D. Mahesh Naik et al Int. Journal of Engineering Research and Applications www.ijera.com
ISSN : 2248-9622, Vol. 4, Issue 7(Version 6), July 2014, pp.131-139

RESEARCH ARTICLE OPEN ACCESS

Dynamic Modeling, Control and Simulation of a Wind and PV Hybrid System for Grid Connected Application Using MATLAB

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Abstract
This paper proposes a dynamic modeling and control strategy for a grid connected hybrid wind and photovoltaic (PV) energy system inter-connected to electrical grid through power electronic interface. A gearless permanent magnet synchronous generator (PMSG) is used to capture the maximum wind energy. The PV and wind systems are connected dc-side of the voltage source inverter through a boost converter individually and maintain a fixed dc output at dc link. A proper control scheme is required to operate power converters to match up the grid connection requirements. This study considered the performance of modeled hybrid system under different case scenarios. All simulation models are developed using MATLAB/Simulink.
***Index Terms*—** Wind turbine (WT) model,PMSG, Photovoltaic (PV) model, Grid side converter (PWM Inverter), Grid connected hybrid system model.

I. INTRODUCTION

The ever-increasing demand for nonrenewable energy sources like coal, natural gas and oil is driving society towards the research and development of renewable energy sources. Many such energy sources like wind energy and Photovoltaic (PV) are now well developed, cost effective and are being widely used. These energy sources are preferred for being environmental-friendly. Renewable energy based distributed generators (DGs) play a dominant role in electricity production, with the increase in the global warming. Distributed generation based on renewable energy sources will give significant momentum in near future. The integration of these renewable energy sources to form a Hybrid system consist of two or more renewable or nonrenewable energy sources [1] [2], is an excellent option for distributed energy production. The Power ranges of renewable energy generation is small compared to nonrenewable energy generation, these renewable energy generation technology is located near the load or connected to the utility grid [2].

The hybrid system consist of two renewable sources which are wind and solar energy are used as an input sources. A Wind Turbine (WT) converts mechanical energy in to electrical energy and it produces ac output voltage is converted to dc output by using rectifier. A PV cell converts light energy in to electrical energy and it produces dc output voltage. In order to maintain constant dc- link voltage, to regulate outputs from the wind and solar systems by using dc-dc boost converter [6]. The Grid-connected hybrid wind and PV system has more reliability to deliver continuous power to the load, if any shortage from the renewable energy sources the loads are directly connected to the grid. A voltage source inverter (VSI) is controlled by using d-q based current control method[1] to control the operation of the grid connected hybrid system.

II. PROPOSED SYSTEM ARCHITECTURE

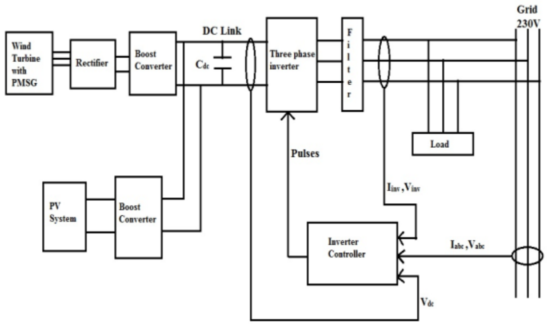


Fig.1 Architecture of the Proposed System

The Architecture of the proposed hybrid system is shown in figure 1. The input sources of the hybrid system are wind and solar energy. A dc-dc boost converter [6] is used to integrate these renewable energy sources at dc link. The constant dc link voltage is given as the input of the inverter, to get desired ac output voltage by using d-q based current control method. The output of the inverter (230V, 50Hz) is fed to the grid through RL filter it gives ripple free voltage.

III. MODELING OF HYBRID SYSTEM

A. Wind Turbine Modeling

The wind turbine captures the wind's kinetic energy in a rotor consisting of two or more blades mechanically coupled to an electrical generator. Aerodynamic power available in the wind can be calculated as [3]:

$$P_w = C_p \frac{\rho A}{2} V_w^{\ 3} \quad (1)$$

Where P_w is output of the wind turbine [W], ρ is the air density [kg/m^3], A is the wind turbine swept area [m^2], V_w is the wind speed [m/s], and C_p is the coefficient of performance.

The coefficient of performance (C_p) is depends on the tip speed ratio (λ) and blade pitch angle (β). The tip speed ratio is defined as the ratio between the rotational speed of a blade and actual velocity of the wind. The blade pitch angle [3] (β=0°) always maintain zero degrees because of WT gives maximum torque. The C_p is the fraction of the upstream wind power, which is captured by the rotor blades. The remaining power is discharged or wasted in the downstream wind, theoretically maximum value of C_p is 0.59.

TABLE 1
Parameters and specifications of wind turbine model

PARAMETER	RATING
Rated Power	20 kW
Rated wind speed	12 m/s
Rated Rotor speed	22.0958 rad/s
Blade Radius	2.7 m
Blade Pitch Angle	0 degree
Air Density	1.225 kg/m^3

The parameters or specifications of wind turbine (WT) used in this paper is shown in table 1. In order to get maximum torque from the WT the blade pitch angle (β) is kept at zero degrees.

B. Generator modeling

The Permanent Magnet Synchronous Generator (PMSG) is used to produce electricity from the mechanical energy obtained from the wind. The two-phase synchronous reference frame is used to derive the dynamic model of the PMSG, which is q-axis is 90° ahead of the d-axis with respect to the direction of rotation [4]. In order to maintain synchronization between the two-phase quantity (d-q reference frame) and the three-phase quantity (abc-three phase frame) by using a phase locked loop (PLL) [4].

The mathematical model of the PMSG in the synchronous reference frame (in the state equation form) is given by [4]

$$\frac{di_d}{dt} = \frac{1}{L_{ds} + L_{ls}} \left(-R_s I_d + \omega_e \left(L_{qs} + L_{ls}\right) i_q + u_d\right) (2)$$

$$\frac{di_q}{dt} = \frac{1}{L_{qs} + L_{ls}} \left(-R_s I_q - \omega_e \left[\left(L_{ds} + L_{ls}\right) i_d + \psi_f\right] + u_q\right) \ (3)$$

Where subscripts d and q refer to the physical quantities that have been transformed into the d-q synchronous rotating reference frame, R_s is the stator resistance [Ω], L_d and L_q are the d and q axis inductances [H] of the generator, L_{ld} and L_{lq} are the d and q axis lekage inductances [H] of the generator, ψ_f is the permanent magnetic flux [Wb] and ω_e is the electrical rotating speed [rad/s] of the generator. The electromagnetic torque equation of the PMSG is given by [4]

$$\tau_e = 1.5p\left(\left(L_{ds} - L_{ls}\right) i_d i_q + i_q \psi_f\right) \quad (4)$$

Where p is the number of pole pairs of the generator. The PMSG is give better performance compared to the induction generator because it does not have rotor current, the additional advantage of the PMSG is using a without gearbox results in reduction of cost and reduction of weight of the nacelle.

TABLE 2
Specifications of Direct Driven PMSG Model

PARAMETER	RATING
Rated Power	20 kW
Rated line Voltage	380.14 V_{rms}
Stator phase inductance	22.0958 mH
Stator phase Resistance	2.7Ω
No. of poles	36
Rated mechanical speed	211 rpm

C. PV Modeling

The PV cell converts light energy to electrical energy through the photoelectric phenomena [5]. The physics of the PV cell is similar to the p-n junction diode [3]. The complex physics of the PV cell can be represented by the equivalent electrical circuit shown in Figure 2.

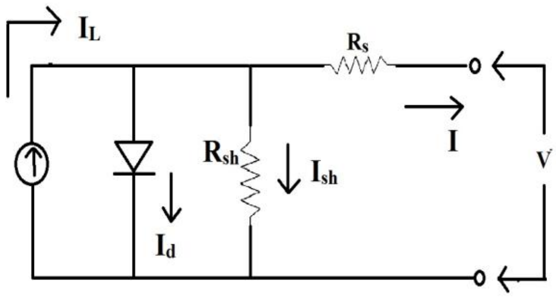


Fig. 2 PV cell in a single diode model

The output terminal current (I) is equal to the current generated by the illumination (I_L), less the diode current (I_d) and the shunt leakage current (I_{sh}). The series resistance (R_s) shows the internal resistance to the current flow, and depends on the p-n junction depth, the impurities and the contact resistance. The PV conversion efficiency is sensitive to small variation in R_s but is insensitive to variations in shunt resistance (R_{sh}). A small increase in R_s can decrease the PV output significantly [3].

To describing the PV cell electrical performance, two important parameters are considered, they are open-circuit voltage (V_{oc}) and the short-circuit current (I_{sc}). The V_{oc} of the cell is obtained when load current is zero is given by the following [3]:

$$V_{oc} = V + IR_{sh} \quad (5)$$

$$I_d = I_D \left[\frac{QV_{oc}}{AKT} - 1\right] \quad (6)$$

Where, I_d = the diode current
I_D = the saturation current of the diode
Q = electron charge $=1.6\times10^{-19}$ Coulombs
A = curve fitting or diode ideality constant
K = Boltzmann constant = 1.38×10^{-23} joule/°K
T = Temperature on absolute scale (°K)

The load current is therefore given by the expression [3]:

$$I = I_l - I_D \left[e^{\frac{QV_{oc}}{AKT}} - 1\right] - \frac{V_{oc}}{R_{sh}} \quad (7)$$

The maximum photovoltage is produced under the open-circuit voltage, by ignoring the ground leakage current, equation 7 with I = 0 gives the open circuit voltage [3] as the following:

$$V_{oc} = \frac{AKT}{Q} Log_n \left(\frac{I_L}{I_D} + 1\right) \quad (8)$$

The photoconversion efficiency [3] of the PV cell is defined as the following:

$$\eta = \frac{electricalpoweroutput}{solarpowerimpingingthecell} \quad (9)$$

In this paper a KC200GT PV module is considered. The parameters or specifications of a KC200GT PV module is shown in Table 3.

Table 3 Parameters of KC200GT PV module under STC

PARAMETER	RATING
Maximum power (P_{max})	$200W$ (+10% /−5%)
Maximum power voltage (V_{mpp})	26.3V
Maximum power current (I_{mpp})	7.61A
Open-circuit voltage (V_{oc})	32.9V
Short circuit current (I_{SC})	$8.21A$
Series Connected cells (N_s)	54
Module Unit	54 cells, 200W, 1kW,25°C
Module Numbers	10×3=30
Power Rating	30×200=6000W

D. DC-DC Boost Converter

The DC-DC Converters are widely used in regulated switch mode DC power supply [6]. In this paper the dc-dc boost converter is used to regulate DC output voltage from the Wind and PV array at dc-link, but wind turbine produces ac output that is converted to dc by using Rectifier. The circuit of the dc-dc boost converter is shown in Figure 3. From the circuit diagram mainly it consists four components: Inductor, Electronic switch, Diode and output capacitor.

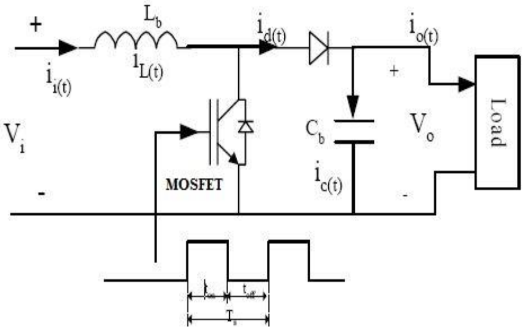


Fig. 3 Circuit of DC-DC Boost converter

The boost converter can operate in two modes of operation. These two operating modes are continuous conduction mode (CCM) for efficient power conversion, and discontinuous conduction mode (DCM) for low power or stand-by operation. In this paper the boost converter operates in continuous conduction mode. The operation of the CCM explained is as follows [6]:

Mode 1: ($0<t\leq t_{on}$)

In this mode of operation, the MOSFET's is switched on at t = 0 and terminates at $t = t_{on}$. The current in inductor is increases linearly when the switch is ON state, at this the inductor voltage is V_i.

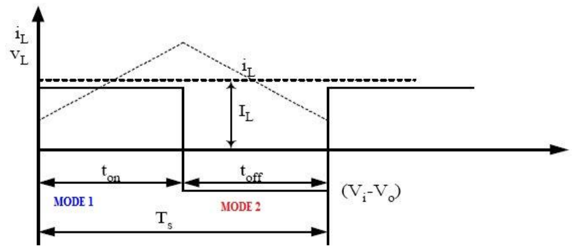


Fig. 4 switching diagram of the dc-dc boost converter in CCM

Mode 2: ($t_{on}<t\leq T_s$)

In this mode of operation, the MOSFET's is switched off at $t = t_{on}$ and terminates at $t = t_s$. The energy stored in the inductor is released through diode, so current in the inductor decreases until the MOSFET's is turned on again during the next cycle. The voltage across the inductor is V_i-V_o. Since in steady state time integral of the inductor voltage over one time period must be zero [6].

$$V_i t_{on} + (V_i-V_0)t_{off}= 0 \qquad (10)$$

Where V_i is the input voltage (V), V_o is the average output voltage (V), t_{on} is the switching on of the MOSFET's (s), and t_{off} is the switching off of the MOSFET's (s). Dividing both sides by T_s and rearranging the equation 10, then

$$\frac{v_o}{v_i} = \frac{T_s}{t_{off}} = \frac{1}{1-D} \qquad (11)$$

Where T_s is the switching period (s), and D is the duty cycle.

IV. CONTROL SYSTEMS DESIGN

In this paper the hybrid system consists of two renewable sources, wind and PV system. The WT is a machine it converts wind energy to the electrical energy, generally it produces ac output voltage is converted to dc output voltage by using Rectifier. In order to get maximum torque from the WT the blade pitch angle (β) is always maintain zero degrees by using pitch angle control. The dc output voltage of the Rectifier is given as an input to the dc-dc boost converter, which regulates dc output voltage to a 480V DC. The PV cell produces the electrical energy from the light energy. The PV array produces DC output voltage. A maximum power point tracking (MPPT) is used to draw the maximum power from the PV array. The unregulated dc output voltage of the PV array is given to the boost converter.

A DC-DC Boost converter is used to regulate the dc output voltage from the Wind and PV system to a 480V DC individually. In order to produce constant output voltage, a voltage feedback control is used. In this control system the measured output voltage of the boost converter is compared with the reference voltage (480V) and the error value is given to the PWM block through a PI controller, then the PWM block produces the required firing pulses to the MOSFET's. Then the boost converter gives the desired output voltage (≈480V DC).

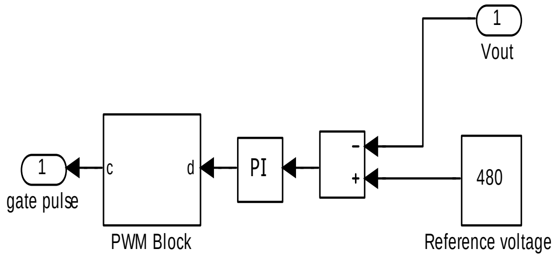


Fig. 5 PI controller of DC-DC boost converter

To integrate the Wind and PV hybrid system at dc link by using boost converter. The constant dc-link voltage (480V DC) is given as an input to the voltage source inverter (VSI), which converts the ac output voltage (230V RMS, 50Hz) is fed to the grid.

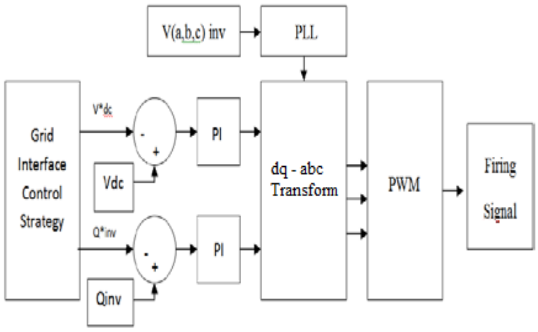


Fig. 6 Current regulated control of Grid side converter

The current regulated control of grid side converter is shown in Figure 6. The grid side converter is a current regulated converter with the

- direct axis current is used to regulate the dc-link voltage and
- quadrature axis current is used to regulate the reactive power. In the study the reactive power demand set to zero to ensure unity power factor.

V. SIMULATION RESULTS

The overall simulation diagram of grid connected wind and PV hybrid system is shown in Figure 7. In this paper the rated power of hybrid system is studied for 26kW, in which the rating of the wind system is 20kW and the rating of PV system is 6kW.

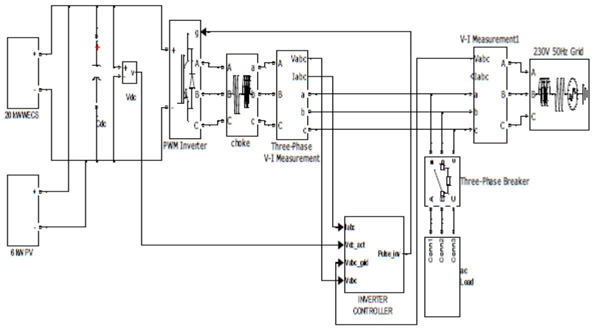


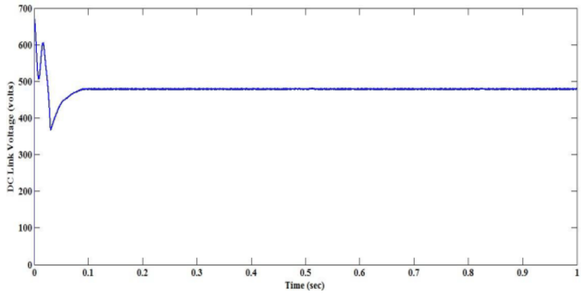
Fig.7 Overall simulation diagram of Grid connected wind /PV hybrid system

The system performance is studied under different case scenarios. The system parameters used in the simulation is shown in Table 4.

Table 4 System parameters for simulation

PARAMETERS		**VALUES**
Wind	*Input (Wind speed)*	*8 m/s*
	Maximum power	*20kW*
	Output voltage	*480*V_{dc}
PV array	*Inputs (Temp. and irradiation)*	*900W/m*^{2}*, 25°C*
	Maximum power	*6kW*
	Output voltage	*480*V_{dc}
Rating of Load	*Load 1*	*7.5kW, 5.0404kVAr*
	Load 2	*4kW, 3.314kVAr*
DC-link voltage		*480*V_{dc}

Case-1: Constant Generation & Constant Load



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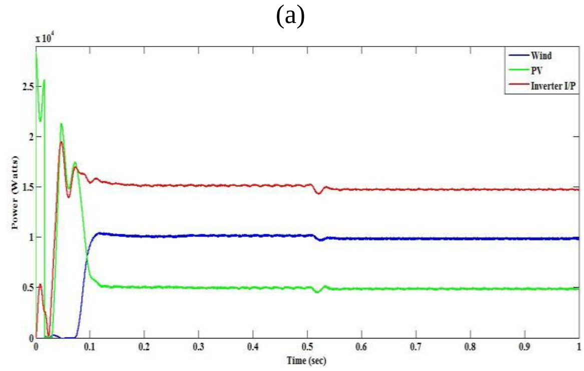

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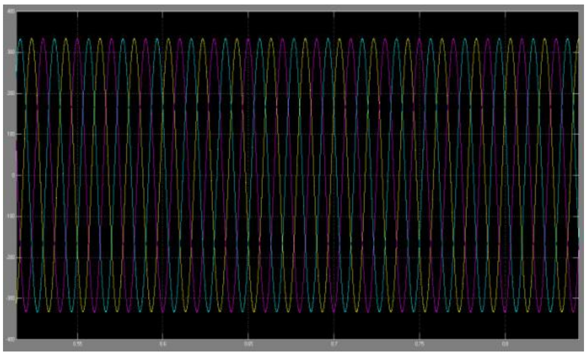

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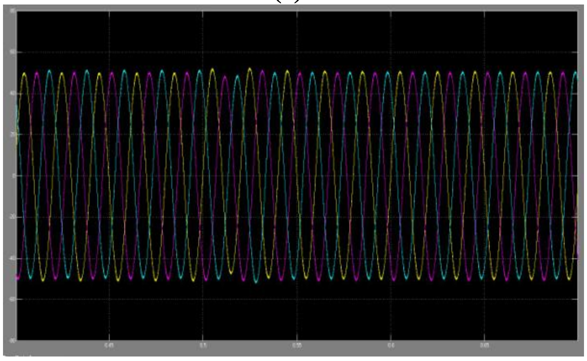

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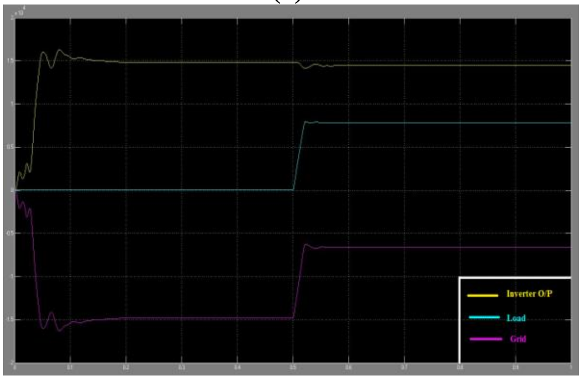

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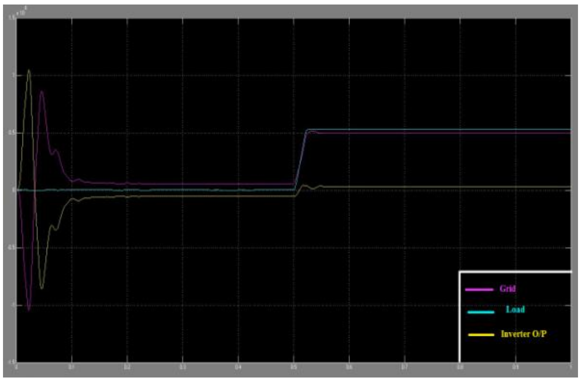

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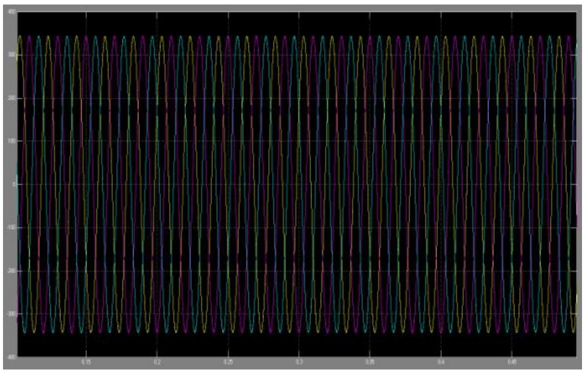

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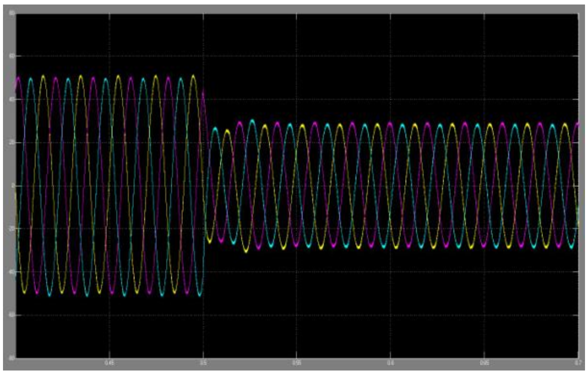

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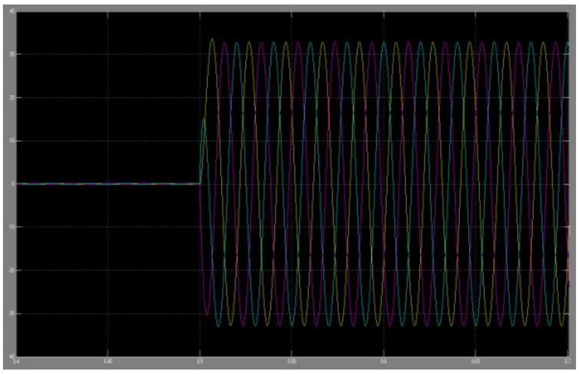

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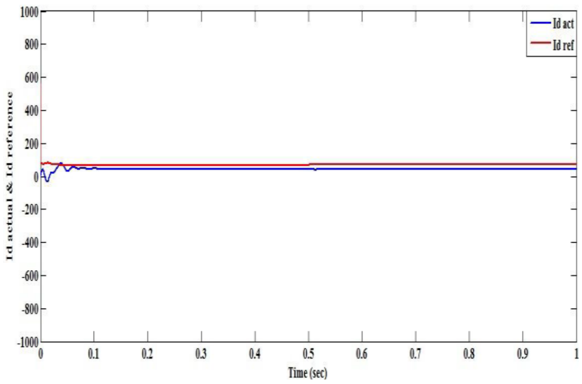

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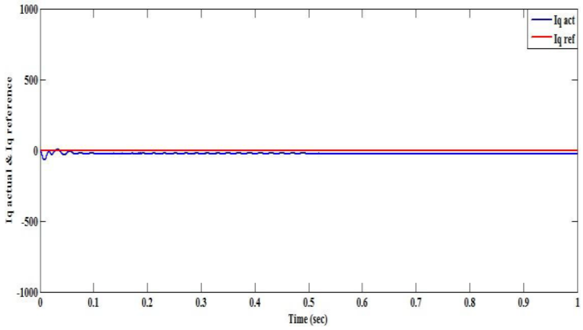
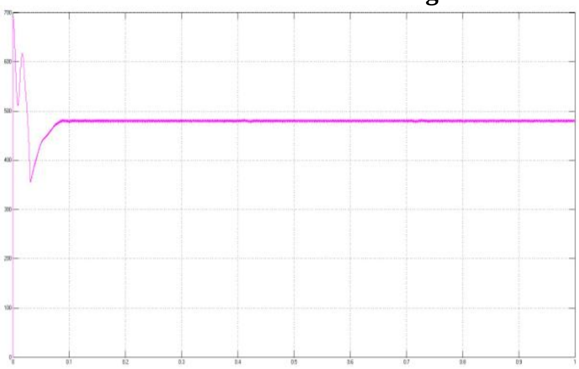


(k)

Fig. 8 Hybrid system case-1 performance. (a). DC-link voltage (V_{dc}),(b) Hybrid system power (kW), (c) Inverter output voltage(V),(d) Inverter output current (A), (e) Active power distribution (kW), (f) Reactive power distribution (kVAr), (g) Grid voltage (V), (h) Grid current (A), (i) Load current (A), (j) I_d actual tracking I_{dref} reference, (k) I_q actual tracking I_{qref} reference.

In this simulation the generation is constant means inputs of the hybrid system is kept constant is shown in Table 4. The load and grid voltage is maintained at Peak voltage 325.26V, 50Hz. The hybrid system is simulated for 1 second. The load 1 is shown in Table 4, is injected at 0.5 s by the breaker to the 230V, 50Hz Grid. The load is supplied from the hybrid system and remaining power is fed in to the grid. To regulate the dc bus voltage to 480$V_{dc}$by using boost converter.

Case-2: Constant Generation & Change in Load



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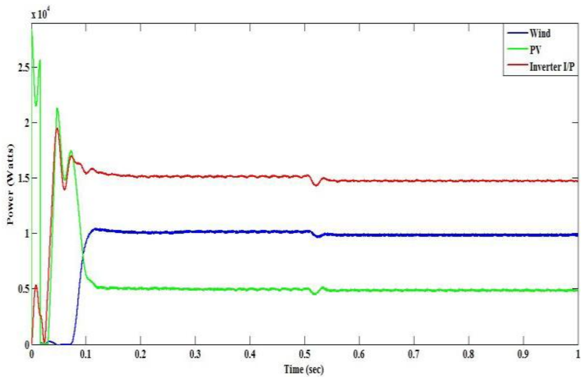

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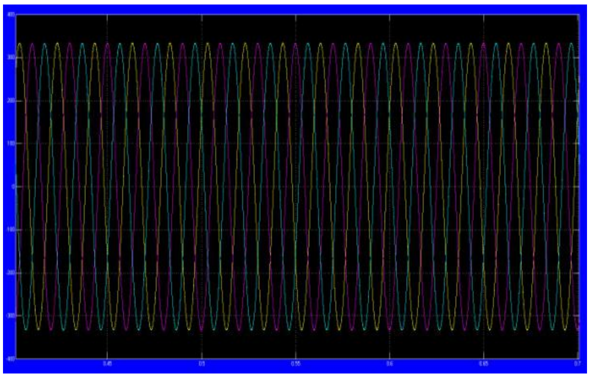

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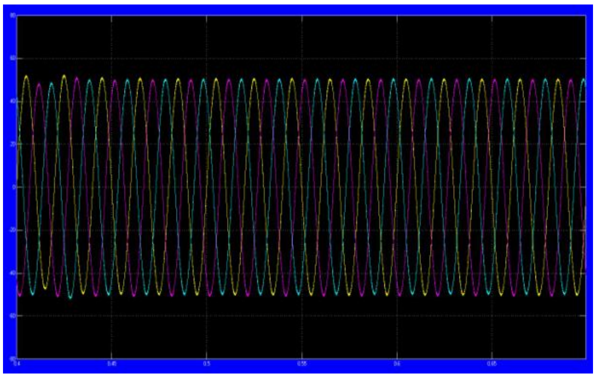

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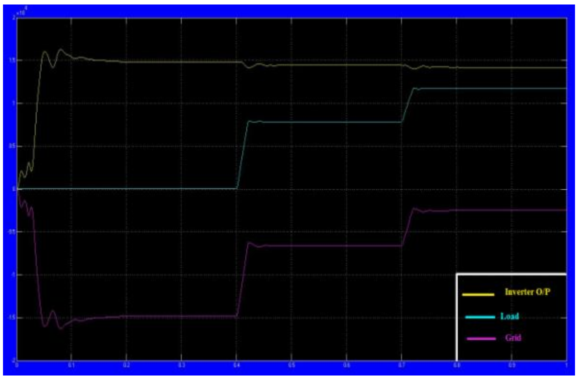

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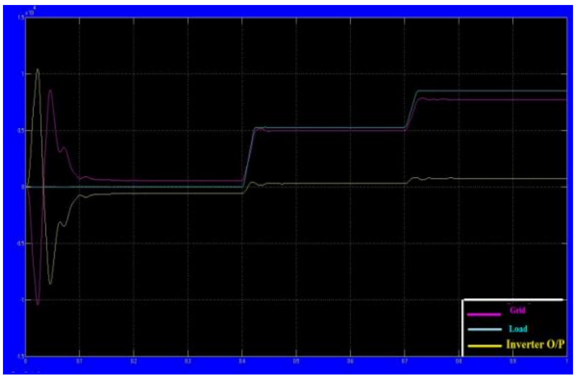

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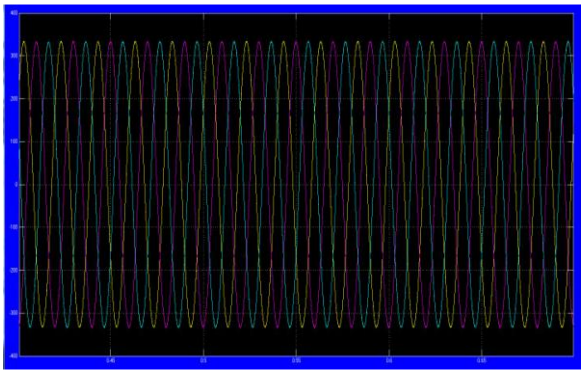

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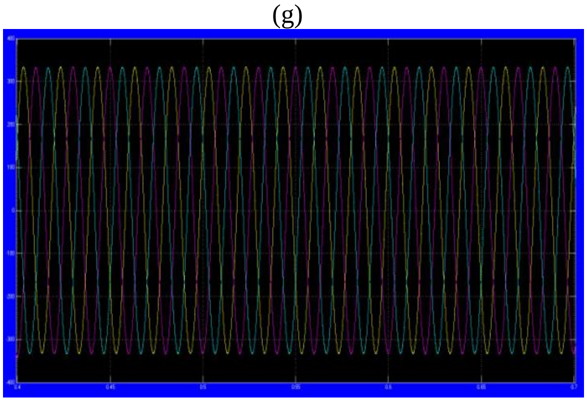

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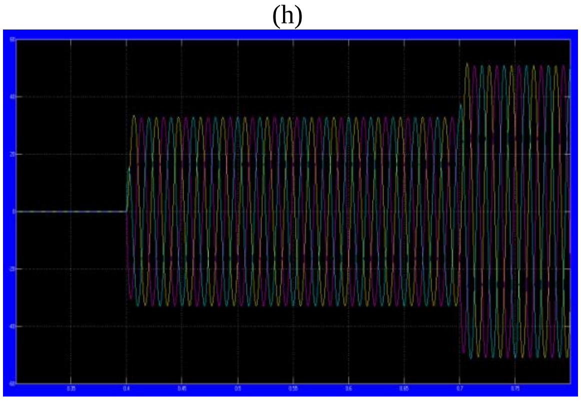
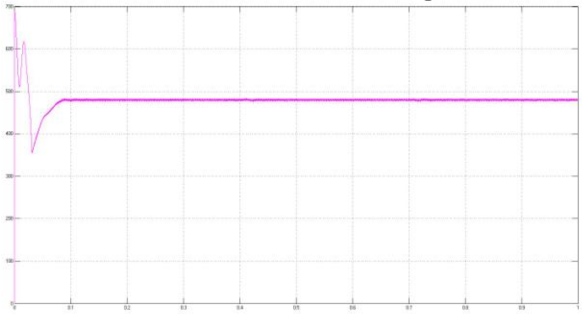


(i)

Fig. 9 Hybrid system case-2 performance. (a). DC-link voltage (V_{dc}),(b) Hybrid system power (kW), (c) Inverter output voltage(V), (d) Inverter output current (A), (e) Active power distribution (kW), (f) Reactive power distribution (kVAr), (g) Grid voltage (V), (h) Load voltage (V), (i) Load current (A).

In this simulation the generation is constant means inputs of the hybrid system is kept constant is shown in Table 4. The load and grid voltage is maintained at Peak voltage 325.26V, 50Hz. The hybrid system is simulated for 1 second. The load 1 is injected at 0.4 s by the breaker 1 and the load 2 is injected at 0.7 s by the breaker 2 is shown in Table 4, to the 230V, 50Hz Grid. The load is supplied from the hybrid system and remaining power is fed in to the grid. To regulate the dc bus voltage to 480$V_{dc}$by using boost converter.

Case-3: Variable Generation & Change in Load



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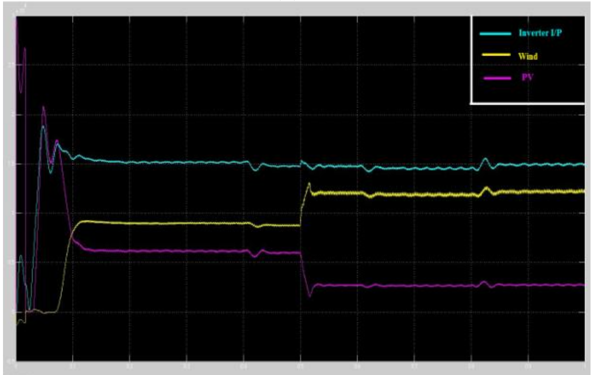

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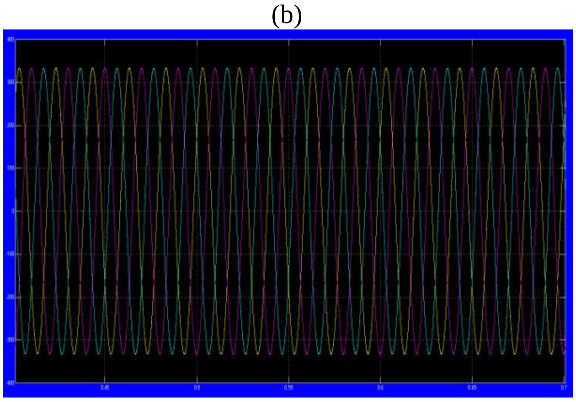

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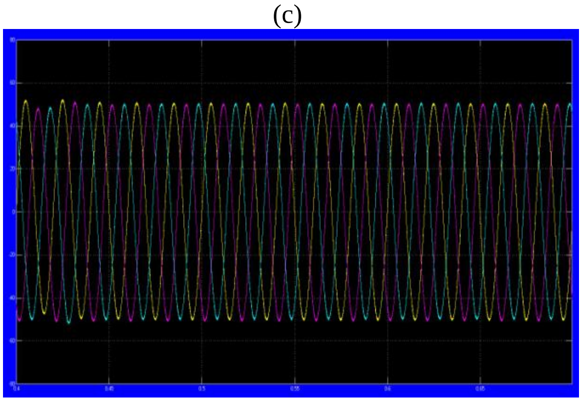

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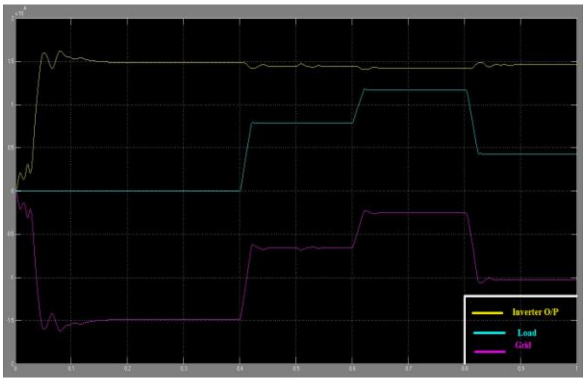

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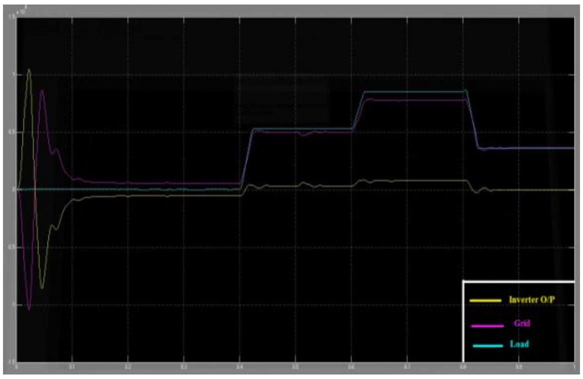
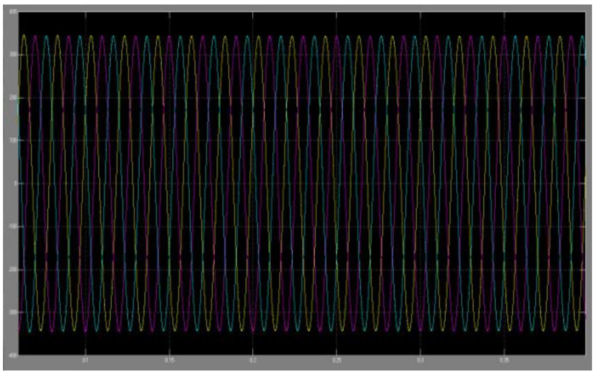
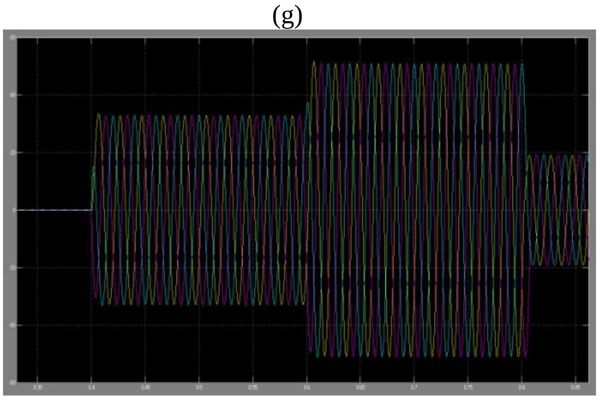


(f)



(g)



(h)

Fig. 10 Hybrid system case-3 performance. (a). DC-link voltage (V_{dc}), (b) Hybrid system power (kW), (c) Inverter output voltage(V), (d) Inverter output current (A), (e) Active power distribution (kW), (f) Reactive power distribution (kVAr), (g) Grid voltage (V), (h) Load current (A).

In this simulation the generation is varying means inputs of the hybrid system shown in Table 4 is change of irradiance from 900 W/m^2 to 600 W/m^2 at 0.5s similarly the change in wind speed from 6 m/s to 8 m/s at 0.5s. The load and grid voltage is maintained at Peak voltage 325.26V, 50Hz. The hybrid system is simulated for 1 second. The load 1 is injected at 0.4 s by the breaker 1 and terminates at 0.8s, the load 2 is injected at 0.7 s by the breaker 2 is shown in Table 4, to the 230V, 50Hz Grid. The load is supplied from the hybrid system and remaining power is fed in to the grid. To regulate the dc bus voltage to 480$V_{dc}$by using boost converter.

VI. CONCLUSION

This paper presented the dynamic modeling and control of grid connected Hybrid system primarily powered by Wind and PV energy. These renewable sources are integrated in to the main dc link through dc-dc boost converters. The present work mainly includes the grid connected application of the hybrid system.

A 26-kW wind and solar hybrid system dynamic model was developed with MATLAB/Simulink. The dynamic performance of Hybrid Wind and Photovoltaic power systems are studied for different case scenarios like,
Case 1: Constant generation and Constant load
Case 2: Constant generation and Change in load
Case 3: Variable generation and Change in load

From the simulation results, it is observed that the developed models for all converters to preserve stable system under various case scenarios, and also it shows that by using a VSI and d-q current control method to give a better performance of grid-connected hybrid system. The hybrid power system can give a reliable power to the loads and it is suitable for stand-alone and Grid-connected application.

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