Modelling And Performance Analysis of A Wind/Diesel Hybrid Power System

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Abstract— **Domestic consumers in the remote places who are not connected by the main electrical grid network, hybrid systems such as wind/diesel generators have been considered as the most reliable, preferred and attractive alternative source of power supply. This paper presents the modeling and performance analysis of wind/diesel hybrid generating system. To regulate the frequency and voltage output of the wind generator, an AC-DC-AC scheme using SPWM technique is employed. The system is simulated for different wind speed and load conditions using EMTDC/PSCAD software.**

Keywords- *wind energy, diesel generator, hybrid system,SPWM, EMTDC/PSCAD*

I. INTRODUCTION

In numerous remote and rural areas in the world, a noteworthy number of domestic consumers, farms and small businesses are not connected to a main electrical grid system. Since the remote areas are normally not connected to the grid supply, their usual method of electricity generation is diesel generating sets. These have the advantage of being able to deliver the required power whenever it is necessary. However, they also suffer from a number of drawbacks. Diesel generator engines are inherently noisy and expensive to run, especially for consumers in rural areas where fuel delivery costs may be high. In addition, small consumers always have a low load factor; this in turn reduces the overall efficiency and increases percentage maintenance costs.

However, many places which require remote power are in regions of high wind energy potential. Wind energy is one of the most important and promising forms of renewable energy sources. Its use is becoming more and more popular nowadays. This is because the price of fossil fuels is continuously increasing and because this source is a clean and inexhaustible energy source. But due to great variation in wind speed which occurs from season to season, it can not be used as an autonomous source of generation. Hence, it is necessary to explore possibilities of combining a wind generator with the diesel generators in order to reduce the running cost per kWh and to increase the reliability of power supply.

In this regard, this paper presents the modeling of a hybrid wind/diesel energy conversion system. Self excited induction generator (SEIG) is used for the wind energy conversion. As the frequency and voltage output of the wind generator is unregulated, an AC-DC-AC scheme employing sinusoidal pulse width modulation (SPWM) technique is implemented. Here the main emphasis is given to reduce the THD of the voltage output of the inverter before feeding it to load. The whole system tested for different wind speed variations and load conditions using PSCAD/EMTDC software.

II. WIND/DIESEL COMPONENT MODELLING

The wind/diesel system of interest to be modelled is shown in Fig.1 in block diagram. It is indicated by arrows, that both the wind turbine and the diesel generator modules generate power, whereas the fixed, varying and dump load consume the power. The controller interprets data input from the wind turbine, diesel generator and fixed and varying loads and tries to determine the most efficient operation mode of the system by controlling the diesel generator's power output and the dump load.

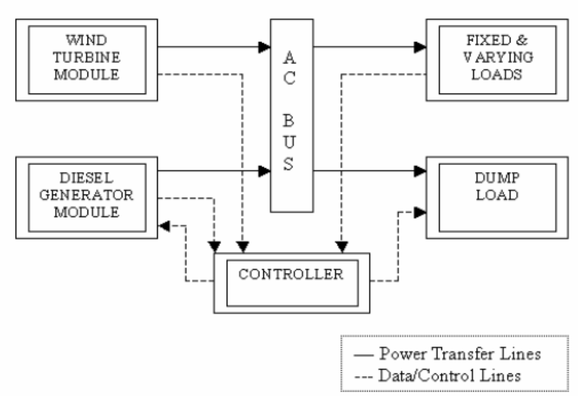

Figure 1. Complete Wind/Diesel Hybrid System

III. SYSTEM MODELING

A. Wind Turbine Model

The mechanical power *(P_{wt})* extracted from the wind is mainly governed by three quantities namely, the area swept by rotor blades *(A_w)*, the upstream wind velocity *(V_w)* and rotor power co-efficient *(C_p)* [1].

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$$P_{wt}=\frac{1}{2}*\rho*A_w*V_w^3*C_p(\lambda,\beta) \quad (1)$$

Cp, the power coefficient of rotor, itself is a function of tip speed ratio (λ) and pitch angle (β). The wind turbine considered in this paper is 'stall controlled'. So, β is kept out of (1) and Cp is function of λ only.

To represent the wind turbine, the power curve of a 250kw stall regulated wind turbine was used. The manufacturer's turbine specification sheet included the wind speed vs. the power output curve. The data provided by the manufacturer takes in to account the losses in the connection of the rotor, generator gear box and mechanical shaft.

Upon implementing the data, of input wind speed and output electric power to MATLAB Polynomial Curve Fitting, the coefficients of a polynomial that fits the set of data in a least-square sense was found.

$$P_{wt}=43.3248-36.7960*V_w+8.7519*V_w^2-0.4778*V_w^3+0.0080*V_w^4 \quad (2)$$

Using PSCAD/EMTDC software, (2) is modeled as a wind turbine. From the constructed circuit, the output power with respect to wind speed curve is obtained. Figure 2 shows power curve of 250 kW modeled wind turbine. Cut-in wind speed of 3 m/sec and cut-out wind speed of 25 m/sec and power output of 250kw at 25m/sec are shown in Fig. 2.

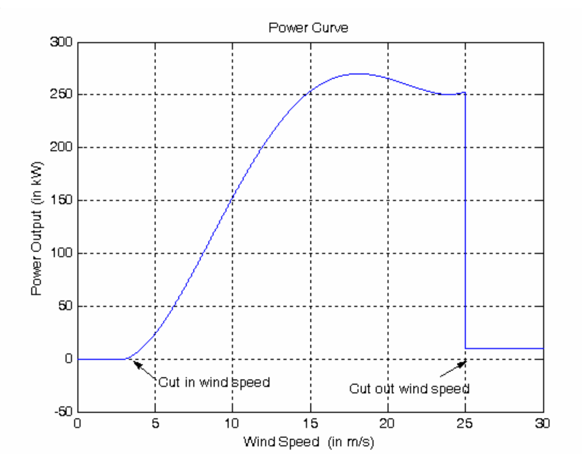

Figure 2. Power Curve of 250kW Wind Turbine

B. *Generator Model*

Induction generators are very popular in wind turbine applications. They are reliable, well developed and resilient. Additionally, induction generators are loosely coupled devices, i.e. they are heavily damped and therefore have the ability to absorb slight changes in rotor speed whilst remaining connected to the grid.

The operation of the induction machine will be determined from the sign of the electromagnetic torque and the slip, that is negative torque and slip correspond to generator operation whereas positive torque and slip correspond to motor operation.

In order to model the induction machine, the d-q equivalent circuit of induction machine is obtained. The direct-axis is assumed to align with the stator terminal voltage phasor, therefore all the rotor variables are referred to the stator side. Following equations are obtained using Park's transformation.

The algebraic equations of stator are:

$$V_d=E_d'-r_s*I_d-X'*I_q \quad (3)$$

$$V_q=E_q'+r_s*I_q+X'*I_d \quad (4)$$

The differential equations describing the dynamics of the rotor windings are:

$$\frac{dE_d'}{dt}=\frac{1}{T_0'}\left[-E_d'+(X-X')*I_q\right]+s*\omega*E_q' \quad (5)$$

$$\frac{dE_q'}{dt}=\frac{1}{T_0'}\left[-E_q'-(X-X')*I_d\right]-s*\omega*E_d' \quad (6)$$

The electromagnetic torque equation is:

$$T_e=E_d'*I_d+E_q'*I_q \quad (7)$$

The active and reactive power output, voltage and current under steady state operation are given as:

$$P_e=\mathrm{Re}\{V_t*I_A'\} \quad (8)$$

$$Q_e=\mathrm{Im}\{V_t*I_A'\} \quad (9)$$

$$V_t=\sqrt{V_d^2+V_q^2} \quad (10)$$

$$I_A=\sqrt{I_d^2+I_q^2} \quad (11)$$

The above equations are in per-unit (p.u.) system with respect to the synchronous reference frame [3].

In Fig. 3, the SQ100 machine model of PSCAD is used to model as an induction generator. The generator is started at constant speed of 1.01 that is higher than the rated speed. Hence with this configuration the induction machine is generating power instead of absorbing power. At 0.5 sec, the operation is being switched to constant torque and run in steady state. The capacitor banks are used to supply most of the reactive power needed by the induction generator.

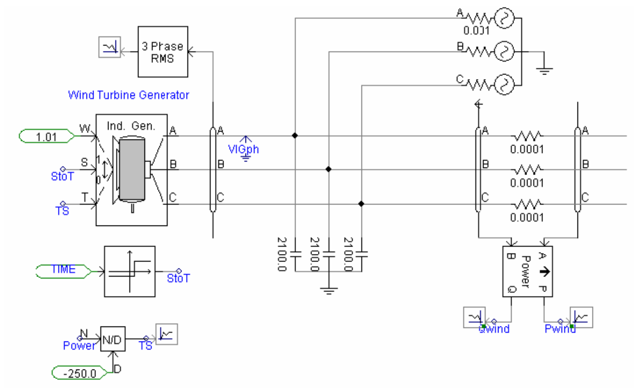

Figure 3. Induction generator model

C. *Diesel Generator Model*

In this paper, a synchronous generator is used to model the diesel generator. Using Park's transformation, the electrical quantities like currents, voltages and flux linkages associated with stator and rotor are converted in to a two dimensional (d-q) reference frame.

In PSCAD, the model of the diesel generator is entirely based on the connections of an IEEE type (SCRX) solid-state exciter, a salient-pole synchronous machine (MAC100) and an IEEE type 2 hydro governor–turbine (HGOV18). Figure 4 shows the diesel generator set from PSCAD. The exciter controls the voltage and the governor controls the frequency.

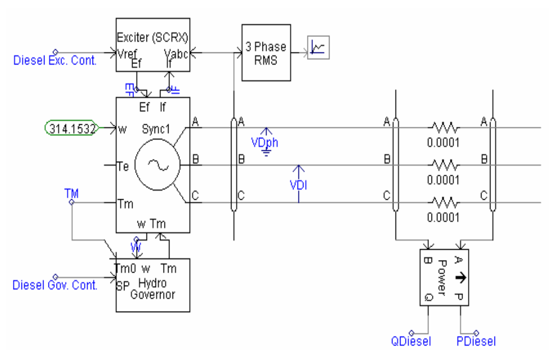

Figure 4. Diesel Engine in PSCAD

D. *Compensation Capacitor Bank*

When an appropriate capacitor bank is connected across an externally driven induction machine, an EMF is induced in the machine windings due to the excitation provided by the capacitor. The induced voltage and current would continue to rise, until the VAR supplied by the capacitor is balanced by the VAR demanded by the machine. This results in an equilibrium state being reached and the machine now operates as a SEIG. Capacitor banks also contribute in maintaining the power factor of the system to acceptable levels [8].

The capacitor banks are connected in steps to wind/diesel system to get the appropriate value of capacitance required for the self excitation of induction generator.

E. *Power Conditioning Unit*

The power conditioning unit consists of a rectifier to convert varying ac voltages from the wind generator to dc voltages and than the dc voltage is converted back to ac voltages using an inverter. This process of converting the energy from the wind is necessary due to the fact that wind energy is not constant with time but varies with respect to time. Hence power conditioning unit is used to convert varying frequency and voltage to constant frequency and fixed voltage of 50 Hz terminal output to match load requirement.

Generally, the power conditioning unit consists of a phase controlled rectifier and a line commutated inverter. Since the reactive power controlled by a controlled rectifier is a function of the firing delay angle (α), there is a limit of maximum value of 'α '.This limits the reactive power burden on the self-excitation capacitor bank, which has to supply VARs required for self excitation and that demanded by the converter. This will prevent the complete utilization of available wind energy. To overcome this constraint, an uncontrolled (diode bridge) rectifier is used [4].

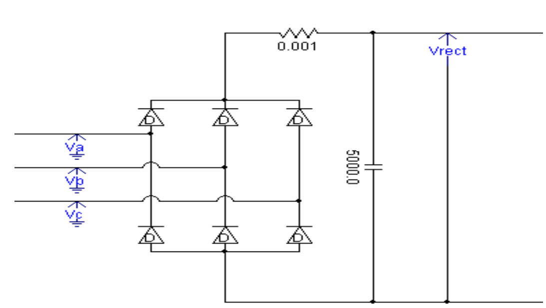

Figure 5. Six Pulse Diode Bridge Rectifier

Figure 5 show the converter model implemented using PSCAD. The rectifier output voltage can be calculated using the following equation:

$$V_{rect}=\frac{3\sqrt{2}}{\pi}V_{L-L}\cos\alpha=\frac{3\sqrt{2}}{\pi}(0.415)\cos(0^{0})=0.5604kV$$

Figure 6 shows the output voltage of the implemented 6 pulse diode bridge converter.

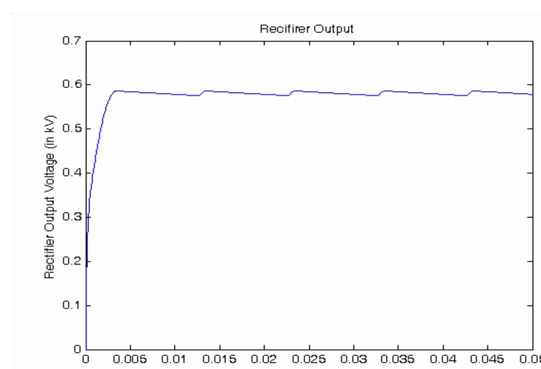

Figure 6. Output of Six Pulse Diode Bridge Rectifier

To model the inverter, different schemes have been tried and it's found that the 12 pulse inverter gives the better dc to ac conversion characteristic than 6 pulse inverter. In other words, it has a smoother sine wave across the three phase load compared to its six pulse equivalent.

The twelve pulse inverter is realized by connecting two six pulse inverter through Y-Y and Y-Δ transformers in parallel. The transformer provides a 30° phase shift between the two inverters. On the secondary side of the transformer, filters are put to reduce the current harmonics generated by the voltage source inverters from entering the system. The gate pulses to the inverter are generated using sinusoidal pulse width modulation (SPWM) technique to reduce the harmonic content in load voltages. Figure 7 shows the control circuit to generate the gate pulse.

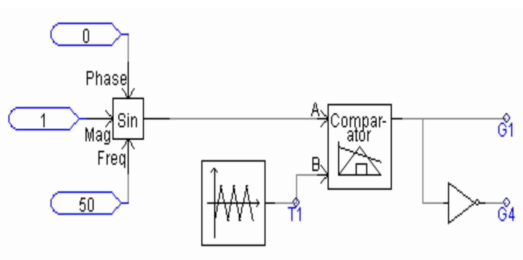

Figure 7. SPWM Gate Pulse Generator Circuit

Figure 8 shows the output phase voltages of the 12 pulse inverter.

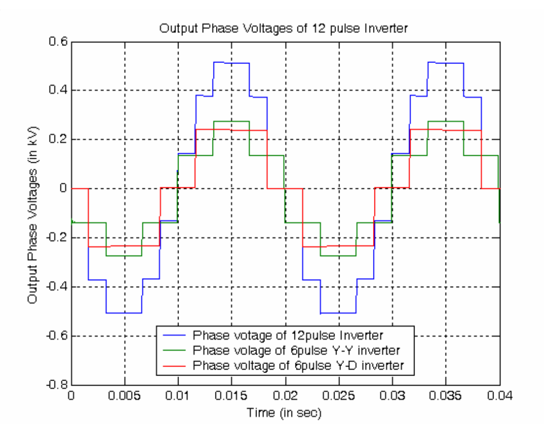

Figure 8. Output Phase Voltages of 12 Pulse Inverter for 50% Duty Cycle Gate Pulses

F. System Loads

The modeled hybrid system consists of three different types of loads. A fixed, 3phase load of 50kw and 20kvar is modeled using passive elements such as resistors and inductors in PSCAD to represent the loads such as refrigerators which will be on for 24 hours.

As the practical system consists of variable loads such as motors, lights, computers, and air conditioners, it is modeled by using an induction motor of 200 kW. Variation in the load consumption is achieved by changing the torque input to the motor at different time settings.

A dump load of 200 kW is realized in the form of an induction motor. The main purpose of the dump load is to keep the diesel-generated power above a user-prescribed fraction of its rated power. It is introduced to avoid overpowering of the diesel generator by the wind turbine. In this simulation, it is assumed that the diesel generator will be in "continuous mode" of operation.

G. System Controllers

A controller is designed for the dump load to consume excess power output from the wind turbine when diesel-powered generation is at minimum. Thus, the power to be absorbed by the dump load is,

$$P_{DumpLoad} = P_{Diesel-min} + P_{Wind} - P_{Load} \tag{12}$$

As the relationship between torque and power of an induction motor at constant rotor angular velocity, is linear, the torque input to the dump load is adjusted to consume the excess power in the hybrid system as given by (12).

In a wind-diesel system, the diesel component would control the voltage and frequency of the system by means of the exciter and the governor. Thus the diesel generator needs to be on at all times. The controller is designed to generate a minimum of 10% diesel generator rating to ensure continuous mode of operation.

The controller scheme for the diesel generator is to provide the insufficient power from the difference in wind turbine power and the load consumption. Hence, the equation of the diesel generator's required output is,

$$P_{Diesel\,Output} = P_{Load} - P_{Wind} \tag{13}$$

Equation (13) is divided by P_{Load} on both sides to get the fraction of total load supplied by the wind turbine and the fraction of total load to be supplied by the diesel generator to meet the total load demand.

$$\frac{P_{Diesel\,Output}}{P_{Load}} = 1 - \frac{P_{Wind}}{P_{Load}} \tag{14}$$

With the help of a controller, the output of diesel geneartor is adjusted (as given by (14)) to meet the total load demand.

IV. Simulation Results

To evaluate the performance and stability of the proposed wind/diesel hybrid power system, it is tested for three different disturbances like,

- Zero wind speed and constant load
- Variable wind speed and constant load
- Variable wind speed and variable load

1) Case1:

This case is simulated for fixed loads of 50 kW and 20 kVAr at zero wind speed, as shown in Fig. 9. At steady state of 7 seconds, the power output from the wind turbine is 0 kW (shown in Fig. 10), the power output from the diesel generator is 51.5 kW (shown in Fig. 11), and the power absorbed by the dump load is 0 kW (shown in Fig. 12).

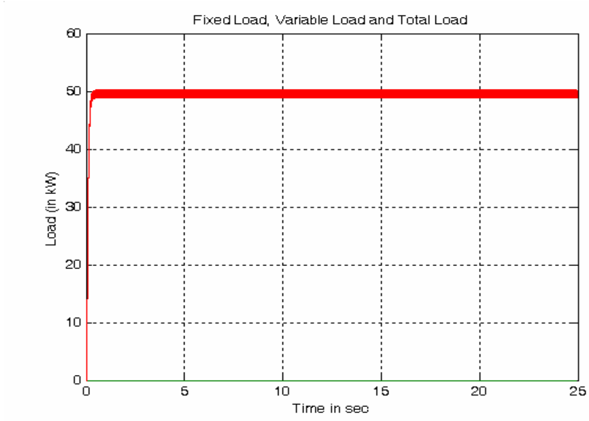

Figure 9. Case One – Fixed Load, Variable Load and Total Load

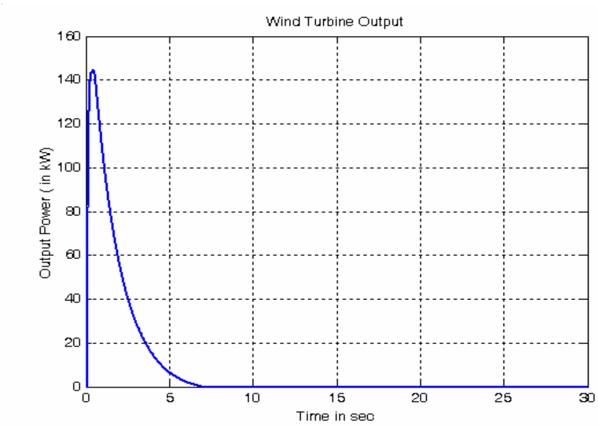

Figure 10. Case One – Power Generated By Wind Turbine

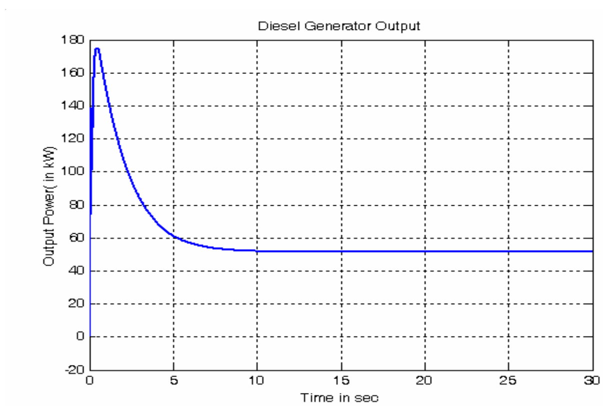

Figure 11. Case One – Power Generated By Diesel Generator

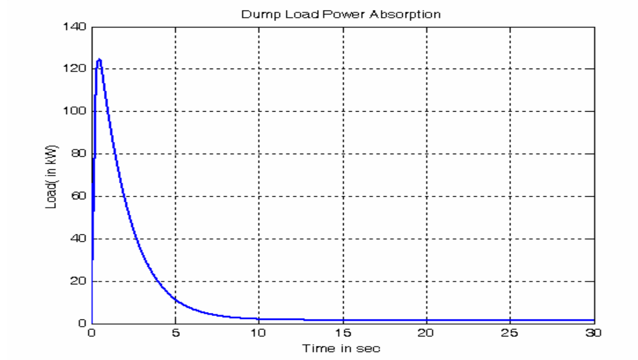

Figure 12. Case One – Dump Load Power Absorption

2) Case2:

This case simulates fixed and motor loads of 173.8 kW with varying wind speeds from 12 m/sec to 8 m/sec at 20 seconds (shown in Fig. 13). At steady state of 8 seconds, the power output from the wind turbine is 187.8 kW and after the change in wind speed at 15 seconds it settles down to 91.6 kW in approximately 8 seconds (shown in Fig. 14). The power output from the diesel generator was initially at 26.5 kW prior to 15 seconds and then increased to 83.1 kW after 8 seconds of change in wind speed (shown in Fig.15). The power absorbed by the dump load had decreased from 40 kW to 0 kW in the same period (shown in Fig. 16).

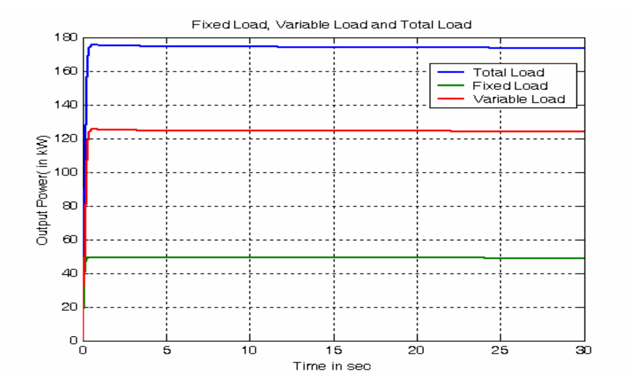

Figure 13. Case Two – Fixed Load, Variable Load and Total Load

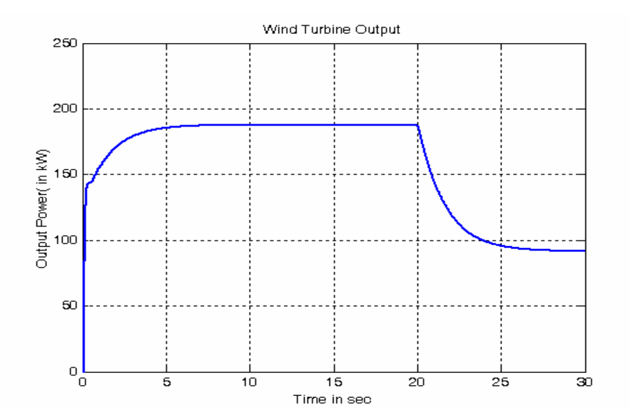

Figure 14. Case Two – Power Generated By Wind Turbine

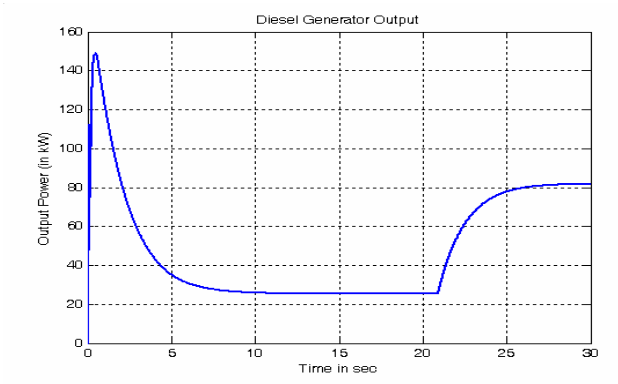

Figure 15. Case Two – Power Generated By Diesel Generator

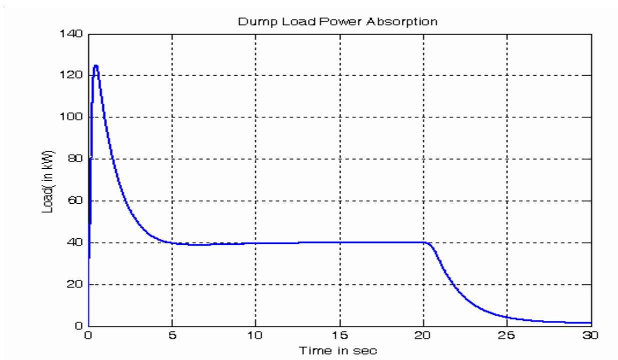

Figure 16. Case Two– Dump Load Power Absorption

3) Case3:

This case simulates variation in motor loads from 218.8 kW to 158.8 kW at 30 seconds, with varying wind speeds from 6 m/sec to 12 m/sec at 15 seconds (shown in Fig. 17). As a result of change in wind profile, the power output of the wind turbine changes from 41.2 kW to 187.8 kW (shown in Fig.18). Power output from the diesel generator was initially at 178.2 kW and then decreases to 36 kW and 26.5 kW due to an increase in wind power at 22 seconds and a decrease in load power at 32 seconds respectively(shown in Fig. 19). The dump load absorbs 60.8 kW in the period when diesel generated power is at minimum, and wind generated power is in excess of load consumption (shown in Fig. 20).

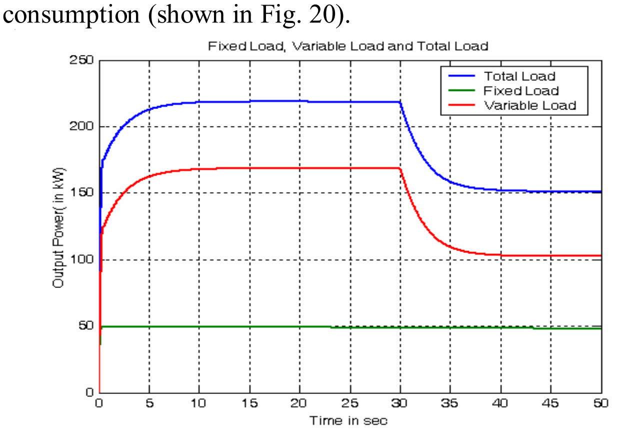

Figure 17. Case Three – Fixed Load, Variable Load and Total Load

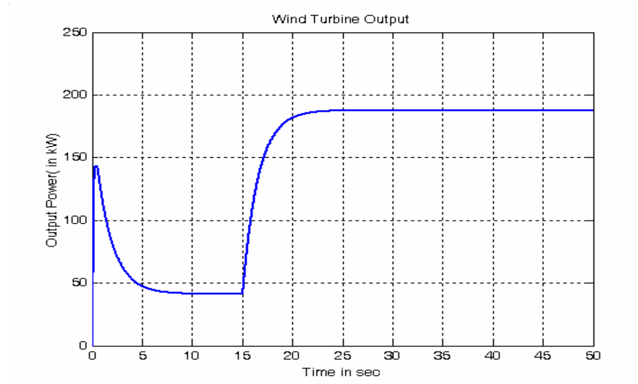

Figure 18. Case Three – Power Generated By Wind Turbine

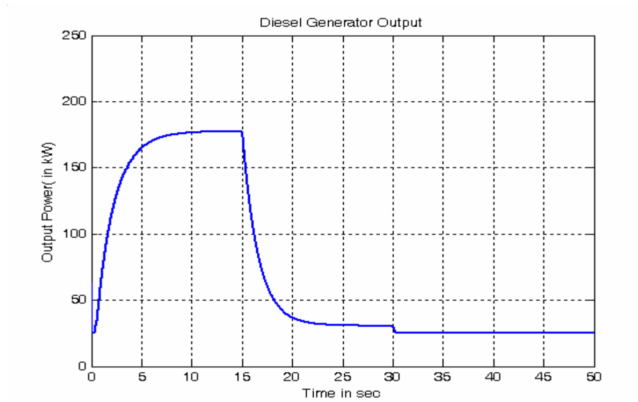

Figure 19. Case Three – Power Generated By Diesel Generator

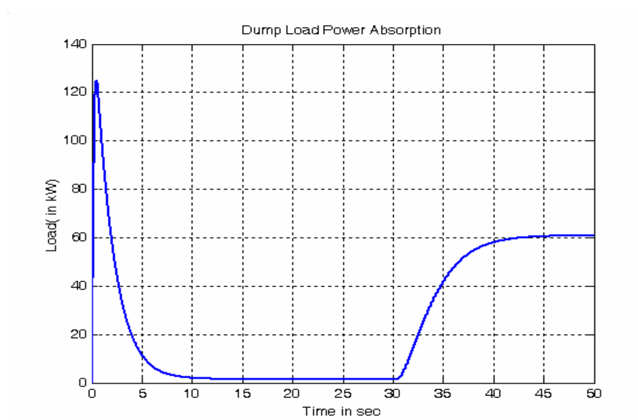

Figure 20. Case Three – Dump Load Power Absorption

V. CONCLUSIONS

In this paper, simulation of wind/diesel hybrid power system is done using PSCAD/EMTDC software. The system is simulated for different cases involving variation in wind velocity and load connected to the system. The power losses for the simulated cases are found to be in the range of 0.5 to 2.7 kW.

As the wind turbine output depends on wind velocity, which varies time to time, a diesel generator is coupled to the system to make the power output of the hybrid system more reliable.

Controllers are designed to operate the diesel generator in an economical way to reduce the total cost of generation, which can be observed from the simulation results.

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VI. APPENDIX

A. Nomenclature

P_{wt} – Mechanical power extracted from wind turbine (kW)

A_w – Area swept by rotor blades (m^2)

V_w – Upstream wind velocity (m/sec)

C_p – Power co-efficient of rotor

ρ – Density of air (kg/m^3)

β- Pitch angle (deg.)

λ – Tip speed ratio

V_{rect} – Output voltage of rectifier (kV)

V_{L-L} – Line to Line RMS voltage (kV)

T_e – Induction generator torque (Nm)

V_d – Direct axis voltage of induction generator (pu)

V_q – Quadrature axis voltage of induction generator (pu)

I_d – Direct axis current of induction generator (pu)

I_q - Quadrature axis current of induction generator (pu)

V_t – Terminal voltage of induction generator (pu)

I_A – Induction generator current (pu)

P_e – Real power generated by induction generator (pu)

Q_e – Reactive power absorbed by induction generator (pu)

E_d', Eq' – Voltages behind transient reactance X' (pu)

r_s – Stator resistance (pu)

X – Open circuit reactance (pu)

X' – Open circuit transient reactance (pu)

T_0' – Rotor open circuit transient time constant (pu)