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Performance of Voltage Control In Wind - Hydro Hybrid System With Battery Energy Storage Inter Connected To Grid

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Abstract

The aim of this paper is the proposed Wind-Hydro hybrid system with battery energy storage is used to maintain the voltage profile and support the real and reactive power in the grid. A model predictive control strategy for the ac-dc-ac converter of wind system is derived and implemented to capture the maximum wind energy as well as provide desired reactive power. In this paper deals with a new isolated wind–hydro hybrid generation system employing one squirrel-cage induction generator driven by a variable-speed wind turbine and another squirrel-cage induction generator driven by a constant-power hydro turbine feeding three-phase four-wire local loads. The main objective of this paper is to maintain constant voltage with various types of load and under varying wind speed conditions. The hybrid grid consists of both ac and dc networks connected together by multi-bidirectional converters. AC sources and loads are connected to the ac network whereas dc sources and loads are tied to the dc network. Energy storage systems can be connected to dc or ac links. The scheme can also be operated as stand-alone system in case of grid failure. The system is simulated in MATLAB/SIMULINK and results are presented for various types of linear, nonlinear and dynamic loads and under varying wind speed conditions.

Keywords: Battery energy storage system (BESS), Squirrel-cage induction generator (SCIG), Wind-energy conversion system (WECS), voltage stability

Introduction

Three phase ac power systems have existed for over 100 years due to their efficient transformation of ac power at different voltage levels and over long distance as well as the Inherent characteristic from fossil energy driven rotating machines. However, as many renewable resources depend on weather conditions a lot, it is hard to predict and dispatch them with high precision, and not a single energy resource has been capable of supplying cost-effective, clean and reliable power generation so far. Fortunately, the wind and the sunlight can be naturally complementary in term of both time and districts. So a hybrid generation with wind power, photovoltaic panels, and storage batteries is proved to be a promising way to generate more reliable, smooth, and economic power, which at the same time can reduce the requirement for the storage. Recently more renewable power conversion systems are connected in low voltage ac distribution systems as distributed Generators or ac micro grids due to environmental issues caused by conventional fossil fueled power plants. [Lasseter et. al. 2002]. A common solution to overcome this problem is to use an energy storage device besides the renewable energy resource to compensate for these fluctuations and maintain a smooth and continuous power flow to the load [Ahmad Saudi Samosir et.al. 2013]. Renewable energy sources have attracted attention worldwide due to soaring prices of fossil fuels. Renewable energy sources are considered to be important in improving the security of energy supplies by decreasing the dependence on fossil fuels and in reducing the emissions of greenhouse gases. The viability of isolated systems using renewable energy sources depends largely on regulations and stimulation measures. Renewable energy sources are the natural energy resources that are inexhaustible, for example, wind, solar, geothermal, biomass, and small hydro generation [Lai et.al. 2007]. Among the renewable energy sources, small hydro and wind energy have the ability to complement each. Although the potential for small hydroelectric systems depends on the availability of suitable water flow, where the resource exists, it can provide cheap clean reliable electricity. Hydroelectric plants convert the kinetic energy of a waterfall into electric energy. The power available in a flow of water depends on the vertical distance the water falls and the volume of flow of water in unit time. The water powers a turbine and its rotational movement are transferred through a shaft to an electric generator other [Castronuovo et.al. 2004]. When SCIG is used for small or micro hydro applications, its reactive power requirement is met by a capacitor bank at its stator terminals. As regards wind-turbine generators, these can be built either as constant-speed machines, which rotate at a fixed speed regardless of wind speed, or as variable-speed machines in which rotational speed varies in accordance with wind speed. For fixed-speed wind turbines, energy-conversion efficiency is very low for widely varying wind speeds. In recent years, wind turbine technology has switched from fixed speed to variable speed. They reduce mechanical stresses, dynamically compensate for torque and power pulsations, and improve power quality and system efficiency [Fox et.al. 2007]. In the case of grid-connected systems using renewable energy sources, the total active power can be fed to the grid. For standalone systems supplying local loads, if the extracted power is more than the local loads, the excess power from the wind turbine is required to be diverted to a dump load or stored in the battery bank. Moreover, when the extracted power is less than the consumer load, the deficit power needs to be supplied from a storage element

Wind Power Generation and Battery Storage

The sschematic representation of micro-wind energy extraction from wind generator and battery energy storage with distributed network is configured on its operating principle and it is based on the control strategy for switching the inverter for critical load application as shown in Fig. 1.

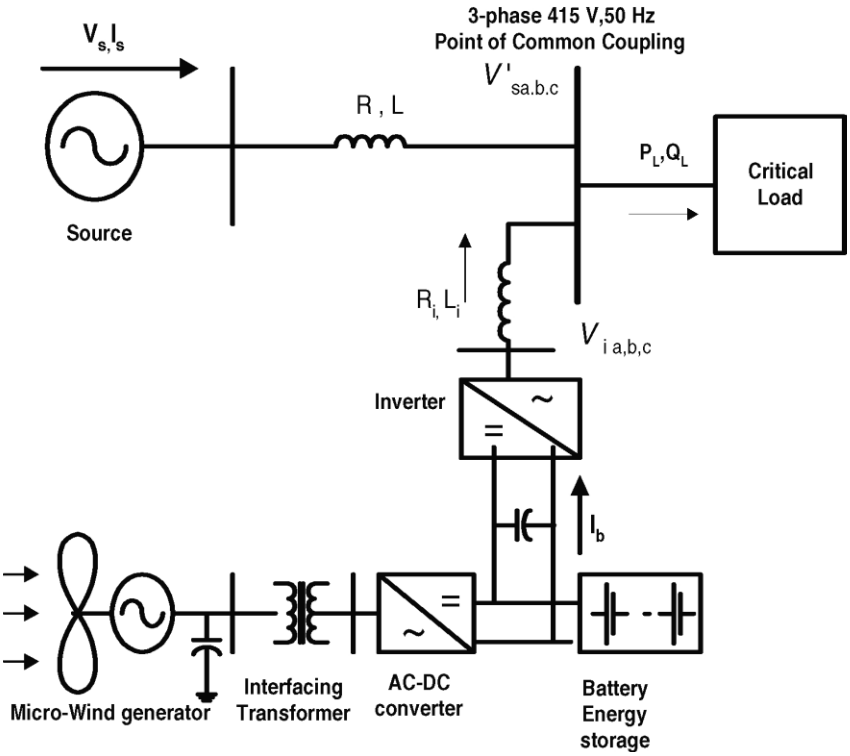


Figure 1: Scheme of micro-wind generator with battery storage for critical load application.

Micro-Wind Energy Generating System

The micro-wind generating system is connected with turbine, induction generator, interfacing transformer and ac-dc converter to get dc bus voltage. The power flow is represented with dc bus current for constant dc bus voltage in inverter operation. Although this approach is similar to unidirectional dc-dc converters, the need to bidirectional power flow significantly adds to the system complexity. Furthermore, when high efficiency soft-switching techniques are to be applied, this complexity tends to be more. In this section, the basic structure of common IBDCs is explained. While different terminologies have been proposed and used in the literature, a unified terminology is introduced and used throughout the paper to simplify the comparison between different structures. A classification is provided which helps in understanding the conceptual similarities and differences between different structures.

The static characteristic of wind turbine can be described with the relationship in the wind is given by

$$P_{\text{wind}} = \frac{1}{2}\rho \Pi R^2 V_{\text{wind}}^3 \tag{1}$$

Where ρ is air density (1.225 kg/m3), R is the rotor radius in meters and V_{wind} is the wind speed in m/s. It is not possible to extract all kinetic energy of wind and is called *CP* power coefficient. This power coefficient can be expressed as a function of tip speed ratio λ and pitch angle θ

The mechanical power can be written as

$$P_{\text{mech}} = C_p P_{\text{wind}} \tag{2}$$

$$P_{\text{mech}} = \frac{1}{2}\rho \Pi R^2 V_{\text{wind}}^3 C_p \tag{3}$$

By using the turbine rotational speed, ω_{turbine} mechanical torque is shown in equation can be written as

$$T_{\text{mech}} = P_{\text{mech}} / \omega_{\text{turbine}} \tag{4}$$

Battery Storage and Micro - Wind Energy Generator

The battery storage and micro WEGS are connected across the dc link as shown in Fig. 2.

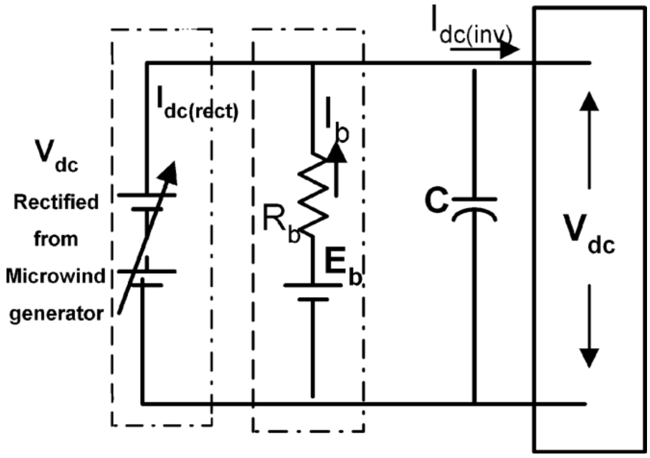


Figure 2: Dc link for battery storage and micro-wind generator

The dc link consists of capacitor which decouples the micro wind generating system and ac source. The battery storage will get charged with the help of micro wind generator. The use of capacitor in dc link is more efficient, less expensive and is modeled as

$$C\frac{d}{dt}V_{\mathrm{dc}} = I_{\mathrm{dc(rect)}} - I_{\mathrm{dc(inv)}} - I_b \tag{5}$$

Where C is dc link capacitance, V_{dc} is rectifier voltage, $I_{\mathrm{dc(rect)}}$ is rectified dc-side current, $I_{\mathrm{dc(inv)}}$ is inverter dc-side current and I_b is the battery current.

The battery storage is connected to dc link and is represented by a voltage source E_b connected in series with an internal resistance R_b. The internal voltage varies with the charged status of the battery. The terminal voltage V_{dc} is given in following equation as

$$V_{\mathrm{dc}} = E_b - I_b * R_b \tag{6}$$

Where I_b represents the battery current.

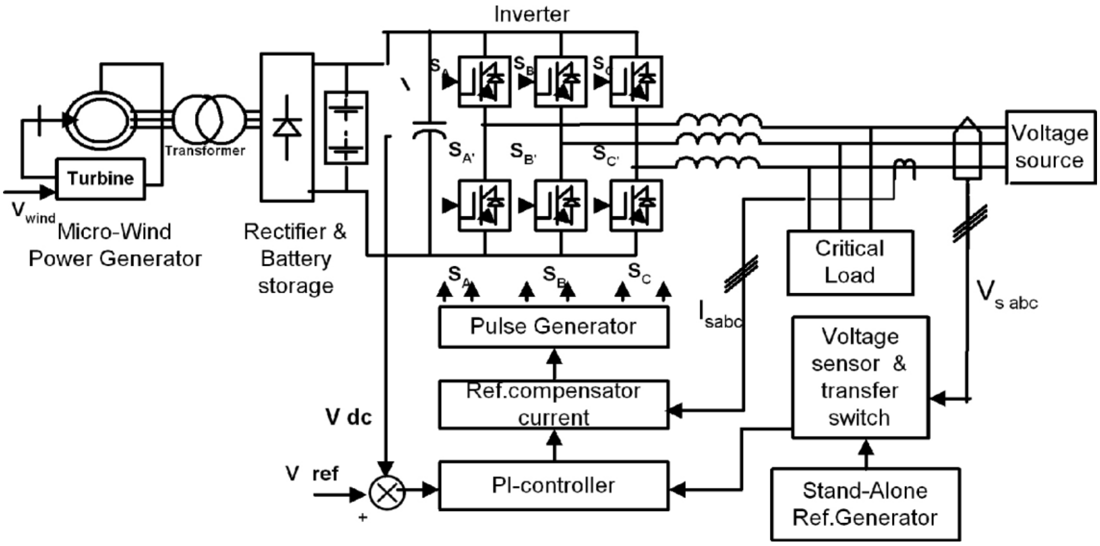


Figure 4: Inverter interface with combination of battery storage with micro WEGS

The control scheme with battery storage and micro-wind generating system utilizes the dc link to extract the energy from the wind. The micro-wind generator is connected through a step up transformer and to the rectifier bridge so as to obtain the dc bus voltage. The battery is used for maintaining the dc bus voltage constant; therefore the inverter is implemented successfully in the distributed system. The three-leg 6-pulse inverter is interfaced in distributed network and dual combination of battery storage with micro-wind generator for critical load application, as shown in Fig. 4.

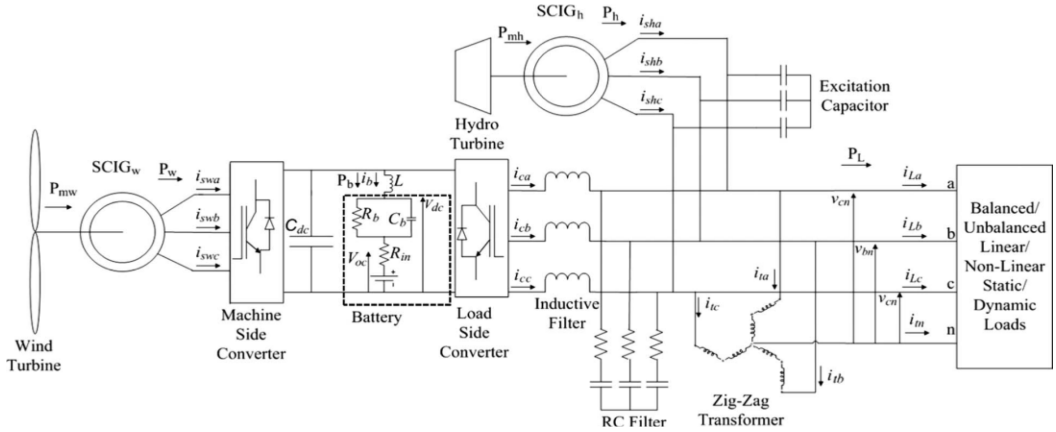


Figure 5: Overall Schematic diagram of wind–hydro hybrid system

A schematic diagram of a three-phase four-wire autonomous system is shown in Fig. 5. Two back-to-back-connected Pulse width modulation (PWM)-controlled insulated-gate-bipolar transistor (IGBTs)-based Voltage-source converters (VSCs) are connected between the stator windings of SCIG*w* and the stator windings of the SCIG*h* to facilitate bidirectional power flow. The stator windings of the SCIG*h* are connected to the load terminals. The two VSCs can be called as the machine (SCIG*w*) side converter and the load-side converter.

The system employs a Battery energy storage system (BESS), which performs the function of load leveling in the wake of uncertainty in the wind speed and variable loads. The BESS is connected at the dc bus of the PWM converters. The advantage of using BESS on the dc bus of the PWM converters is that no additional converter is required for transfer of power to or from the battery. Further, the battery keeps the dc-bus voltage constant during load disturbances or load fluctuations. An inductor is connected in series with the BESS to remove ripples from the battery current.

Design Considerations of Scig-Based Wind-Hydro Hybrid System

The following subsections describe the procedure for selection of ratings for SCIGs, battery voltage, battery capacity, machine-side converter, load-side converter, specifications of wind turbine and gear ratio.

Selection of rating of SCIG

The wind-hydro hybrid system being considered has a wind turbine of 187 KVA and a hydro turbine of 43 KVA. Both turbines are coupled to SCIGs. The rating of the SCIG_w is equal to the rating of the wind turbine, which is 187 KVA. The rating of the SCIG_h should be equal to the rating of the hydro turbine, which is 43 KVA.

Selection of voltage of DC link and battery design

The dc-bus voltage (V_{dc}) must be more than the peak of the line voltage for satisfactory PWM control as

$$V_{\mathrm{dc}} > \left\{2\sqrt{(2/3)}V_{\mathrm{ac}}\right\} m_a \tag{7}$$

Where m_a is the modulation index normally with a maximum value of one and V_{ac} is the rms value of the line voltage on the ac side of the PWM converter. In this case, there are two PWM converters connected to the dc bus; therefore, the constraint on the dc-bus voltage is from the ac voltages of both the converters. The maximum rms value of the line voltage at SCIG*w* terminals as well as the rms value of the line voltage at the load terminals is 415 V.

Selection of rating of machine ($\mathrm{SCIG_w}$) side converter

The maximum reactive power flow provided from the machine-side converter (Q_{sw}) is calculated as

$$Q_{sw} = \left\{V_{\mathrm{msc}}^2/(2\pi f L_m)\right\} \tag{8}$$

The maximum rms machine-side converter current as

$$I_{sw} = VA_{\mathrm{msc}}/(\sqrt{3}V_{\mathrm{msc}}) \tag{9}$$

Where V_{msc} is the maximum line voltage generated at the SCIG_w terminals, which is 415 V, at a frequency (f) of 50 Hz generated at a wind speed of 11.2 m/s. The *VA* rating (VA_{msc}) of the machine-side converter is given by

$$VA_{\mathrm{msc}} = \sqrt{P_{sw}^2 + Q_{sw}^2} \tag{10}$$

Selection of rating of load-side converter

The rating of the load-side converter is determined by the case when the connected load is at its maximum value. The reactive power of the load is supplied by the load-side converter. Hence, the reactive-power flow through load-side converter (Q_{lsc}) is equal to the reactive power demand of the load (Q_L).

Therefore, the kVA rating of the load-side converter ($\mathrm{kVA_{lsc}}$) is calculated as

$$\mathrm{kVA_{lsc}} = \sqrt{P_{\mathrm{lsc}}^2 + Q_{\mathrm{lsc}}^2} \tag{11}$$

The maximum rms current through the load-side converter (I_{lsc}) is calculated as

$$I_{\mathrm{lsc}} = \mathrm{VA_{lsc}}/(\sqrt{3}V_{\mathrm{lsc}}) \tag{12}$$

Selection of AC Inductor and RC filter on AC side of load-side converter

An inductor is used on the ac side of the load-side converter for boost function. For 5% ripple in the current through the inductive filter, inductance (L_f) of the inductive filter can be calculated as

$$L_f = \left\{(\sqrt{3}/2) m_a V_{\mathrm{dc}}/\left(6 a f_s I_{r(p-p)\mathrm{lsc}}\right)\right\} \tag{13}$$

Where f_s is the switching frequency and is equal to 10 kHz and $I_{r(p-p)\mathrm{lsc}}$ is the peak-to-peak ripple current in the load-side converter and inductive filter. During transients, the current in the inductive filter is likely to be more than the steady-state values.

Selection of specifications of wind turbine and gear ratio

For wind speeds below the rated wind speed, the mechanical power P_m captured by the turbine is a function of wind speed V_w, radius of turbine r_w, density of air ρ, and coefficient of performance C_p, and is given by

$$P_m = 0.5 C_p \pi r^2 \rho V_w^3 \tag{14}$$

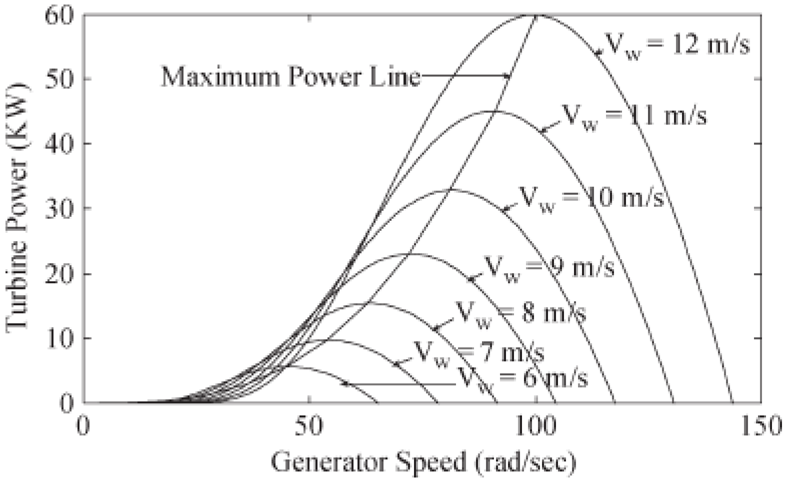


Figure 5: Mechanical power output of the wind turbine versus SCIG*w* speed for different wind speeds

The relationship between the coefficient of performance and tip speed ratio for a typical wind turbine is shown in Fig. 5. The maximum coefficient of performance ($C_{p\max}$) is achieved at optimum tip ratio (λ^*_w).

Computation of Controller Gains

The gains of the controllers are obtained using Zeigler–Nichols step-response technique. A step input of amplitude (U) is applied, and the response is obtained for the open-loop system. The maximum gradient (G) and the point at which the line of maximum gradient crosses the time axis (T) are computed. The gains of the controller (K_p and K_i) are computed using the following equations

$$K_p = \left|\frac{1.2U}{GT}\right| \tag{15}$$

$$K_i = \left|\frac{0.6U}{GT^2}\right| \tag{16}$$

Simulated Results and Discussion

The test system comprises of A 150 KW wind energy conversion system exports power to a 150 kV grid through a 30 km, 25 kV feeders. Wind turbines using a Squirrel Cage Induction generator (SCIG) consist of a cage rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to the 50 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. The SCIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed while minimizing mechanical stresses on the turbine during gusts of wind. Here the wind speed is maintained constant at 11 m/s.

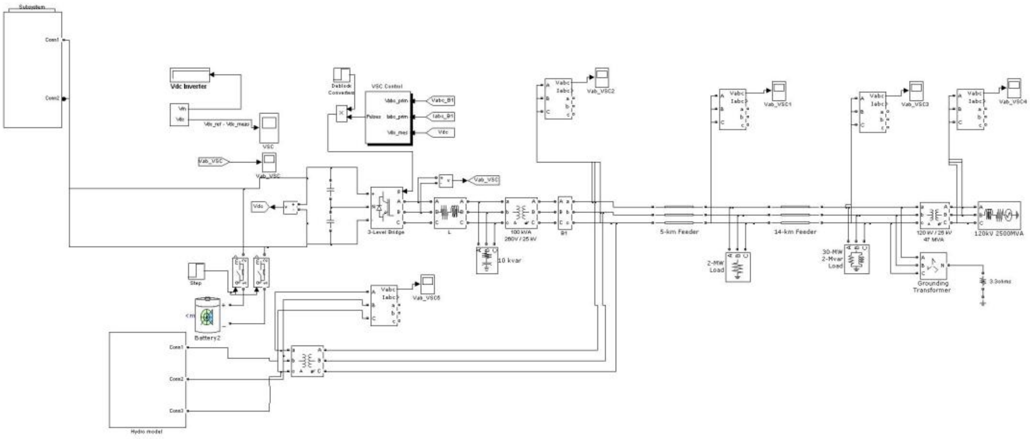


Figure 6: Test system of grid connected wind-hydro hybrid system with battery energy storage system

The SCIG technology allows extracting maximum energy from the wind for low wind speed by optimizing the turbine speed. The optimum turbine speed producing maximum mechanical energy for a given wind speed is proportional to the wind speed. For wind speeds lower than 10 m/s the rotor is running at sub synchronous speed and at high wind speed it is running at hyper synchronous speed. Test system of grid connected wind-hydro hybrid system with battery energy storage system simulation model is shown in Fig.6.

Installed capacity of 150KW, three phase, 415V squirrel cage induction generator (SCIG) is used. The proposed system studied for under varying wind speed conditions. Squirrel Cage Induction Generator (SCIG) stator winding is connected directly to the grid and the rotor is driven by the wind turbine. The power captured by the wind turbine is converted into electrical power by the induction generator and is transmitted to the grid by the stator winding. SCIG has inherent advantages such as cost effectiveness, robustness and there is no need for separate field excitation.Installed capacity of 35KW, three phase, 415V squirrel cage induction generator (SCIG) is used. SCIG is driven by a constant-power hydro turbine feeding to the grid.

AC to DC PWM converter converts 415V AC voltage into 412V DC. At the time of grid connection requires synchronization of source voltage and grid voltage, so the system needs 415V dc is achieved with the help of Battery energy storage system (BESS). The converted 415V DC voltage is again inverted into 415V AC with the help of above DC to AC inverter. Then the corresponding voltage is feeding to the grid. The basic requirement for connecting to grid is synchronization of voltage, frequency and phase sequence. If any mismatch in voltage means that mismatch voltage improved by battery energy storage system (BESS). The proposed system is implemented for various types of loads like linear, non linear, static and dynamic loads.

Table 1: Design Parameters of Wind Turbine Data

WIND TURBINE CHARACTERISTICS	DESIGN VALUE (UNITS)
No. of blades	3
Rated capacity	187KVA
Rotor speed	43-81 rpm
Nominal wind speed	6.0-11.2 m/s
Cut in wind speed	5 m/s

Table 2: Design Parameters of Induction Generator Data

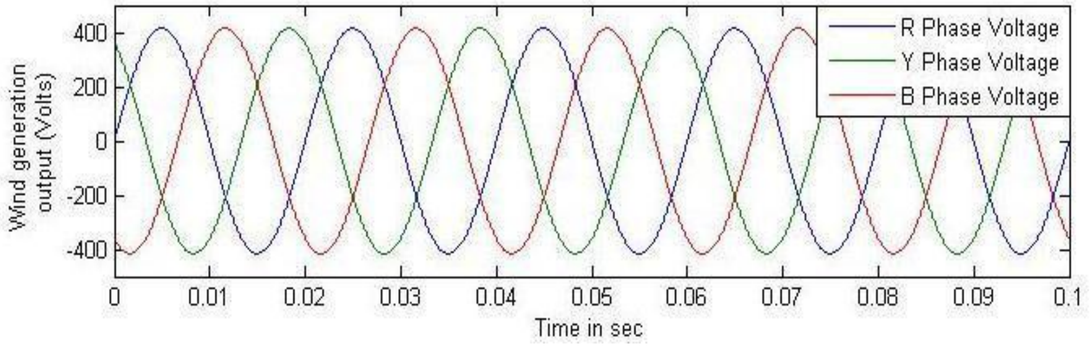
SCIG CHARACTERSTICTIS (WIND)	DESIGN VALUE (UNITS)
P_{rated}	187 KVA
V_s, rated	415 V
Mutual inductance L_m	0.0298 H
Stator leakage reactance L_s	0.678 mH
Rotor leakage reactance L_r	0.867 mH
Stator resistance R_s	0.059 Ω
Rotor resistance R_r	0.0513 Ω

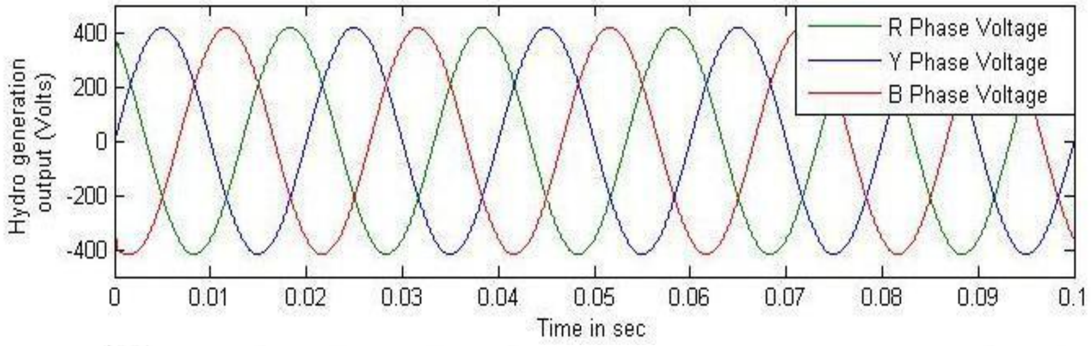
Table 3: Design Parameters of Hydro Generator Data

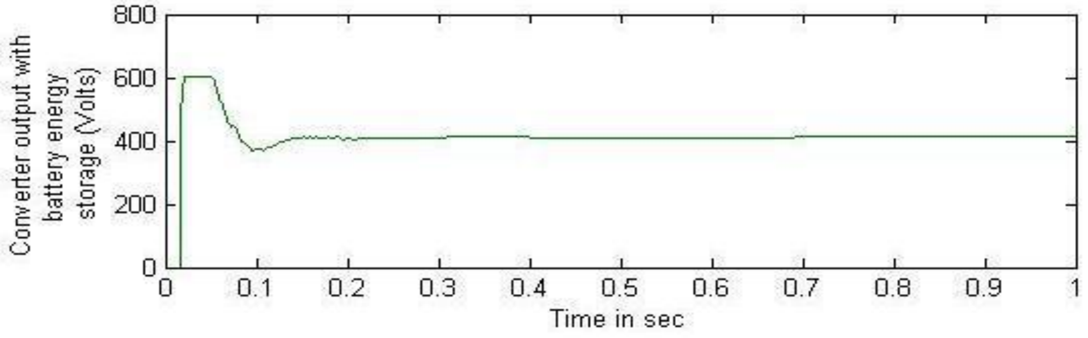
SCIG CHARACTERSTICTIS (HYDRO)	DESIGN VALUE(UNITS)
P_{rated}	43 KVA

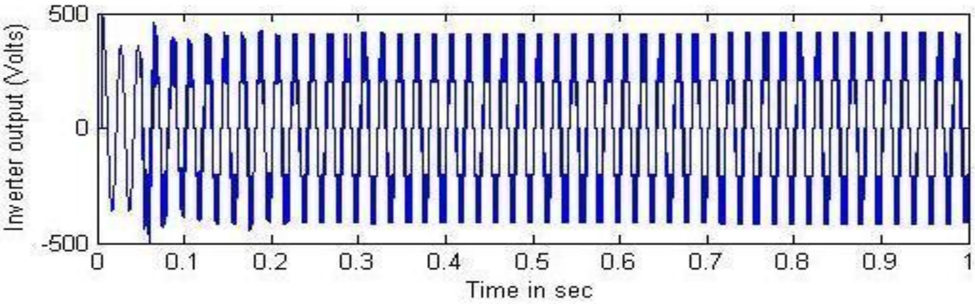
Vs, rated	415 V
Mutual inductance L_m	0.030369 H
Stator leakage reactance L_s	0.867 mH
Rotor leakage reactance L_r	0.867 mH
Stator resistance R_s	0.09961 Ω
Rotor resistance R_r	0.058 Ω

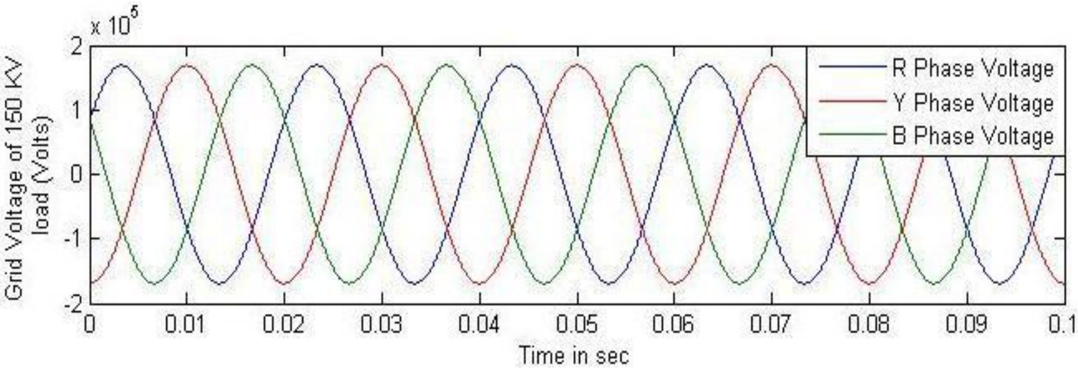
Table I, II and III summarizes the various design parameters of wind turbine data, induction generator data and hydro generator data respectively.

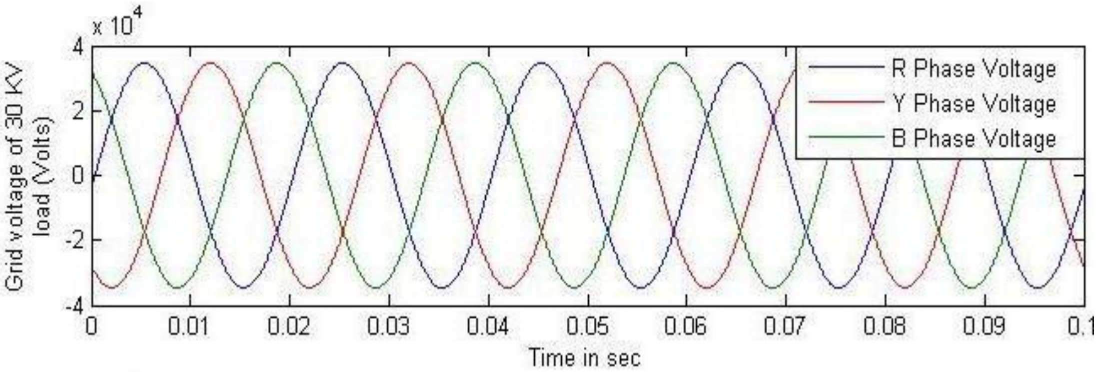


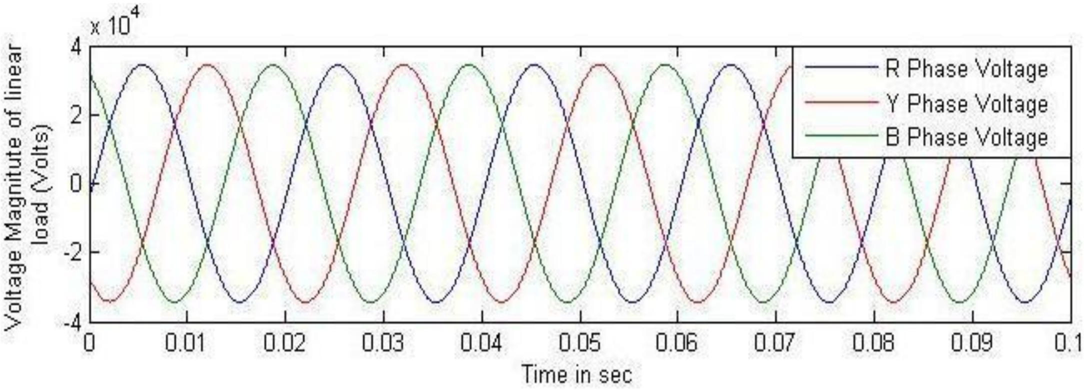





Inverter output (Volts)
500
0
-500
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time in sec


x 10^5
Grid Voltage of 150 KV load (Volts)
2
1
0
-1
-2
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time in sec
R Phase Voltage
Y Phase Voltage
B Phase Voltage


x 10^4
Grid voltage of 30 KV load (Volts)
4
2
0
-2
-4
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time in sec
R Phase Voltage
Y Phase Voltage
B Phase Voltage


x 10^4
Voltage Magnitute of linear load (Volts)
4
2
0
-2
-4
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time in sec
R Phase Voltage
Y Phase Voltage
B Phase Voltage

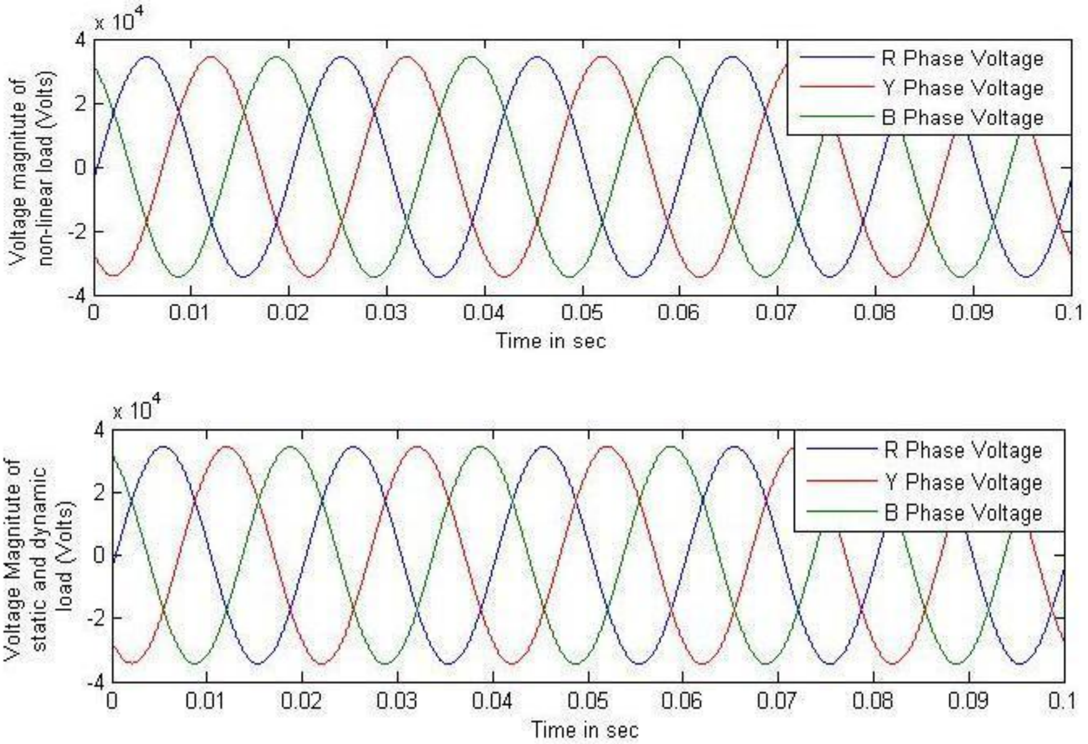


Figure 7: Performance analysis of hybrid model for different input voltage sources (wind, hydro and battery) with different load conditions

The test system consist of grid connected wind–hydro hybrid generation system with battery energy storage system(BESS) employing one squirrel-cage induction generator (SCIG) driven by a variable-speed wind turbine and another SCIG driven by a constant-power hydro turbine. The test system studied for various types of linear, non linear, static and dynamic loads. In the test system generated wind power can be extracted under varying wind speed and can be stored in the batteries at low power demand hours. The combination of battery storage With wind-hydro hybrid system, which will synthesize the output waveform by injecting or absorbing reactive power and enable the real power flow required by the load. The test system comprises of A 150 KW wind energy conversion system exports power to a 150 kV grid through a 30 km, 25 kV feeders shown in Fig.7.

For the test system of wind-hydro hybrid system, there are three modes of operation. In the first mode, the required active power of the load is less than the power generated by the SCIG*h*. Moreover, the power generated by the SCIG*w* is transferred to the BESS. In the second mode, the required active power of the load is more than the power generated by the SCIG*h* but less than the total power generated by SCIG*w* and SCIG*h*. Thus, portion of the power generated by SCIG*w* is supplied to the load through the load-side converter and remaining power is stored in BESS. In the third mode, the required active power of the load is more than the total power generated by SCIG*w* and SCIG*h*. Thus, the deficit power is supplied by the BESS, and the power generated by SCIG*w* and the deficit met by BESS are supplied to the load.

From the simulation results the test system initially checks with 2MW and 30MW, 2Mvar loads, the system response on output voltage is same without any interruption shown in Fig7. The system also provides uninterrupted power supply to the grid connected network. In the grid connected network it is especially difficult to support the non linear load without uninterrupted power supply.

The test system checks with various types of linear, non linear, static and dynamic loads are shown in Fig.7. The grid connected wind-hydro hybrid system with battery energy storage is operates with linear load and voltage measurements with respect to linear load is found to be 30KV and current is 4A is shown in Fig.7. Then again the grid connected wind-hydro hybrid system with battery energy storage is operates with non linear load and voltage measurements with respect to non linear load is found to be 30KV and current is 4A. Finally the test system maintain constant voltage under varying wind speed conditions and while using various types of linear, non linear, static and dynamic loads. The system provides uninterrupted power supply to grid connected network and also reduces the burden on conventional sources.

Conclusion

Among the renewable energy sources, small hydro and wind energy have the ability to complement each other. The proposed system connected to the grid and where the wind potential and hydro potential exist. The design procedure for selection of various components has been demonstrated for the proposed hybrid system. The performance of the proposed hybrid system has been demonstrated under different electrical and mechanical dynamic conditions. It has been demonstrated that the proposed hybrid system performs satisfactorily under different dynamic conditions while maintaining constant voltage. The battery energy storage provides rapid response and enhances the performance under the fluctuation of wind turbine output and improves the voltage stability of the system.

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