An integrated Control Approach and Power Management of Stand-alone Hybrid Wind/PV/Battery Power Generation System with Maximum Power Extraction Capability*

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ABSTRACT

The production of electricity from renewable energy sources like wind and photovoltaic energy has increased in recent years, due to environmental problems and the shortage of traditional energy sources. In this article we present a detailed mathematical model and a control scheme for hybrid wind and PV based DG system with battery and maximum power extraction capability for isolated mode of operation. The wind power generation system uses wind turbine (WT), a permanent magnet synchronous generator (PMSG), a three-phase diode rectifier bridge, DC/DC boost converter with maximum power point tracking (MPPT) controller. The PV generation system uses PV array, a boost converter with maximum power point tracking controller. Both sources and battery are connected to common dc bus with a dc link capacitor and supply power to load through PWM voltage source inverter. The overall control system consists of MPPT controller for both Wind and PV power system, a bi-directional dc-dc converter controller for battery energy storage management and load side inverter controller for voltage and frequency regulation. Control strategies for individual system components of the proposed system are designed with a view to achieve an acceptable level of voltage and frequency regulation while extracting the maximum power from wind and PV system. The performance of the developed hybrid system is investigated in terms of voltage and frequency regulation capability under changing wind, solar irradiation

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and variable load conditions.

Keywords: Distributed generation, wind power generation system, PMSG, PV power generation system, MPPT controllers, battery storage, PWM voltage source inverter, PV control

INTRODUCTION

Due to rising public awareness of environmental protection, ever increasing energy consumption and steady progress in power deregulation, alternative distributed generation (DG) systems (renewable and fuel cell based) have attracted increased interest. Most of these renewable sources are pollution free and abundant. Wind and photovoltaic (PV) power generation are two of the most promising renewable energy technologies. Remote area power supply schemes are now becoming popular in remote areas including islands. However, the design and operation of such a power system are challenging due to the absence of a main grid supply system. When designing and implementing power system for remote areas, voltage and frequency control are the most important aspects to be controlled. In addition, coordination between different system components, maximum power extraction from the renewable energy sources and power quality are the other major issues of interest [1].

Two kinds of control schemes are adopted to operate an inverter device. They are: the active and reactive power control scheme (PQ control), when the inverter is operated to meet a given real and reactive power set point and the control of active power and voltage (PV control), when the inverter is controlled to supply the load with fixed values of voltage and frequency [2]. In this work the PV control strategy is adopted for the inverter by means of Park transformation and has been implemented in Matlab/Simulink environment. In many countries, there are remote communities where connection with the power grid is too expensive or impractical. Under such circumstances, a locally placed small-scale standalone distributed generation system can supply power to the customers [3]. Autonomous wind and PV power systems are among the most interesting and environment friendly technological solutions for the electrification of remote consumers. Compared with an individual generation system (wind power or PV power), the wind–PV hybrid generation system can harness more energy from nature. Also the wind power and PV power can compensate each other to some extent during the day and night; the development of the wind–PV hybrid power generation is very attractive [4]. The battery system solves the inconsistencies that renewable energy offers [5, 6]. Lead-acid batteries are ideal for renewable energy systems and applications. Hence, the hybrid generation system forms a highly independent and source variability tolerant generation system from day to night. Over the years, there have been only a few research works on the stand-alone wind–PV hybrid generation system [7] in which the wind generators are focused on induction generators.

To determine the optimal operating point of the wind turbine, it is essential to include a maximum power point tracking (MPPT) algorithm in the system [8]. A maximum power point tracking (MPPT) algorithm increases the power conversion efficiency by regulating the turbine rotor speed according to actual wind speeds [9]. We use a Perturb and Observe (P&O) technique for a maximum power tracking wind power system. The proposed maximum power point algorithm operated at without measurement values of wind speed is suitable for large inertia systems. Among the electric generators, PMSG has received much attention in wind-energy application because of their property of self-excitation, which allows an operation at a high power factor and high efficiency [10, 11]. Maximum power point tracking (MPPT) will be discussed for PV system as well. MPPT algorithm based on incremental conductance is used to get maximum power output. Also, this algorithm can track rapidly increasing and decreasing irradiance conditions with higher accuracy than other methods [12].

Thus, this article presents a stand-alone wind–PV hybrid generation system with battery for remote or isolated areas. The keys are to extract the maximum power from the wind turbine and to harness the maximum power from the PV panels. Our objectives are: i) to achieve effective control coordination among the wind generator, PV system and battery to maintain the dc-link voltage constant and ii) to maintain constant and balanced voltages at the load bus as three phase dynamic loads need a balanced three-phase supply for their proper operation. A coordinated control scheme is developed in order to manage power between the maximum power captured from the wind turbine and solar arrays, battery and consumed load power. The performance of the developed hybrid system is investigated in terms of voltage and frequency regulation capability under changing wind, solar irradiation and variable load conditions.

CONFIGURATION OF THE WIND BASED DG SYSTEM AND MPPT ALGORITHM

Wind turbine power depends on both rotor speed and wind speed [13, 14]. Aerodynamic power available in the wind can be calculated using equation (1).

$$P = 0.5\rho A C_p(\lambda,\beta) V_w^3 \tag{1}$$

Where P = Power in watts, ρ = air density, A = rotor swept area, V_w = wind speed in m/sec, C_p is coefficient of performance. The relationship between rotor speed and wind speed can be given by

$$\lambda = \frac{\omega_m R}{V_w} \tag{2}$$

Where R = wind machine rotor radius, ω_m = rotor speed in rad/sec, λ = tip speed ratio (TSR) = ratio between the linear speed of the tip of the blade with respect to the wind speed.

$$C_p(\lambda,\beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{21}{\lambda_i}} \tag{3}$$

$$Where\ \ \lambda_i = \left[\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}\right]^{-1} \tag{4}$$

The MPPT algorithm keeps the power coefficient C_p at its maximum, $C_p = C_{pmax}$, corresponds to λ_{opt} [15, 16]

Where $\omega_{ref} = \frac{V_w \lambda_{opt}}{R}$ (5)

We deduce $P_m = 0.5\rho A C_{p\max}\left(\frac{R\omega_{ref}}{\lambda_{opt}}\right)^3$ (6)

The reference turbine speed ω_{ref} is generated by the MPPT code using Perturb and Observe technique. The different steps for maximum power point tracking (MPPT) algorithm are

i. The initial reference rotor speed (ω_{ref}) is chosen and the output power of the generator (P_{ref}) is calculated.

ii. Vary the reference rotor speed (ω_{refnew}) by one step (increase or decrease) and calculate the corresponding output power (P_{refnew}) again.
iii. Calculate $\Delta\omega = \omega_{refnew} - \omega_{ref}$ and $\Delta P = P_{refnew} - P_{ref}$;
iv. Calculate sign ($\Delta\omega$); If $\Delta\omega > 0$ then sign ($\Delta\omega$) = 1, else sign ($\Delta\omega$) = -1;
v. Calculate sign (ΔP); If $\Delta P > 0$ then sign (ΔP) = 1, else sign (ΔP) = -1;
vi. Determine $\omega_{ref}(n) = \omega_{ref}(n-1) + \text{sign}(\Delta P) * \text{sign}(\Delta\omega) * \omega_{step}$;
vii. Repeat from step (ii) to reach to optimum operating point.

Let us assume the speed of wind is V1 and operating point of the turbine is point X, represented as (ω_X, P_X) in P vs. ω characteristic curve. Also, let us assume that the turbine speed is increased by ω_{step}, which results in a new speed ω_Y. The new operating point will be (ω_Y, P_Y) which gives:

$\Delta\omega = \omega_Y - \omega_X > 0$; then sign ($\Delta\omega$) = 1
$\Delta P = P_Y - P_X > 0$; then sign (ΔP) = 1
Therefore, $\omega_Y = \omega_X + \omega_{step}$

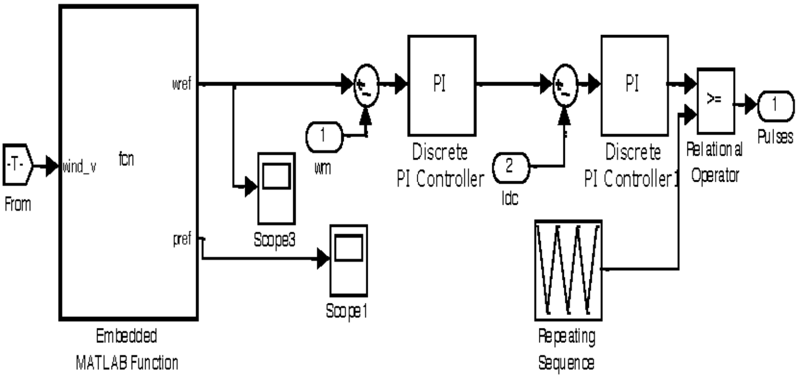


Fig. 1 MPPT controller for wind power system

The reference turbine speed ω_{ref} is generated by the MPPT code using P&O method written in Embedded MATLAB Function block as shown in Fig. 1. This reference rotor speed is compared with the actual value and the difference is fed to a PI Controller. This is then compared with the input current of the Boost Converter and the difference is fed to a comparator. The pulse is generated by comparing it with a repeating sequence and this pulse is then fed to the gate of the DC/DC Converter to control its duty cycle and maximum power output is obtained. The purpose of this circuit is to control the shaft speed of the PMSG so that the maximum power can be captured from wind by the turbine.

The synchronous generator model is expressed in the (d, q) synchronous Park's model, where the d-axis is rotating along the magnetic field direction. The voltage equations of the PMSG are given by [17, 18]

$$V_{ds} = -R_s i_{ds} - L_d \frac{di_{ds}}{dt} + \omega L_q i_{qs} \tag{7}$$

$$V_{qs} = -R_s i_{qs} - L_q \frac{di_{qs}}{dt} - \omega L_d i_{ds} + \omega \phi_m \tag{8}$$

Where V_{ds} and V_{qs} are the two-axis machine voltages; i_{ds} and i_{qs} are the two-axis machine currents; R_s is the stator resistance ω is the electrical angular frequency; L_d is the direct axis inductance, L_q is the quadrature inductance; is the amplitude of the flux linkages established by the permanent magnet.

The expression for the electromagnetic (EM) torque in the rotor is written as

$$T_e = \frac{3}{2} p\left[(L_d - L_q) i_{ds} i_{qs} - \phi_m i_{qs}\right] \tag{9}$$

Where 'p' is the number of pole pairs of the PMSG and if the rotor is cylindrical, $L_d \approx L_q = L_s$ so that

$$T_e = \frac{3}{2} p \phi_m i_{qs} \tag{10}$$

MODELING OF PHOTOVOLTAIC SYSTEM AND MPP TRACKING

Energy from the sun is the best option for electricity generation and the solar energy is directly converted into electrical energy by solar photovoltaic module. Electricity from the sun can be generated through the solar photovoltaic modules (SPV). The photovoltaic modules are made up of silicon cells. When many such cells are connected in series we get a solar PV module. For obtaining higher power output the solar PV modules are connected in series and parallel combinations forming solar PV arrays. Fig. 2 shows the well-known equivalent circuit of the solar cell composed of a light generated current source, a diode representing the nonlinear impedance of the p-n junction, and series and parallel resistances. The series resistance R_s represents the internal losses due to the current flow. The parallel resistance R_p in parallel with the diode, this corresponds to the leakage current to the ground. The mathematical model of the PV cell is given by the following equation [19].

$$I = I_{ph} - I_o\left[\exp\left(\frac{q(V+IR_S)}{akT}\right)-1\right]-\frac{V+IR_S}{R_P} \tag{11}$$

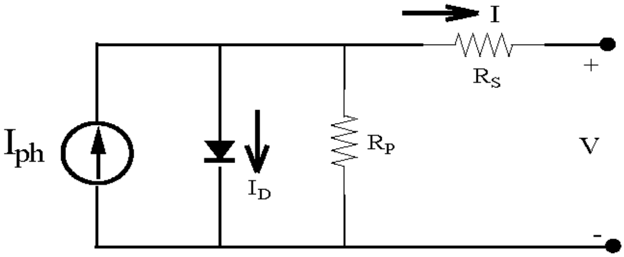


Fig. 2 Simplified PV cell circuit model

Maximum power point trackers (MPPTs) play a crucial role in PV power systems because they maximize the power output from a PV system for a given set of conditions, and therefore maximize the array efficiency. Thus, an MPPT can minimize the overall system cost. In incremental conductance method the array terminal voltage is always adjusted according to the MPP voltage, it is based on the incremental and instantaneous conductance of the PV module. This method exploits the assumption that the ratio of change in output conductance is equal to the negative output instantaneous conductance [12]. As known from a Power-Voltage curve of a solar panel, there is an optimum operating point such that the PV delivers the maximum possible power to the load. The optimum operating point changes with solar irradiation and cell temperature [20]. This article deals with Incremental conductance MPPT algorithm method due to its simple approach and this algorithm can track rapidly increasing and decreasing irradiance conditions with higher accuracy than other methods.

We have PV array output power $P_{pv} = V_{pv}I_{pv}$

Applying the chain rule for the derivative of products yields to

$$\frac{dP_{pv}}{dV_{pv}} = \frac{d(V_{pv}I_{pv})}{dV_{pv}} \tag{12}$$

At maximum power point, $\frac{dP_{pv}}{dV_{pv}} = 0$ and the above equation could be written in terms of array voltage V_{pv} and array current I_{pv} as

$$\frac{dI_{pv}}{dV_{pv}} = -\frac{I_{pv}}{V_{pv}}$$

Where I_{pv} and V_{pv} are PV array output current and voltage respectively. The left hand side of equations represents the incremental conductance of P-V module and the right hand side represents the instantaneous conductance. When the ratio of change in output conductance is equal to the negative output conductance, the solar array will operate at the maximum power point. The MPPT regulates the PWM control signal of the DC to DC boost converter until the condition = 0 is satisfied.

$$\frac{dI_{pv}}{dV_{pv}} = -\frac{I_{pv}}{V_{pv}}$$

BATTERY AND INVERTER CONTROLLER

A battery system is very important in all stand-alone PV, wind and hybrid systems and it is used to minimize the demand-generation mismatch of the system. The interfacing of battery on dc-link is achieved with the help of buck-boost DC/DC converter [1]. During charging the controller act as a buck converter while it act as a boost converter during discharge period. The main objective of battery controller is to store excess energy in the battery during high wind and irradiation condition and discharge the energy in temporary when wind and solar power fall. The dc-link voltage is regulated by two PI loops. The outer voltage loop regulates the voltage and error is passed through a PI controller to obtain a reference battery current. The reference battery current is compared with the measured battery current. The error is passed through another PI controller and generates the necessary PWM signal for switches Q_1 and Q_2 of buck-boost DC/DC converter. In addition, a safety feature is integrated to monitor the state of charge (SOC) of the battery storage system during its operation. The SOC should be regulated within predetermined limits ($SOC_{min} \leq SOC \leq SOC_{max}$) as described in [21]. The charging or discharging of battery maintains the power balance between fluctuating wind and PV power and time varying load. The schematic of the dc–dc converter controller used to regulate the charging/discharging current of the battery to maintain the dc bus voltage constant is shown in Fig. 3.

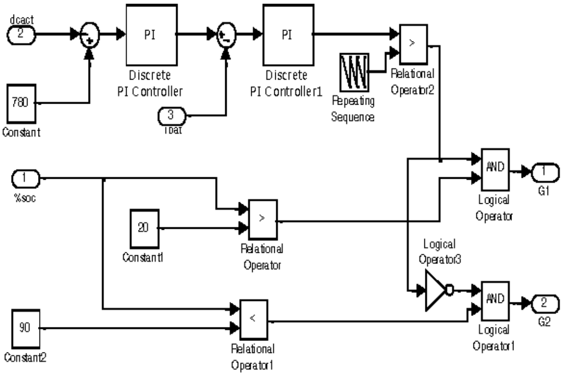


Fig. 3 Control of Buck-Boost DC/DC Converter for Battery Charging

The output voltage and frequency of the hybrid system is regulated by the load side converter. A vector control scheme is developed based on the rotating reference frame [22]. A stand-alone inverter must supply power according to the load demand with fixed values of voltage and frequency. When a PV control is implemented, it is possible to use a control based on Park transformation and compute the direct and quadrature voltage components V_{dref} and V_{qref}, which are considered as the reference values [2]. In the PV control there is no ac side frequency available for reference, so an internal voltage signal, at the desired frequency, must be produced. Moreover, in the PV control, the voltage errors have to be used to drive two PI regulators producing the signals for the inverter PWM modulation and allowing to derive the amplitude and frequency modulating indexes (m_a and m_f) for the PWM control. The schematic of control strategy for inverter is shown in Fig. 4. A lower bound on the dc bus voltage can be determined from the following equation at a unity power factor [23].

$$0.6124 m_a V_{DC} \geq \sqrt{(V_{ACLL})^2 + 3(\omega L_f I_{AC})^2} \tag{13}$$

Where V_{ACLL} = line-line RMS voltage on the inverter side, L_f = filter inductance, I_{AC} = maximum possible RMS Value of the AC load current m_a = modulation index of the inverter.

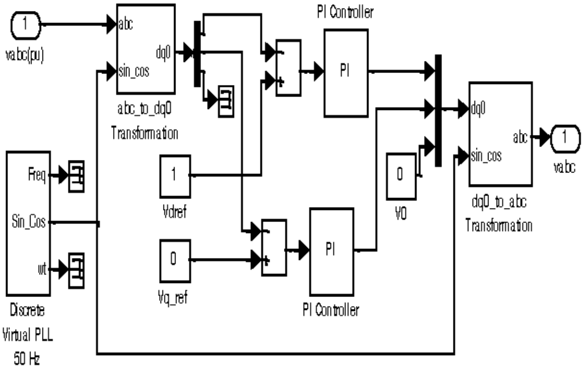


Fig. 4 Schematic of control strategy for inverter

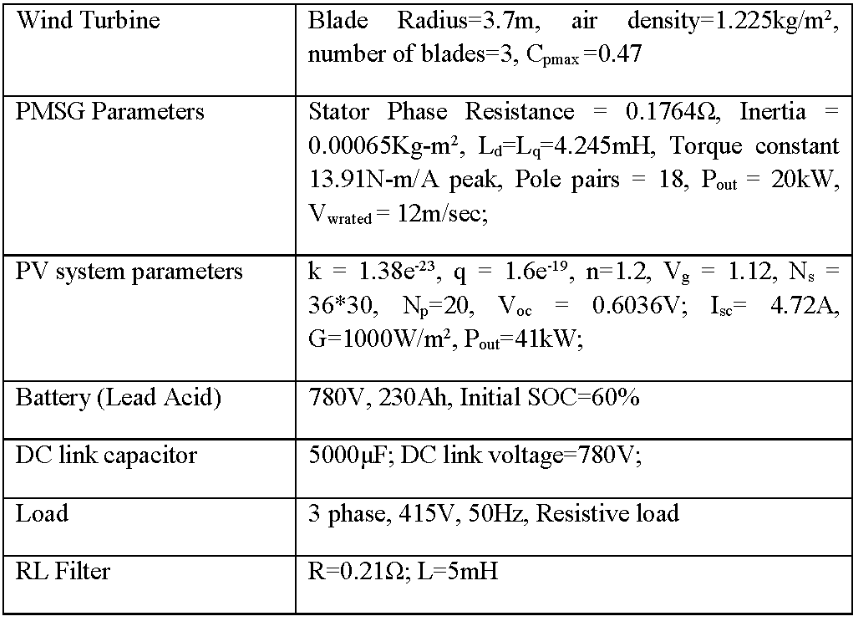
RESULTS AND DISCUSSIONS

In this section, time domain simulated responses of the proposed hybrid system using Matlab/Simulink under different operating conditions are presented. The proposed structure of the stand-alone hybrid power generation system in Matlab/Simulink environment is shown in Fig. 5 and consists of the following sub-systems:

- Wind power system with MPPT controller
- PV arrays with MPPT controller
- Battery storage system controlled by a bi-directional (buck-boost type) battery controller
- Load side voltage and frequency controller with filter.

The variations in wind velocity, solar irradiation and load conditions are considered for the simulation study. The following two cases are considered for the study and a simulation interval of 3 sec has been chosen. The simulation parameters of the system are given in Table 1.

Table 1: Simulation parameters of the hybrid system



Wind Turbine	Blade Radius=3.7m, air density=1.225kg/m^2, number of blades=3, C_{pmax}=0.47
PMSG Parameters	Stator Phase Resistance = 0.1764Ω, Inertia = 0.00065Kg-m^2, L_d=L_q=4.245mH, Torque constant 13.91N-m/A peak, Pole pairs = 18, P_{out} = 20kW, V_{wrated} = 12m/sec;
PV system parameters	k = 1.38e^{-23}, q = 1.6e^{-19}, n=1.2, V_g = 1.12, N_s = 36*30, N_p=20, V_{oc} = 0.6036V; I_{sc}= 4.72A, G=1000W/m^2, P_{out}=41kW;
Battery (Lead Acid)	780V, 230Ah, Initial SOC=60%
DC link capacitor	5000µF; DC link voltage=780V;
Load	3 phase, 415V, 50Hz, Resistive load
RL Filter	R=0.21Ω; L=5mH

A. With Constant Load:

A constant resistive load of 50 kW is considered to study the dynamic behavior of the system. Initially the wind speed is 9m/sec and is increased to 12m/sec at t = 1.5 sec. Solar irradiation is varied from 700W/m^2 to 1000W/m^2. Fig. 6 illustrates the time domain simulated results for solar irradiation, dI_{pv}/dV_{pv} and $-I_{pv}/V_{pv}$ curves for PV System. Due to sudden variations in wind speed, the turbine reference speed ω_{ref} changes. Accordingly the active power output of the wind generation system changes. The wind generator output tracks the corresponding maximum power very successfully with just small delays in the dynamic response as shown in Fig 7. The simulated results for State of Charge (%) of battery and Power coefficient C_p of wind turbine for different wind speeds are shown in Fig. 8. By implementing the proposed MPPT control

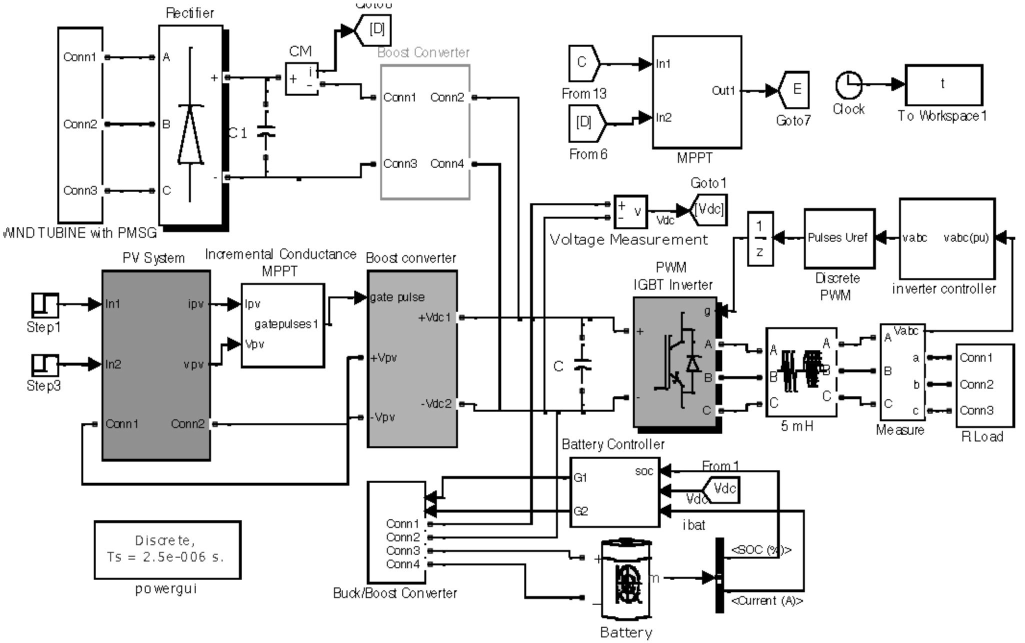


Fig. 5 Block diagram of the hybrid stand-alone power system in Matlab/Simulink

technique, the rotor speed of PMSG should be adjusted to achieve maximum value of power coefficient (C_p) which is 0.47 according to tip speed ratio.

As solar irradiation changes, the active power generation from PV array also varies. From the results from PV system we can observe that incremental conductance MPPT works in such a way that for every instant

$$\frac{dI_{pv}}{dV_{pv}} = -\frac{I_{pv}}{V_{pv}}$$

i.e. PV array is operating at its maximum power point. So the MPPT is able to track the maximum power point. From Fig. 7 it is seen that if the generated power is decreased and the load demand is still 50 kW, so now the excessive load demand is supplied by the battery. Also the extra generated power is utilized to charge the battery in order to maintain the power balance, which is clearly indicated by the negative sign of battery power.

B. With Variable Load:

In this case, initially the resistive load is 60 kW and is suddenly decreased to 40 kW at t=1.5 sec. The wind speed is kept constant at 12m/sec and solar irradiation variation considered is same as in Fig. 6. Fig. 9 shows the simulated results for active power outputs of wind, PV system, battery and power supplied to load for step change in load variation. The simulated results for State of Charge (%) of battery and system frequency for different operating conditions are shown in Fig. 10. The simulated result for DC link voltage is shown in Fig. 11. During all kind of source power and load fluctuations, the dc-link voltage is well maintained nearly to 780 V. The simulated results for inverter output voltage and current for variable load are shown in Fig. 12. Fig. 13 illustrates the percentage THD variation in inverter output voltage. The voltage across the inverter terminals is purely sinusoidal and while maintaining constant voltage and frequency under different dynamic conditions.

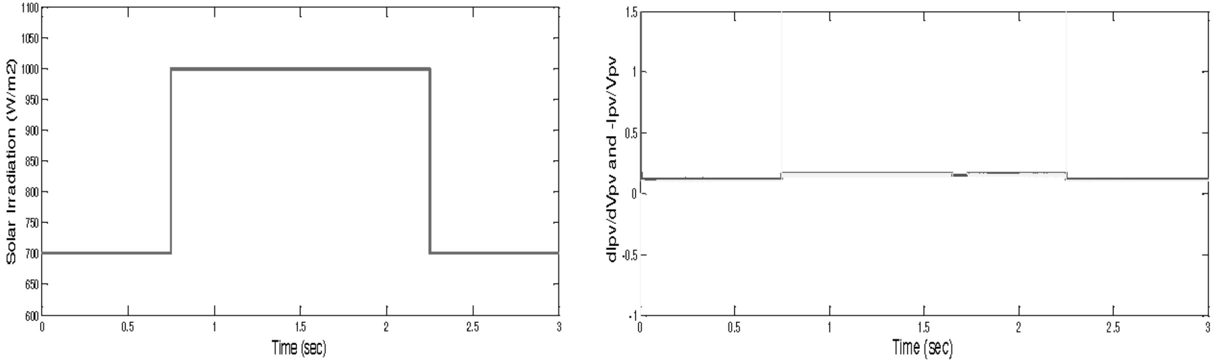


Fig. 6 solar irradiation and dI_{pv}/dV_{pv} and $-I_{pv}/V_{pv}$ curves for PV System

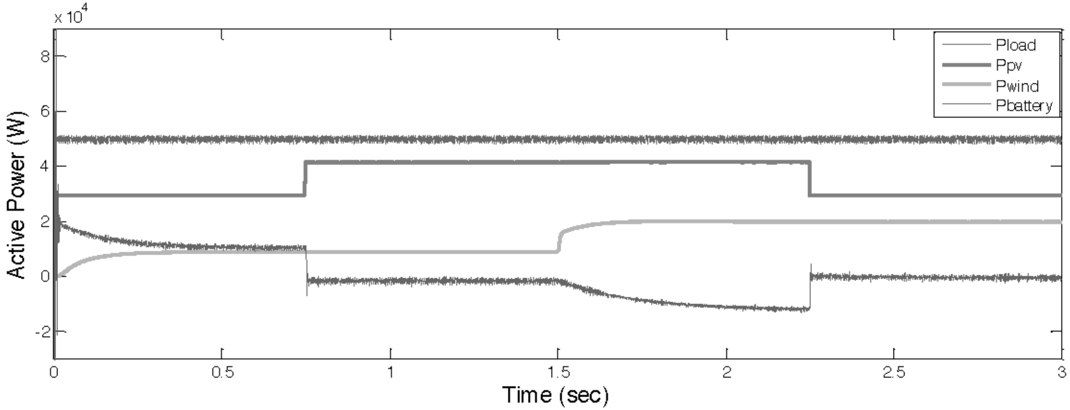


Fig. 7: Simulated results for active power outputs of wind, PV system, battery and power supplied to load

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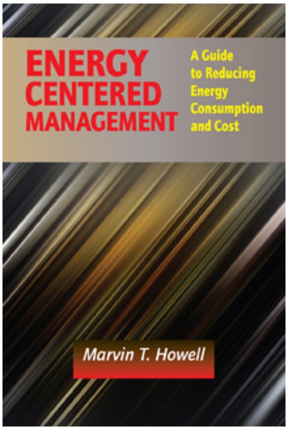

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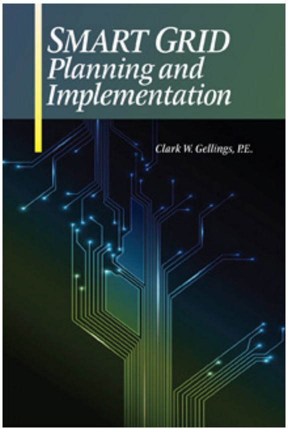

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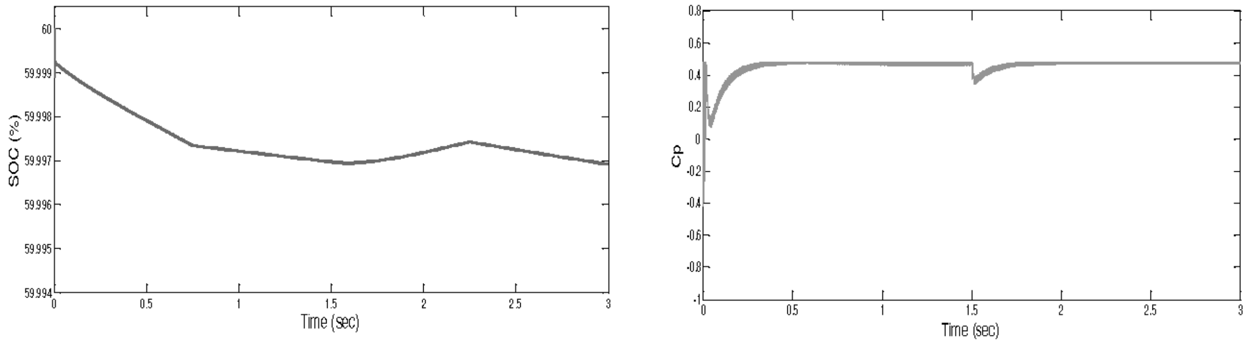
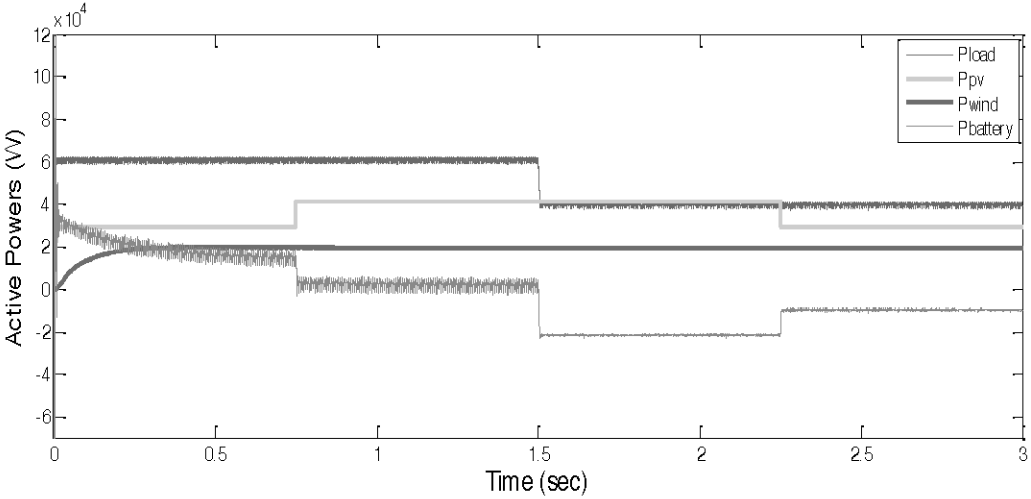


Fig. 8: State of Charge (%) of battery and Power coefficient Cp of wind turbine

Fig. 9: Simulated results for active power outputs of wind, PV system, battery and power supplied to load



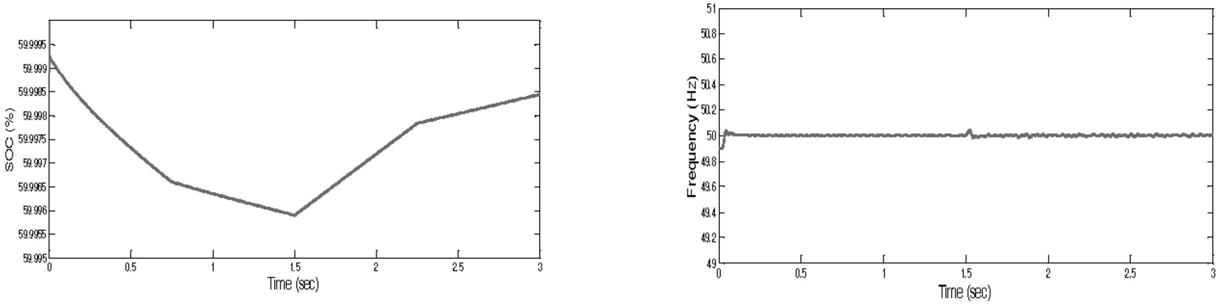


Fig. 10: State of Charge (%) of battery and system frequency

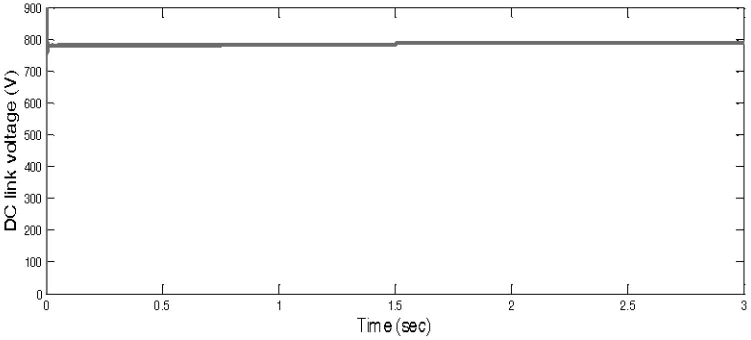


Fig. 11: DC link voltage

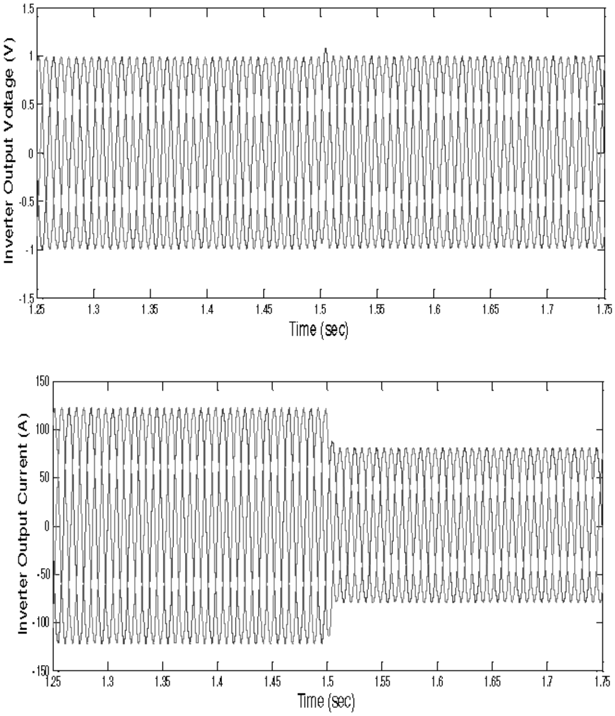


Fig. 12: Inverter output voltage and current for variable load

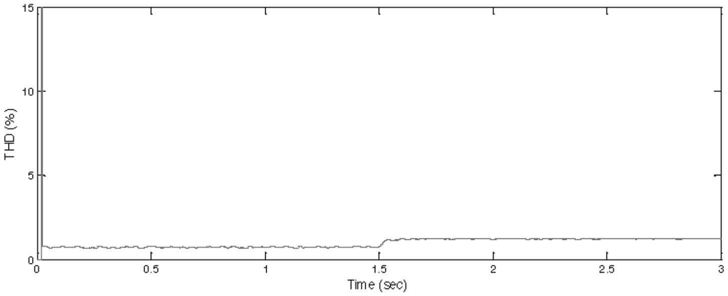


Fig. 13: Percentage THD variation in inverter output voltage

VERIFICATION AND VALIDATION OF RESULTS

From the above simulation results it is clearly observed that the proposed model has constant DC link voltage and a purely sinusoidal controlled ideal voltage source at the inverter terminals. And the power balance between wind, PV power system, battery and load has been maintained that verifies the results obtained. It is also seen that the proposed hybrid system performs satisfactorily under different dynamic conditions while maintaining constant voltage and frequency. To demonstrate the validity of the proposed system the percentage THD variation of inverter output voltage is evaluated. One of the important aspects of DG system operation is to maintain the harmonic distortion level as minimum as possible. As per IEEE Std. 1547-2003, it should be less than 5%. It can be observed from Fig. 13 that the harmonic distortion level is less than 1.5%, which is well within the standards.

CONCLUSION

The modeling and performance analysis of stand-alone hybrid Wind/PV/Battery power generation system with MPPT Controllers using Matlab/Simulink environment is presented in this article. The variations in wind velocity, solar irradiation and dynamic load conditions are considered for the simulation study. Perturb and Observe (P&O) technique is used for maximum power tracking for wind power system. For PV system MPPT algorithm based on incremental conductance is used to get maximum power output. The algorithm changes the duty cycle of the DC/DC converter to maximize the power output of the array and make it operate at the peak power point of the array. The PV control strategy of a DC/AC converter connected to the load has been proposed. The system is also able to meet the variable load demand while maintaining dc-link voltage constant. It has been demonstrated that the proposed hybrid system performs satisfactorily under different dynamic conditions while maintaining constant voltage and frequency. The power balance between wind, PV power system, battery and load has been maintained while extracting maximum power for both sources. The simulation results showed the effectiveness of the integrated control strategy adopted.

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