and magnetizing inductance, f, k: Field and damper winding quantity.  $R_s$  represents stator resistance,  $L_{ls}$  stator leakage inductance,  $L_{md}$  and  $L_{mq}$  represent d-axis and q-axis magnetizing inductances.  $R'_f$  denotes field resistance and  $L'_{fd}$  leakage inductance both referred to the stator. Damper d-axis resistance  $R'_{kd}$  and leakage inductance  $L'_{kd}$ , Damper q-axis resistance  $R'_{kq1}$  and leakage inductance  $L'_{kq1}$  and the q-axis resistance  $R'_{kq2}$  and leakage inductance  $L'_{kq2}$ . All these values are referred to the stator. All rotor parameters and electrical quantities are viewed from the stator and are identified by primed variables. The simplified synchronous machine block implements the mechanical system described by:

$$\Delta w(t) = \int (T_m - T_e) dt / (2H) - K_d \Delta w(t) \quad (12)$$

$$w(t) = \Delta w(t) + w_0 \quad (13)$$

### 4.3. Modeling of Supply system

The supply system consists of three-phase (PMSG) system, diesel engine and governor blocks. The model of Permanent magnet synchronous generator (PMSG) is realized by considering fixed excitation of an alternator. The mathematical representation of all these are given above.

### 4.4. Design of a P, PI & PID controller

To change the duty cycle of the converter the constants involving in P, PI and PID controller can be calculated separately by using a suitable trial and error technique. The controllers are used for providing suitable signals for DC-DC buck converter is designed.

### 4.5. Wind Turbine Modeling

This block implements a wind energy conversion system. The inputs are actual and desired speed and the output of the block is mechanical power ( $P_{\omega}$ ) [14]. The amount of power harnessed from the wind of velocity  $v$  is as follows.

$$P = 0.5 \rho A C v^3 \quad (14)$$

Where

$P_{\omega}$  = wind power in watts

$\rho$  = air density in  $kg/m^3$

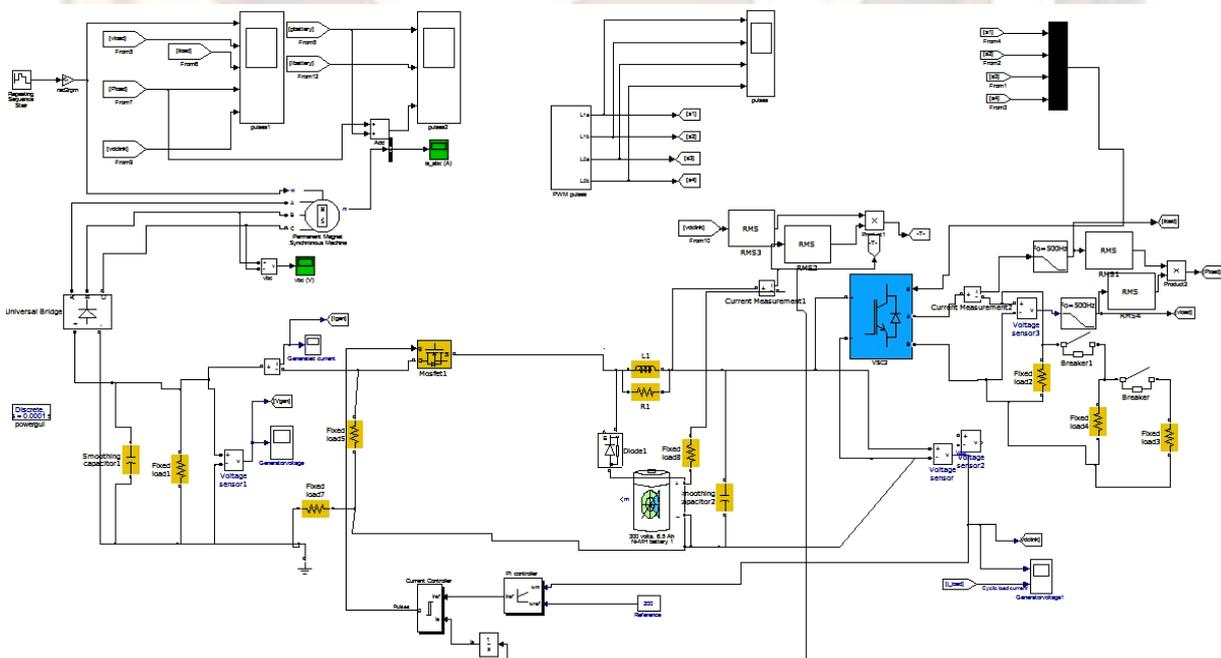
$A$  = swept area in  $m^2$

$C_p$  = power coefficient of wind turbine

$v$  = wind speed in m/s

### 5. Matlab Simulation model of the proposed topology

The MATLAB Simulation of proposed topology [9] has been shown in the Fig.2. The matlab Simulink tool box simpower has been used for getting the required results



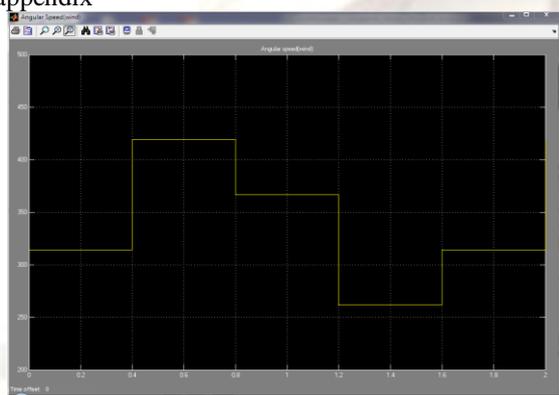
**Fig. 3.** MATLAB Simulated model of PMSG connected to local Load

**6. Simulation Results**

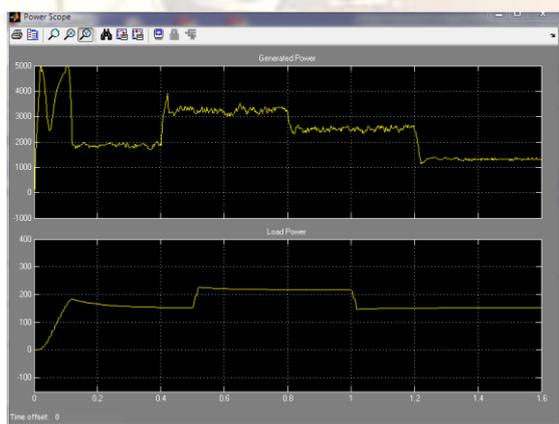
The MATLAB Simulation of proposed topology has been shown in the Fig.3. The MATLAB Simulink tool box Simpower System has been used for getting the required results.

6.1 Performance of PMSG with PWM rectifier with battery for storing the extra wind energy:

The wind driven PMSG is run at 300 rpm. The output voltage is 200 V at 60 hertz. This variable voltage and variable frequency output is converted to constant voltage and constant frequency source. The Fig.4 to 8 shows the Variation of speed for the wind Turbine, Variation of load power, generated power, battery power, battery current & d c-link voltage using P, PI and PID controllers. The rating of the PMSG is given in the appendix

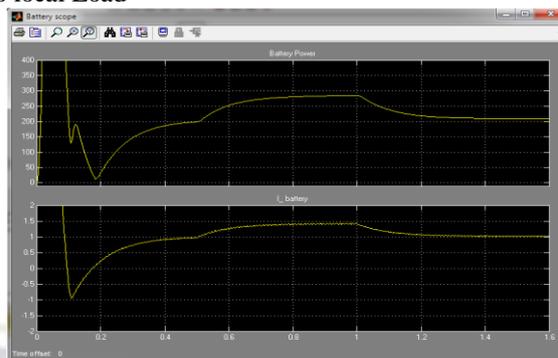


**Fig.4.** Variation of Speed for the wind turbine

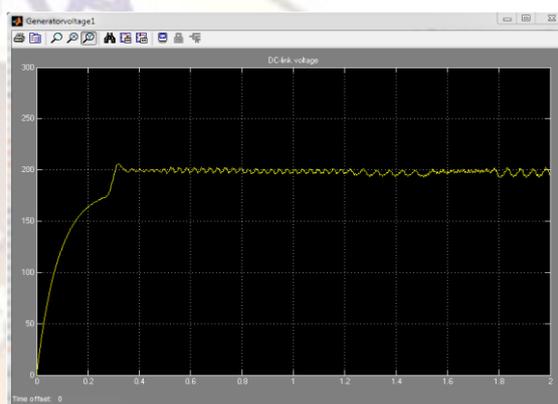


**Fig.5.** Variation of Generated power and Load side power

The load perbutations are made to occur at  $t=0.5$  sec and there is a sudden increase in the level of load side current to 3 amps which draws more current from the generator. After certain period,  $t=1$  sec the current in the load side again reaches to 2 amps. The sudden increase in the current implies that the more current is drawn from the generator and the system balance is obtained by suitable battery energy storage systems.

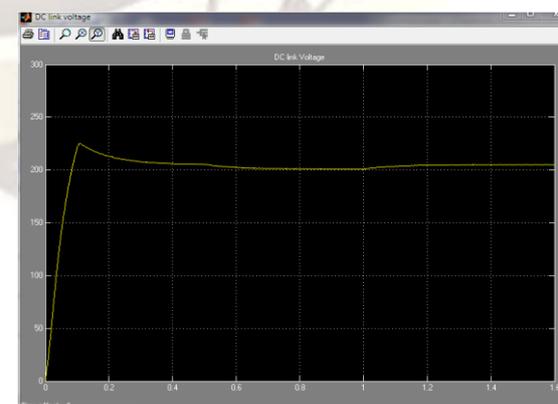


**Fig.6.** Variation of battery power and battery current

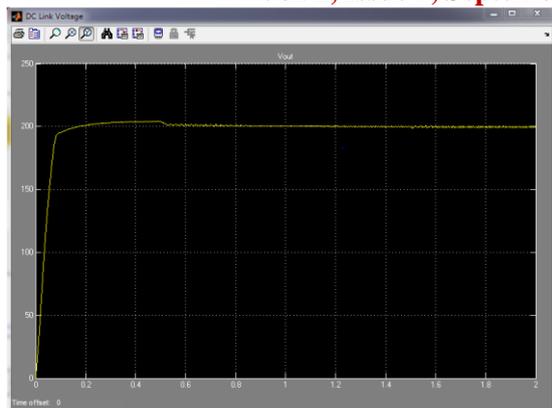


**Fig.7.** Variation of DC-link voltage using a P-controller

The change in the level of power varies with respect to the change in load demand. The maximum power generated at the rotor-side of PMSG is 3200 watts and later the change in the level of generated power varies with respect to the variation in load demand at different time instants. The battery energy storage mechanism used in the system regulates the system from severe imbalances by exchanging the energy from generator and the battery. The response of dc-link voltage using a proportional-controller is shown in fig. 7. In fig. 7 though the peak –overshoot is less but the output oscillates around 200 volts.



**Fig.8.** Variation of DC-link voltage using a PI controller



**Fig.9.** Variation of DC-link voltage using a PID controller

The PI-controller offsets or eliminates the steady state oscillations that are occurred using a proportional-controller and the system stability is improved as shown in fig.8. In fig.9, the output voltage using PID controller got changed by reducing the peak-overshoot & the time of response got decreased to a certain extent. Hence for economical savings; PID controller serves better purpose apart from the other controllers proposed in this design. So, PID controller serves the efficient choice for the selection of the controller.

### 7. Conclusion

In the proposed scheme, battery energy storage system provides power balance between the generated power and the load. The power mismatch is absorbed by the BESS. From the obtained results it is clearly observed that the oscillations free output can be obtained by using a PID-controller and PID-controller improves the stability of the system and hence is the best choice for the selection of the controller.

### APPENDIX

#### Permanent Magnet Synchronous Generator:

3-Phase, 300 V, 60 Hz, 3000 rpm, 4-pole  
 Electromagnetic Torque : 0.8 Nm  
 Stator Resistance (RS) : 18.7  $\Omega$   
 Inductance: Ld (H) = Lq(H) : 0.02682 H  
 Flux induced by magnets : 0.1717 Wb.

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