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Isolated Wind Hydro Hybrid Generation System with Battery Storage

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Abstract: *In this paper, a new isolated wind- hydro hybrid generation system comprising one squirrel - cage induction generator (SCIG) driven by a variable-speed wind turbine and another synchronous generator driven by constant power hydro turbine feeding three phase four wire local loads is proposed. The system utilizes two back to back connected voltage-source converters (VSCs) with a battery energy storage system at their dc link. The main objective of the control algorithm for the VSC is to achieve control of the magnitude and the frequency of the load voltage. The proposed wind-hydro hybrid system has a capability of bidirectional active- and reactive-power flow, by which it controls the magnitude and the frequency of the load voltage. The proposed electromechanical system is modelled and simulated in MATLAB using Simulink.*

Keywords: *Battery energy storage system (BESS), squirrel cage induction generator (SCIG), synchronous generator, wind energy conversion system (WECS), voltage source converter (VSC).*

I. INTRODUCTION

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. Among the renewable energy sources, small hydro and wind energy have the ability to complement each other.

Hybrid power systems are combinations of two or more energy conversion devices (e.g., electricity generators or storage devices), or two or more fuels for the same device, that when integrated, overcome limitations that may be inherent in either. System efficiencies are typically higher than that of the individual technologies used separately, and higher reliability can be accomplished with redundant technologies and/or energy storage. Some hybrid systems include both, which can simultaneously improve the quality and availability of power.

In general, well-designed hybrid systems will substantially reduce diesel fuel consumption while increasing system reliability. In addition to the diesel generator and the renewable energy generator, hybrid systems consist of a battery bank for energy storage, a control system and particular system architecture that allows optimal use of all components. Hybrid systems are potentially very cost-effective solutions to rural AC electricity needs. For low load applications (< 10 kWh/day), wind/PV hybrid systems are very attractive. For larger applications, wind/diesel hybrids are very attractive as long as a reasonable wind resource is available. Bilateral and multilateral finance and market stimulation programs should be based on best service at least cost.

There exists a wide collection of literatures on the modeling of WECS, specifically on the modeling of individual components in the system which is mainly comprised of two subsystems, namely a wind turbine part and an electric generator part. Detailed descriptions of these concepts can be found in references [5],[6],[7].The conversion of mechanical power of the wind turbine into electrical power can be accomplished by an electrical generator which can be a DC machine, a synchronous machine, or an induction machine. DC machines were used widely until 1980s in smaller installations below 100 kW, because of its extremely easy speed control. The presence of commutators in DC machines has low reliability and high maintenance.

The second kind of electric generators are synchronous generators suitable for constant speed systems. Another choice for the electric generator in a WECS is a permanent magnet synchronous generator PMSG.

But PMSGs have the weakness of uncontrollable magnetic field decaying over a period of time. Induction generators on the the other hand have many advantages over conventional synchronous generators due to their ruggedness, no need for DC field current, low maintenance requirements and low cost.

Many wind power systems for economy and reliability reasons used induction machines driven by a wind turbine through a gear box as an electrical generator. Based on the rotor construction induction machine can be one of two types based on the rotor construction, squirrel cage type or wound rotor type. Squirrel cage rotor construction is popular because of its ruggedness, lower cost and simplicity of construction. Hence, nowadays it is most commonly used.

In the case of stand-alone or autonomous systems, the issues of voltage and frequency control (VFC) are very important. In references [17]–[18], the issues of VFC for stand-alone systems using SCIGs have been addressed. However, maximum power tracking (MPT) could not be realized in this battery-based isolated system employing SCIG operated at fixed speed. Reference [4] proposes an electronic load controller for VFC at the stator terminals, and the controller transfers excess power from the hydropower generator to a dump load, whenever the load is less than the generated power.

In this paper, a new three-phase four-wire autonomous (or isolated) wind–small hydro hybrid system is proposed for isolated locations, which cannot be connected to the grid and where the wind potential and hydro potential exist simultaneously. One such location in India is the Andaman and Nicobar group of islands [24].The proposed system utilizes variable speed wind-turbine-driven SCIG and a constant-speed/constant-power small hydro-turbine-driven synchronous generator.

A schematic diagram of a three-phase four-wire autonomous system is shown in Fig. 1.Two back-to-back-connected pulse width modulation (PWM)-controlled insulated-gate-bipolar transistor (IGBTs)-based

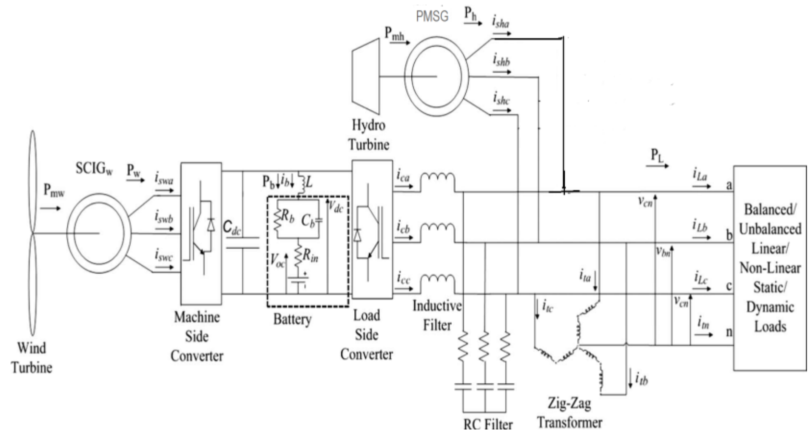

Figure 1: Schematic of wind hydro hybrid system

voltage-source converters (VSCs) are connected between the stator windings of SCIG and the stator windings of the PMSG to facilitate bidirectional power flow. The stator windings of the PMSG are connected to the load terminals. The two VSCs can be called as the machine 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. A zigzag transformer is connected in parallel to the load for filtering zero-sequence components of the load currents. Further, the zigzag windings trap triplen harmonic (third, ninth, fifteenth, etc.) currents. As shown in Fig. 1, the zigzag transformer consists of three single-phase transformers with a turn ratio of 1 : 1. The zigzag transformer is to be located as near to the load as possible. The neutral terminal of the consumer loads is connected to the neutral terminal of the zigzag transformer.

In the conventional control of variable-speed SCIGs, the objective of the load-side converter (called as grid-side converter in the grid-connected systems) is to maintain the dc-bus voltage constant at the dc link of two back-to-back connected VSCs. Because in the proposed system the dc-bus voltage is kept constant by the battery, the control objective of the load-side converter is different, i.e., to maintain an active power balance in the system by transferring the excess power to the battery or for providing deficit power from the battery. Further, the load-side converter provides the requisite reactive power for the load. .

A novel control strategy using indirect current control is proposed for the load-side converter. The control signals for switching of the load-side converter are generated from the error of the reference and the sensed stator currents of SCIG rather than by the errors of the load-side converter currents. With this control strategy, the switching of the load-side converter is controlled to make the SCIG currents balanced and sinusoidal at the nominal frequency. Any unbalance and harmonics in the load currents are compensated by the zigzag transformer and the load-side converter. The proposed control algorithm for load-side converter requires sensing of the load voltage and stator currents of SCIG.For the control purpose, sensing of load-side-converter currents and load currents is not required, thus reducing the requirement of current sensors for the control of load-side converter.

II. Principle Of Operation Of Hybrid System

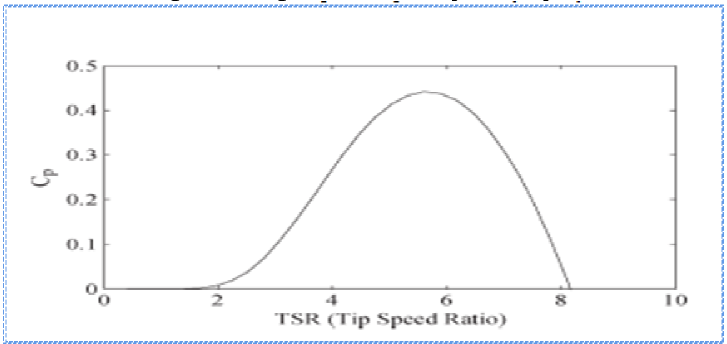

Figure 2: Coefficient of performance versus tip speed ratio

The proposed system uses two back to-back-connected VSCs. These VSCs are referred to as the machine side converter and load-side converter.The objective of the load-side converter is VFC at the load terminals by maintaining active- and reactive-power balance. To achieve MPT, the SCIG is required to be operated at optimal tip speed ratio as shown in Fig. 2. The tip speed ratio determines the SCIG*w* rotor-speed set point for a given wind speed, and the mechanical power generated at this speed lies on the maximum power line of the turbine.

The load-side converter is controlled for the regulation of load-voltage magnitude and load frequency. Further, for maintaining the load-frequency constant, it is also essential that any surplus active power in the system is diverted to the battery. Alternatively, the battery system should be able to supply any deficit in the generated power. Similarly, the magnitude of the load voltage is maintained constant in the system by balancing the reactive-power requirement of the load through the load side converter.

For the proposed 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 synchronous generator and the excess power generated by the PMSG is transferred to the BESS through the load-side converter. Moreover, the power generated by the SCIG is transferred to the BESS. In the second mode, the required active power of the load is more than the power generated by the PMSG but less than the total power generated by SCIG and PMSG. Thus, portion of the power generated by SCIG 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 and PMSG. Thus, the deficit power is supplied by the BESS, and the power generated by PMSG and the deficit met by BESS are supplied to the load through the load-side converter.

2.1 Control of Load-Side Converter

The objectives of the load-side converter are to maintain rated voltage and frequency at the load terminals irrespective of connected load. The power balance in the system is maintained by diverting the surplus power generated to the battery or by supplying power from the battery in case of deficit between generated power and load requirement. Similarly, the required reactive power for the load is supplied by the load-side converter to maintain constant value of the load voltage.

1) Generation of Reference Three-Phase SCIGw Currents:

The reference voltages (V*an, V*bn, and V*cn) for the control of the load voltages at time t are given as

$$V^*_{an} = \sqrt{2}\, V_t \sin(2\pi ft) \quad (1)$$

$$V^*_{bn} = \sqrt{2}\, V_t \sin(2\pi ft - 120) \quad (2)$$

$$V^*_{cn} = \sqrt{2}\, Vt \sin(2\pi ft + 120) \quad (3)$$

where *f* is the nominal frequency, which is considered as 50 Hz, and *Vt* is the rms phase-to-neutral load voltage, which is considered as 240 V. The load voltages (van, vbn, and vcn) are sensed and compared with the reference voltages. The error voltages (v_{anerr},v_{bnerr} and v_{cnerr}) at the *n*th sampling instant are calculated as

$$V_{anerr(n)}) = V_{*an(n)} - V_{an(n)} \quad (4)$$
$$V_{bnerr(n)} = V*_{bn(n)} - V_{bn(n).} \quad (5)$$
$$V_{cnerr(n)} = V_{*cn(n)} - V_{cn(n)} \quad (6)$$

The reference three-phase SCIG*w* currents ($i*_{swa}$, $i*_{swb}$, $i*_{swc}$) are generated by feeding the voltage error signals to PI voltage voltage controller with proportionate gain K_{pv} and integral gain K_{iv}. The reference three-phase SCIGw currents are then compared with the sensed SCIGw currents (i_{swa}, i_{swb}, and i_{swc}) to compute the SCIGw current errors as

$$i_{swaerr} = i_{*swa} - i_{swa} \quad (7)$$
$$i_{swberr} = i_{*swb} - i_{swb} \quad (8)$$
$$i_{swcerr} = i_{*swc} - i_{swc} \quad (9)$$

These current errors are amplified with gain (*K*=5), and the amplified signals are compared with a fixed-frequency (10 kHz) triangular carrier wave of unity amplitude to generate gating signals for IGBTs of the load-side converter. The sampling time of the controller is taken as 50μs, as this time is sufficient for completion of calculations in a typical DSP controller.

III. DESIGN

3.1 Turbine

The wind hydro hybrid system being considered has a wind turbine of 55kW and a hydro turbine of 60 kW respectively. The rating of the $SCIG_w$ is equal to the rating of the wind turbine, ie 55 kW.

3.2 Selection of Voltage of Dc Link And Battery Design

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

$$Vdc > 2\sqrt{(2/3)}V_{ac}\, m_a \quad (10)$$

where ma is the modulation index normally with a maximum value of one and Vac is the rms value of the line voltage on the ac side of the PWM converter .The maximum rms value of the line voltage at the load terminals is 415 V. Substituting this value in (10), Vdc should be more than 677.7 V. The voltage of the dc link and the battery bank is selected as 700 V. The maximum rms value of the line voltage at the load terminals is 415 V. Substituting this value in V_{dc} should be more than 677 V.The voltage of the dc link and the battery bank is selected as 700 V.

Considering the ability of the proposed system to supply electricity to a load of 60 kW for 10 h, the design storage capacity of the battery bank is taken as 600 kWh. . The commercially available battery bank consists of cells of 12 V. The nominal capacity of each cell is taken as 150 A.h. To achieve a dc-bus voltage of 700 V through series connected cells of 12 V, the battery bank should have (700/12) = 59 number of cells in series. Since the storage capacity of this combination is 150 A · h, and the total ampere hour required is (600 kW · h/700 V) = 857 A · h, the number of such sets required to be connected in parallel would be (857 A.h /150 A.h) = 5.71 or 6 (selected). Thus, the battery bank consists of six parallel-connected sets of 59 series connected battery cells.

Thevenin's model is used to describe the energy storage of the battery in which the parallel combination of capacitance (Cb) and resistance (Rb) in series with internal resistance (Rin) and an ideal voltage source of voltage 700 V are used for modelling the battery.

$$Cb = (Kw.h*3600*1000)/0.5\,(V_{2ocmax} - V_{2ocmin})\,) \quad (11)$$

Taking the values of V_{ocmax} = 750 V, V_{ocmin} = 680 V, and Kw.h = 600, the value of Cb obtained is 43156 F.

3.3 Selection of Rating 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. inductance (Lf) of the inductive filter can be calculated as

$$Lf = \{(\sqrt{3}/2)m_a V_{dc} /(6a\, f_s Ir_{(p-p)} I_{sc}\} \quad (12)$$

where fs is the switching frequency and is equal to 10 kHz and Ir(p−p)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. For calculation of inductance, current rating of 120% (a = 1.2) of steady-state current is taken; modulation index ma is taken as one. Thus, the value of inductance of the filter is

0.76mH . A high-pass first-order filter tuned at half the switching frequency is used to filter out the noise from the voltage at the load terminals. The time constant of the filter should be very small compared with the fundamental time period (T), or

$$RC << T/10. \quad (13)$$

When T = 20 ms, considering, C = 5μF, R can be chosen as 5 Ω. This combination offers a low impedance of 8.1 Ω for the harmonic voltage at a frequency of 5 kHz (half of the switching frequency).

3.4 Selection of Specifications Of Wind Turbine And Gear Ratio

The wind turbine is designed for 55 kW at 11.2 m/s, which is considered as rated wind speed. For wind speeds below the rated wind speed, the mechanical power *Pm* captured by the turbine is a function of wind speed *Vw*, radius of turbine *rw*, density of air *ρ*, and coefficient of performance *Cp*, and is given

$$Pm = 0.5Cp\pi r^2 \rho V^3 \quad (14)$$

The relationship between the coefficient of performance and tip speed ratio for a typical wind turbine is shown in Fig. 3.The maximum coefficient of performance (*Cp*max) is achieved optimum tip ratio ($\lambda *_w$). The values of *Cp*max and $\lambda *_w$ obtained from the Figure. 3.1 are 0.4411 and 5.66, respectively. Substituting, *Pm* = 55 kW, *Cp* = 0.4411, wind speed *Vw* = 11.2 m/s, and density of air *ρ* = 1.1544 kg/m3 in 4.1, the radius of the wind turbine *rw* is obtained as 7.5m.

At 11.2 m/s wind speed, the generator rotor speed is considered as 100 rad/s. Substituting the value of tip speed ratio = 5.66, radius of the wind turbine = 7.5 m,wind speed = 11.2 m/s, and generator speed = 100 rad/s, the gear ratio is obtained as

$$\eta w = \omega_{rw} r_w / \lambda w V w \quad (15)$$

$$=100 * 7.5/5.66 * 11.2$$

$$= 11.811 \sim= 12 \text{ (selected).}$$

Above equations are used to simulate wind turbine. In the real turbines above the rated wind speed, the blade-pitch control comes in operation, and the turbine blades are pitched slightly out of the wind to limit power. Conversely, the blades are turned back into the wind whenever the wind drops again. The ratings and the specifications of the selected components of the hybrid system based on the aforementioned design procedure are used for simulation purpose.

IV. Simulation Results

The performance of the wind hydro hybrid system is demonstrated in figure 2.1. A balanced linear load and a secondary dynamic load at wind speed of 11m/s is connected to the above network. At this speed the wind turbine generates 55 kW and the hydro generates 60 kW. So the total power generation is 115 kW. The model is tested for the following loads.

1. Half load of 57.5 kW
2. Full load of 115 kW
3. Overload of 10%

In each case the output waveforms of load voltage, load current and load frequency are studied. The model is working satisfactorily for the above mentioned loads. The waveforms are purely sinusoidal as expected for the above three conditions. Also, under the above conditions both the magnitude and frequency of the load voltage are maintained constant. The obtained waveforms are shown in figures.

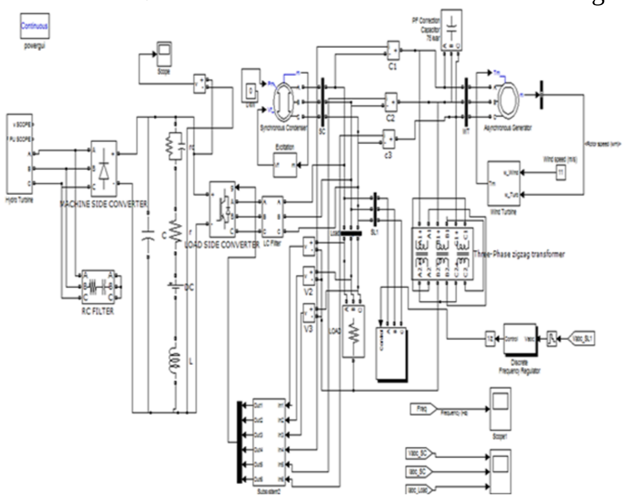

Figure 4.1: Simulink Block diagram of proposed system

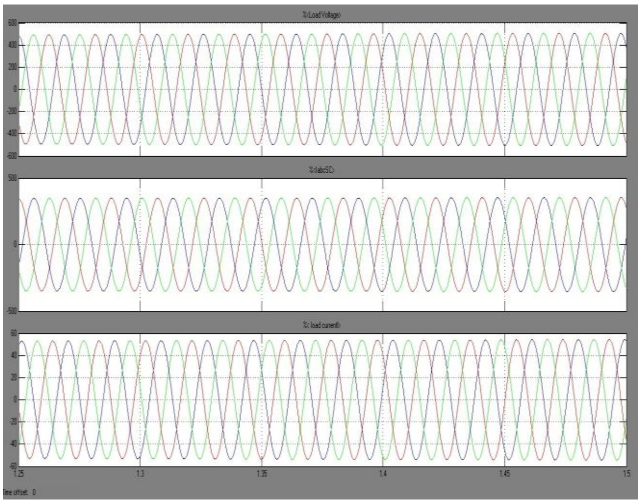

Figure 4.2 Output voltage and current waveforms for half load

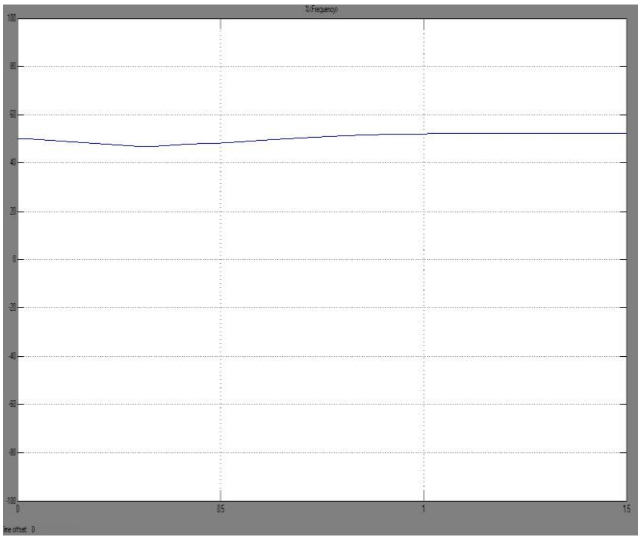

Figure 4.3: Frequency waveform for half load

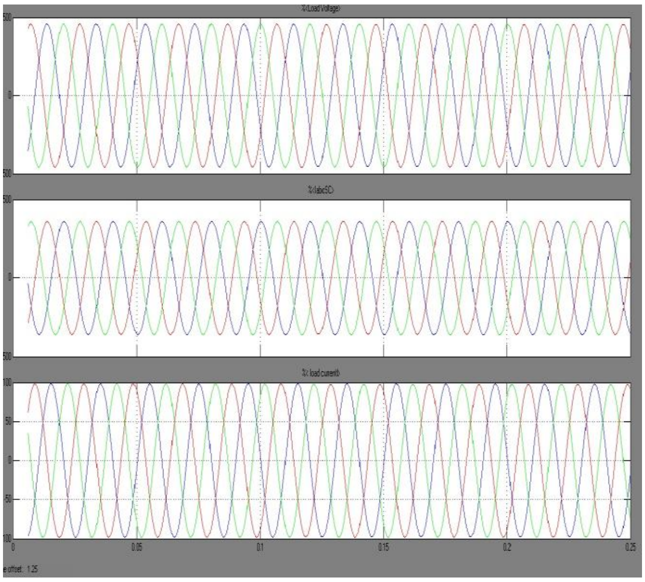

Figure 4.4 Output voltage and current waveforms for full load

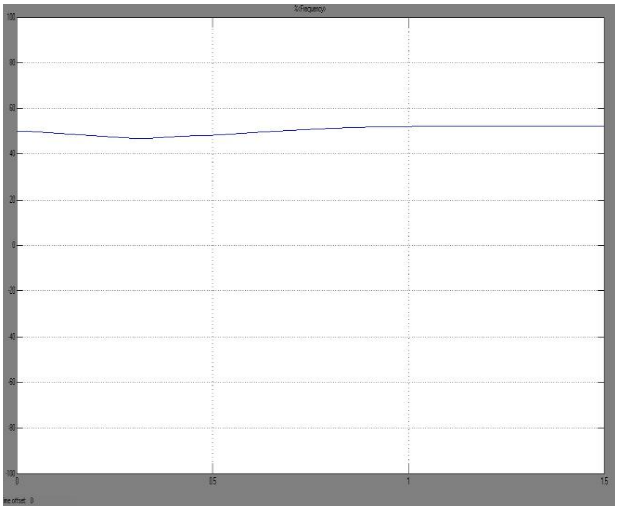

Figure 4.5: Frequency waveform for full load

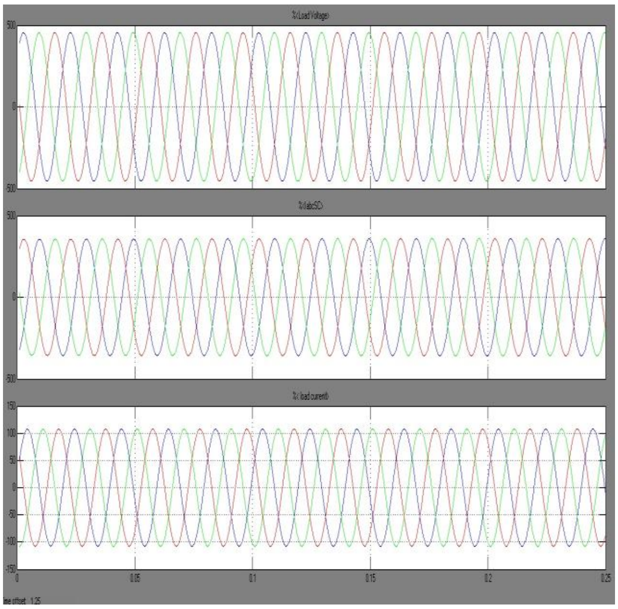

Figure 4.6: Output voltage and current waveforms for over load

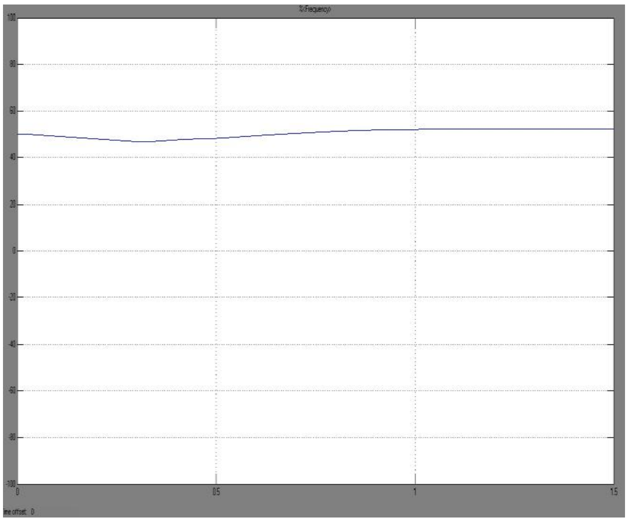

Figure 4.7: Frequency waveform for over load

V. Conclusion

Among the renewable energy sources, small hydro and wind energy have the ability to complement each other. Further, there are many isolated locations which cannot be connected to the grid and where the wind potential and hydro potential exist simultaneously. For such locations, a new three-phase four wire autonomous wind-hydro hybrid system, using one cage generator driven by wind turbine and another synchronous generator driven by hydro turbine along with BESS, has been modeled and simulated in MATLAB using Simulink and Sim Power System tool boxes. 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 (consumer load variation) and mechanical (with wind-speed variation) dynamic conditions. It has been demonstrated that the proposed hybrid system performs satisfactorily for linear loads while maintaining constant voltage and frequency.

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