

A Discrete PLL based Load Frequency Control of FLC-based PV-wind Hybrid Power System with Real Time Data

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ABSTRACT

The sun and wind-based generation are considered to be source of green power generation which can mitigate the power demand issues. As solar and wind power advancements are entrenched and the infiltration of these Renewable Energy Sources (RES) into the network is expanding dynamically. So, as to outline a legitimate control and to harness power from RES the learning of natural conditions for a specific area is fundamental. Fuzzy Logic Controller (FLC) based Maximum Power Point Tracking (MPPT) controlled boost converter are utilized for viable operation and to keep DC voltage steady at desired level. The control scheme of the inverter is intended to keep the load voltage and frequency of the AC supply at a constant level regardless of progress in natural conditions and burden. A Simulink model of the proposed Hybrid system with the MPPT controlled Boost converters and Voltage regulated Inverter for stand-alone application is developed in MATLAB R2015a, Version 8.5.0. The ongoing information of Wind Speed and Solar Irradiation levels are recorded at BITS-Pilani, Hyderabad Campus the performance of the voltage regulated inverter under constant and varying linear AC load is analyzed. The investigation shows that the magnitude of load voltage and frequency of the load voltage is maintained at desired level by the proposed inverter control logic.

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1. INTRODUCTION

A Hybrid Power system is a mix of distinctive types of power generations from Renewable Energy Sources (RES). The RES power generation, for example, Photovoltaic (PV), Wind, Fuel cell and so forth can be coordinated together to have a superior eco-friendly answer for power generation. Such generations are favorable as the power produced from RES will be complementing the other source. Keeping in mind the end goal to choose RES for a stand-alone application that will be complementary by nature, the learning of ecological conditions is key. The location with rich solar irradiance level and moderate wind speed profile gives the combination of PV-Wind hybrid power system with PV as the main source of generation and wind power as a complementing source. Similarly depending on the geographical locations the climatic conditions can be analyzed and perfect choice of RES can be selected to harness power the environmental conditions. In this study BITS-Pilani, Hyderabad Campus, TS, India is selected to analyze environmental conditions for the proposed PV-Wind hybrid power system. The major drawback of the stand-alone hybrid power system is to maintain the magnitude of output voltage and frequency in the desired limits [1]. To achieve the task to maintain the output voltage and frequency constant, many researchers have proposed control strategies and different combination of power electronic converters. H. Nian and R. Zeng [2] has presented a modified

control scheme for islanding operation of decentralized generation. The output voltage at the load-side has to be controlled with constant amplitude and frequency by the load side inverter. The authors have proposed a dual-loop control of the system under unbalance and non-linear load conditions. An experimental setup of 5kW stand-alone generation is shown in the paper. E. Barklund et. al [3] has contributed towards energy management by adjusting power generated in the system thereby minimizing the fuel requirement with stable operation. The control strategy employed was using Droop characteristics control of the micro-grid. The task is achieved by employing good mathematical analysis and small signal analysis. A laboratory prototype is built to analyze the performance of the EMS. Ozdemir, E. et. al [4] has worked towards a power supply frequency modulated inverter topology for a 3 ϕ islanded photovoltaic generation system with induction motor as a load. The simulated and experimental analysis exhibits the switching of the inverter can be achieved significantly at power frequency for an islanded operating Photovoltaic generation system.

It has been observed that a number of researchers have worked on PV-wind hybrid power system in terms of improving the MPPT tracking algorithm, optimal placement of PV-wind or combination of RES sources, energy management system, and optimization techniques for sizing of RES generation. Different topologies of inverter configurations were proposed and under investigation of various inverter topologies where the environmental conditions are assumed to be constant or simulated at Standard Test Conditions (STC)[5]–[8]. No specific research is reported on PV-Wind hybrid power system with real-time data of wind speed and solar irradiation for the southeast India. With the above backdrop, a simulation study is carried out to investigate the performance of voltage regulated three-phase inverter feeding an AC resistive load under different loading conditions with the ongoing values of wind speed and solar irradiation level recorded at BITS-Pilani, Hyderabad campus.

2. MODELLING OF PV-WIND HYBRID POWER SYSTEM

The block diagram of PV-wind hybrid power system is shown in Figure 1. The hybrid generation consists of Photovoltaic based generation, Wind Power Generation, Battery; Voltage regulated inverter and AC load. A comprehensive mathematical study of the RES generation will be discussed in this section.

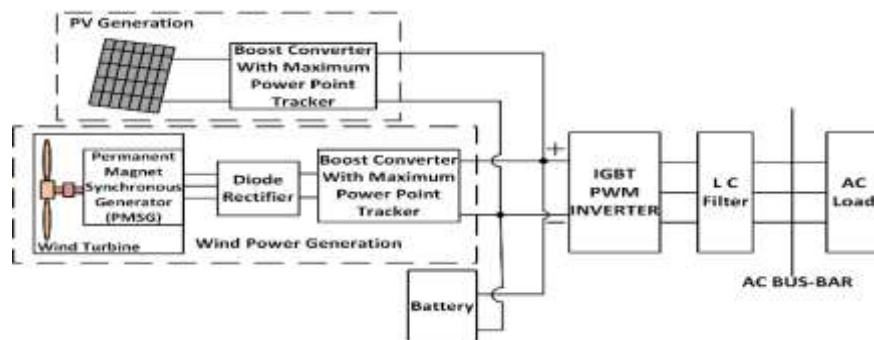


Figure 1. Block diagram of PV-Wind hybrid power system

2.1. Mathematical Modelling of PV Based Generation

The PV based generation consists of a PV panel, Maximum Power Point Tracking (MPPT) algorithm i.e. Perturb & Observe (P & O) algorithm, Boost converter. Innumerable mathematical model of PV cell was proposed in the literature out of which a two-diode model of PV cell [9]–[11] is selected for the simulation study. The output current of the two-diode model of PV cell can be written as (1)

$$I_{pv} = I_{PH} - I_{D1} - I_{D2} - I_{SH} \quad (1)$$

where the diode currents due to diffusion are I_{D1} , I_{D2} are rewriting (1) the load current of the PV cell is expressed by (2).

$$I = I_{ph} - I_{s1} \left[e^{\left(\frac{V + R_s \times I}{N_1 \times V_t} \right)} - 1 \right] - I_{s2} \left[e^{\left(\frac{V + R_s \times I}{N_2 \times V_t} \right)} - 1 \right] - \frac{V + R_s \times I}{R_p} \quad (2)$$

where, $V_t = \frac{N_s \times k \times T}{q}$ = thermal voltage, q is the charge on an electron (1.602×10^{-19} C), V is the cell output voltage, N_1 , N_2 is the quality factors of the diode D_1 , D_2 , k is the Boltzmann constant (1.38×10^{-23}), and T is the junction temperature. In order to achieve desired output power from PV generation, the PV panels are connected in arrays and string combination. To extract maximum power from the PV generation P & O MPPT algorithm is realized using Fuzzy Logic Controller (FLC) [12]-[13]. A boost converter is used to step up the output voltage of the PV generation to the desired level and to maintain the output voltage constant at that level. The duty cycle of the boost converter is controlled by the MPPT algorithm. Fuzzy implementation of P&O algorithm for PV system is based on calculating the error ($E(x)$) and change in error (ΔE). The equations involved in implementation are (3)-(7).

$$\Delta I = I(x) - I(x-1) \quad (1)$$

$$\Delta V = V(x) - V(x-1) \quad (2)$$

$$\Delta P = P(x) - P(x-1) \quad (3)$$

$$E(x) = \frac{\Delta P}{\Delta V} \quad (4)$$

$$\Delta E = E(x) - E(x-1) \quad (5)$$

2.2. Mathematical Modelling of Wind Based Generation

The Wind based generation consists of Wind turbine, Permanent Magnet Synchronous Generator (PMSG), Diode rectifier, MPPT algorithm (Hill Climb Search (HCS)), Boost converter. The wind turbine captures kinetics energy from the wind and converts it into mechanical energy. The power extracted from the wind by the wind turbine is expressed as (8).

$$P_o = \frac{1}{2} \rho A V^3 C_p \quad (8)$$

where,

P_o = the turbine output power, ρ = density of air (Kg/m³), A = swept area (m²), V = velocity of the air (m/s), C_p = Power Coefficient. The amount of mechanical power (P_m) extracted from the wind and torque (T_m) produced by the wind turbine is expressed as (9)

$$T_m = \frac{P_m}{\omega_m} \quad (9)$$

where, ω_m = rotor angular speed (rad/s).

$$\omega_m = \frac{\lambda V}{R} \quad (10)$$

where, R is the radius of wind turbine rotor in meters (m). The electromagnetic torque can be expressed in terms of i_q as (11).

$$T_e = 1.5 p i_q \lambda_o \quad (11)$$

The mechanical torque applied to the PMSG can be computed by (12)

$$T_m = T_e + D \omega_m + J \frac{d\omega_m}{dt} \quad (12)$$

where, D is the friction coefficient.

The load frequency and voltage of the generated power by PMSG directly depends on the wind speed. With the variation of wind speed the output voltage and frequency of the output voltage varies [14]. In order to maintain Load voltage and frequency constant the three-phase output voltage is converted into DC voltage using a diode rectifier. The DC voltage (V_s) is boosted up to the required load voltage (V_o) using an MPPT controlled boost converter. The output voltage can be computed by (13) [15].

$$V_s DT = (V_o - V_s)(1 - D)T \quad (13)$$

where, $D = \text{Duty cycle} = \frac{t_{on}}{t_{on} + t_{off}} = \frac{t_{on}}{T}$, T = Total time period of the switching. From which the dc voltage transfer function turns out to be

$$\frac{V_o}{V_s} = \frac{1}{1 - D} \quad (14)$$

The duty cycle of the boost converter is controlled using MPPT controller i.e. Hill Climbing Search (HCS). In order to compute the error the equations involved are

$$\Delta P(k) = P(k) - P(k-1) \quad (15)$$

$$\Delta \omega(k) = \omega(k) - \omega(k-1) \quad (16)$$

Where $P(k)$, $\omega(k)$ is the sample measured and $P(k-1)$, $\omega(k-1)$ is the previous sample. The HCS MPP tracking algorithm is realized using the fuzzy implementation in Matlab, Simulink, and equations involved in implementation are (3)-(5), (15) – (16) [16]. The modeling of voltage regulated inverter will be discussed in detail in the following section.

3. VOLTAGE REGULATED INVERTER DESIGN

The inverter plays a key role in the hybrid power generation. The load voltage, frequency is controlled and maintained constant using inverter in stand-alone operation. The proposed voltage regulated inverter maintains the output voltage and frequency constant irrespective of change in wind speed, solar irradiation levels, and load condition. The rectified and boosted DC voltage from the PV, the wind is applied as an input to the inverter. The schematic diagram of Voltage regulated inverter is shown in Figure 2.

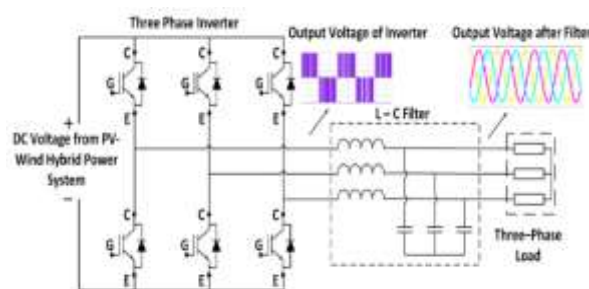


Figure 2. Voltage Regulated Inverter

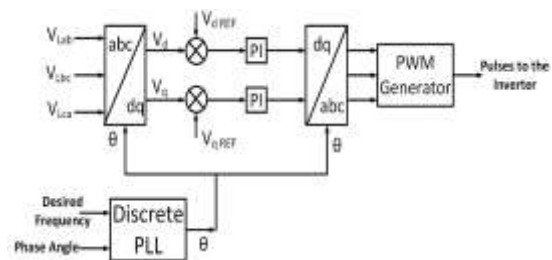


Figure 3. Block diagram of voltage regulated inverter

The important aspect of voltage regulated inverter is to maintain output voltage and frequency constant. In order to achieve the task, a discrete Phase Lock Loop (PLL) with Synchronous Reference Frame (SRF) is implemented to generate a control signal of the inverter. The block diagram of the control scheme is shown in Figure 3. Where V_{Lab} , V_{Lbc} , V_{Lca} are the live voltage of the load. The three-phase load voltage V_{Labc}

is sensed and using Clark transformation V_{Labc} is converted into $V_{a\beta}$ and this $V_{a\beta}$ reference frame is converted into dq reference frame. The angle θ is the estimated phase computed by the discrete PLL with the given value of the desired frequency i.e. 50 Hz and the phase angle is 0° . Depending on the phase estimated the V_α , V_β and V_d , V_q are computed which are then compared with the reference values and the error is fed to the PI controller further the control signal from dq frame is converted to abc and controlled Pulse Width modulated (PWM) signals are generated to control the switches in the inverter [17]. With this proposed control scheme the performance of the Voltage regulated inverter is investigated to maintain the three phase output voltage and frequency constant irrespective of change in load and environmental conditions. The real-time data of solar irradiation and wind speed measured at BITS-Pilani, Hyderabad campus is graphically represented in Figures 4-7.

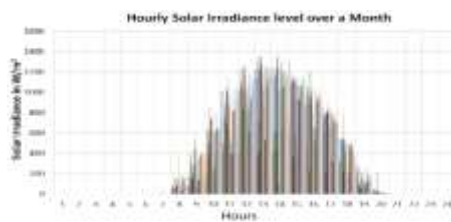


Figure 4. Hourly Solar Irradiance level measured over a month

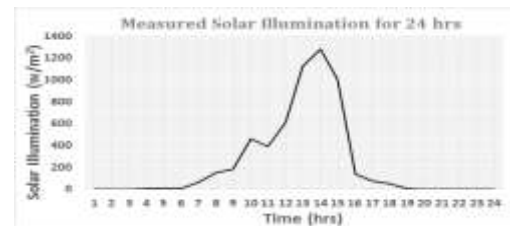


Figure 5. Solar Illumination measured for 24 Hr.



Figure 6. Hourly wind speed measured over a month

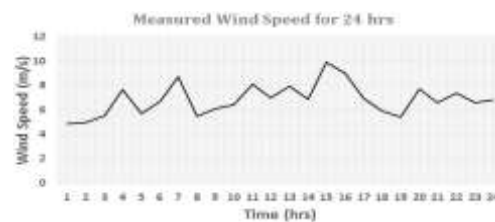


Figure 7. Hourly Wind speed measured over 24 Hr

Figure 4 shows the graphical representation of solar irradiation level measured over a month at the location. From the solar irradiation plot, it is clear that the location has a good solar energy with maximum solar irradiations level touching 1500 W/m^2 with average solar irradiation level around 600 W/m^2 . Figure 5 shows the graphical representation of hourly solar irradiance for the day it can be clinched that the location under consideration has a good solar irradiation level from 9 am to 5 pm with minimum irradiation of 400 W/m^2 and maximum value touching 1400 W/m^2 . From Figure 6 it can be projected that the wind profile is quite good for low wind speed generation with average wind speed above 3 m/s and with the average maximum wind speed of 12 m/s . It can be clearly comprehended from Figure 6 that the monthly average is above 3 m/s and touching 5 m/s and maximum wind speed is between 8 m/s to 14 m/s . Figure 7 shows hourly average and maximum wind speed for a day in the month of July it is clear that wind profile is quite good enough to build a direct driven wind power generation system with average wind speed above 4 m/s and maximum wind speed is stable at 11 m/s .

4. SYSTEM DESCRIPTION AND SIMULATION RESULTS

4.1. System Description

A 16 kW PV-Wind hybrid system implemented in MATLAB, Simulink consists of 6 kW of PV based generation and 10 kW of Wind based generation with a 1 kW of energy storage device i.e. battery supplying a variable three-phase AC load at 415 V . The control logic implementation of voltage regulated inverter is tested for different load variation till full load i.e. 16 kW at rated voltage of 415 V with Increasing and decreasing pattern of load. The increasing and decreasing load pattern are selected as the load on the system will be varying continuously and in order to investigate the performance of the control technique to maintain the output voltage and frequency constant under the said condition. The PV-Wind generation can

be extracted to its maximum value for a period of 8 hrs. in a day as solar irradiation is quite good from 9 am to 5 pm. considering this the simulation is carried out for 0.8 sec considering 0.1 sec to be 1 hour and the wind power generation will be complimenting the PV power generation to meet the load. The MATLAB, Simulink implementation of PV-Wind Hybrid power system is shown in Figure 8. The sub-system implementation of PV based generation and Wind based generation are shown in Figure 9 and Figure 10.

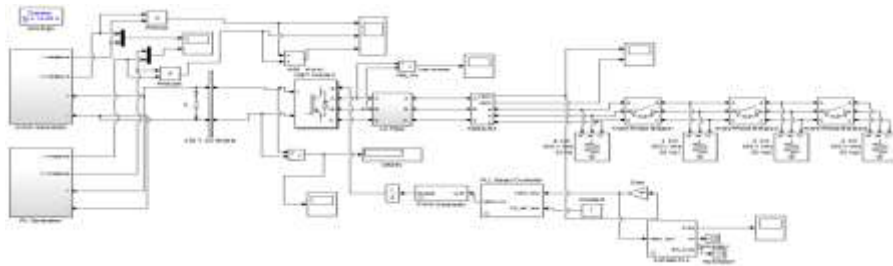


Figure 8. MATLAB, Simulink implementation of 16 kW PV-Wind hybrid power system

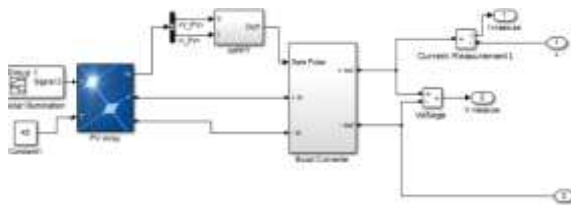


Figure 9. Sub-system implementation of PV based generation

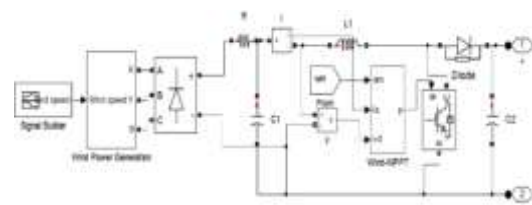


Figure 10. Sub-system implementation of Wind based generation

4.1. Simulation Results

4.1.1. Case i: Increasing Load Pattern

The load in the PV-Wind hybrid power system is gradually increased in steps from 8 kW to 16 kW and the performance of the control technique is investigated. The real-time data of wind speed and solar illumination as shown in Figure 7 and Figure 5 are realized in simulation using a signal builder as shown in Figure 9 and Figure 10 and the amount of power generated from the PV-Wind hybrid power system is simulated and graphical representation of the power output from RES generation is shown in Figure 11. It can be clearly comprehended that the PV and wind-based generations that the wind-based generation is complimenting the PV based generation in the variable load and environmental condition and the control logic implementation of inverter achieved the power flow control of the system. The DC Bus-Bar acts as input to the inverter and the simulated DC voltage, current and power input to the inverter are shown in Figure 12.

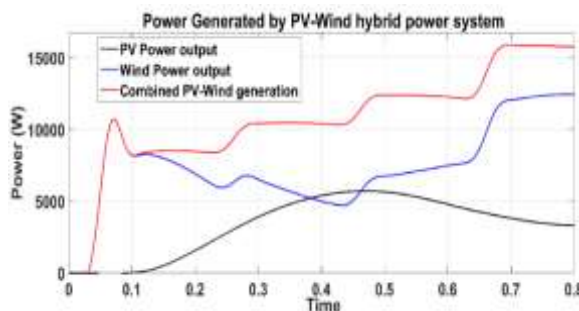


Figure 11. PV-Wind hybrid power output for increasing load pattern with the real-time data

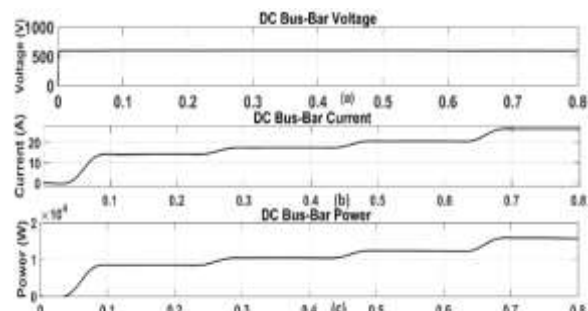


Figure 12. Simulated DC Bus-Bar (a) Voltage, (b) Current and (c) Power under increasing load pattern

It can be comprehended from Figure 12 that the fuzzy implementation of MPPT controlled boost converter maintained the DC bus-bar voltage at 600 V constant irrespective of change in environmental condition and load condition thereby ensuring power flow in the system. The simulated AC load voltage, current, and frequency are plotted in Figure 13, Figure 14 and Figure 15 respectively.

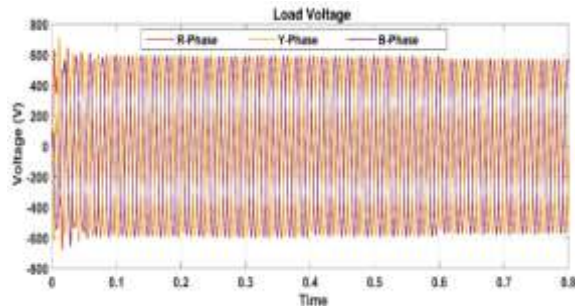


Figure 13. Simulated Load voltage

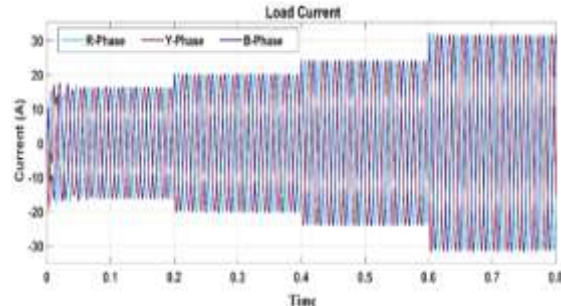


Figure 14. Simulated Load Current

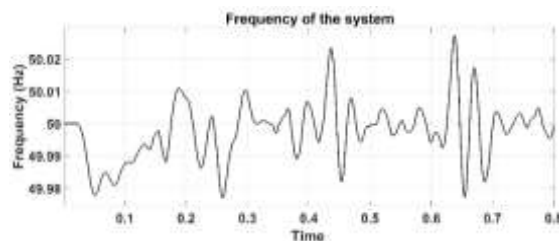


Figure 15. Simulated Frequency of the system

Table 1. THD for Increasing load pattern

	THD (before filter)	THD (after filter)
Voltage	63.68 %	1.52%
Current	8.12%	1.91%

From Figure 13 it can be observed that the load voltage remains constant at 590 V maximum value and 417 V RMS value with respect increasing pattern of the resistive load from 8kW, 10kW, 12kW and 16kW which can be observed by a change in load current drawn in Figure 14. The Frequency of the system under increasing load pattern is within the grid code with the maximum frequency of 50.025Hz and minimum of 49.975 Hz as shown in Figure 15. The allowed frequency deviation according to the grid code is 49.7-50.2 Hz. The control implementation is showing a better frequency control with less than 2% deviation. The Total Harmonic Distortion (THD) of the system is analyzed for both voltage, current and tabulated as shown in Table 1. It can be comprehended that the THD of the load voltage and current from the inverter has a tremendous reduction.

4.1.2. Case ii: Decreasing Load Pattern

The PV-Wind hybrid power system is tested for decreasing load pattern from full load of 16 kW to 8 kW in steps. This pattern of the load is considered to investigate the performance of the control logic implementation of voltage regulated inverter to maintain the load voltage and frequency constant irrespective of change in environmental conditions. The real-time data of wind speed and solar illumination as shown in Figure 7 and Figure 5 are inputs to the PV-Wind Hybrid power system and the amount of power generated from the PV-Wind hybrid power system is simulated and graphically represented in Figure 16.

The simulated dc voltage, current and power input to the inverter are plotted in Figure 17. From the Figure 17(a) it can be comprehended that the DC bus-bar voltage is maintained constant at 600 V irrespective of change in environmental and load conditions. From Figure 17(b), (c) represents dc bus-bar current and power. The simulated AC load voltage, current, and frequency of the system are plotted.

From Figure 18 it can be observed that the load voltage remains constant at 590 V maximum value and 417 V RMS value with respect increasing pattern of a load from 16kW, 12kW, 10kW and 8kW which can be observed by a change in load current drawn in Figure 19. The Frequency of the system under increasing load pattern is within the grid code with the maximum frequency of 50.037Hz and minimum of 49.935 Hz as shown in Figure 20. The allowed frequency deviation according to the grid code is 49.7-50.2 Hz. The control implementation is showing a better frequency control with less than 2% deviation. The Total Harmonic

Distortion (THD) of the system is analyzed for both voltage, current and tabulated as shown in Table. 2. It can be comprehended that the THD of the load voltage and current from the inverter has a tremendous reduction.

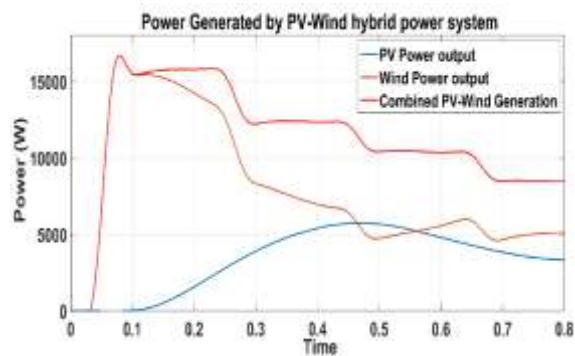


Figure 16. PV-Wind hybrid power output for decreasing load pattern with the real-time data

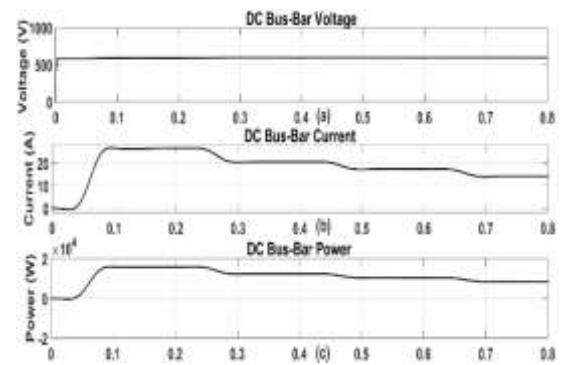


Figure 17. Simulated DC Bus-Bar (a) Voltage, (b) Current and (c) Power under decreasing load pattern

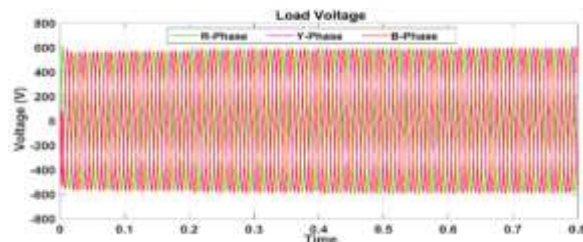


Figure 18. Simulated Load Voltage

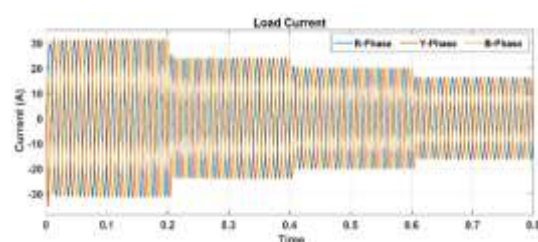


Figure 19. Load Current

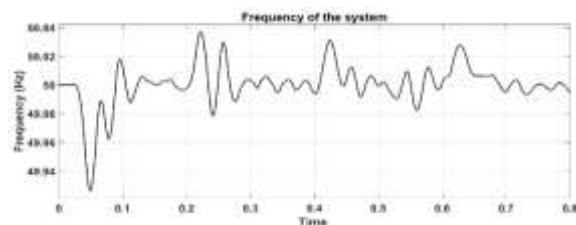


Figure 20. Simulated frequency of the system

Table 2. THD for Decreasing load pattern

	THD (before filter)	THD (after filter)
Voltage	62.64 %	1.8%
Current	9.77%	2.04%

5. CONCLUSION

In this paper, a mathematical model of PV-Wind hybrid system is presented with a two-diode model of PV cell and PMSG based generation. A 16 kW PV-Wind hybrid system is implemented in the MATLAB, Simulink. The real-time data of solar irradiation, wind speed are measured at BITS-Pilani, Hyderabad campus is utilized as the input to the PV-Wind hybrid system. A P&O, HCS MPPT tracking algorithm is used for PV, Wind based generation to control the duty cycle of the boost converter. The performance of FLC-based MPPT controlled boost converter and Voltage regulated inverter are investigated for PV, Wind based generation individually and interconnected PV-Wind hybrid power system for varying load conditions. In interconnected PV-Wind hybrid power system, a common DC bus-bar with 600 V is formed and this DC voltage acts as input to the voltage regulated inverter. A voltage regulated inverter is implemented in order to control the output AC voltage at 415 V, 50 Hz. A discrete PLL based control logic is proposed to control the AC output voltage of the inverter.

The performance analysis of the voltage regulated inverter is tested under different loading conditions with resistance load. It can be concluded that the proposed control logic operates as desired and the output voltage of the PV-Wind hybrid system is maintained constant at desired level of 415 V and the system

frequency is maintained within the frequency deviation is 49.93 to 50.05 Hz. The proposed discrete PLL based control scheme operates as desired by maintaining the load voltage and frequency constant thereby making the system more reliable, efficient. Future work may include analyzing the performance of the voltage regulated inverter for grid integration and realization of simulation results with a prototype model development.

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