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Performance Study of Integrated Solar/Wind Energy Conversion System into Smart Grid

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Abstract*— The limited global stock of fossil and nuclear fuel resources has coerced an urgency for alternative sources of energy. The utilization of distributed energy resources is accrediting day by day and is being pursued as a supplement and an alternative to large conventional central power stations. Hybrid renewable energy systems such as wind-solar energy based sources are feasible and reliable options. Smart grid system embodies three key characteristics namely: performance optimization, system reliability and operational efficiency. In the present communication a novel model of smart grid-connected PV/WT hybrid system has been developed. It consists of photovoltaic array, DFIG wind turbine, controller and converters. The proposed model has been executed using MATLAB/SIMULINK software package. Perturb and Observe (P&O) algorithm has been applied for maximizing the generated power based on maximum power point tracker (MPPT) implementation. The proposed model and its control strategy offer a proper tool for smart grid performance optimization.

Index Terms*— Solar Photovoltaic systems, Smart grids, Wind power generation, Maximum power point tracking (MPPT), dc/dc converter, dc/ac converter, doubly fed induction machine(DFIG), hybrid system.

I. INTRODUCTION

Globalization, industrialization with burgeoning population and people's desire for acquiring more and more comfort have led to consistent rise in the demand for electricity and to meet such elevating demand have resulted in increasing conventional power generating stations. Such escalation is resulting in enormous stress on the existing infrastructure which in turn has led to a rapid depletion of conventional fuel reserves. Growing concerns in reference with awful effects of conventional fuels on the environment have further complicated the issue and have drawn mankind's attention towards renewable energy sources to fulfill the growing need of electric energy. Hence, a way is needed to be sorted out in order to balance supply and demand without turning towards coal and gas fueled generators [1], [2].

A smart grid is an upgraded electricity grid network that enables two-way information and power exchange between suppliers and consumers, due to the extensive incorporation of intelligent communication monitoring and management systems [3]. Smart grid aims at reducing the emission of greenhouse gases (GHG) utilizing renewable sources which will ensure flexible system and efficient utilization of electricity [4]. The key characteristics of smart grids are:

1) Grid optimization: system reliability and operational efficiency.
2) Distributed generation: not only traditional large power stations, but also individual PV panels, micro-wind, etc.
3) Advanced metering infrastructure (AMI): smart meters.
4) Grid-scale storage.
5) Demand response.
6) Plug-in hybrid electric vehicles (PHEVs) and vehicle to grid (V2G) [5].

The present paper focuses primarily on the smart grid integration of PV/WT hybrid system (grid optimization and distribution generation).Electricity generated from wind energy integrated with power grid is a known and well-established technology. Wind farms with doubly fed induction generators (DFIGs) are actually time-tested systems for greatly varying wind velocity-based variable speed turbine systems [6]. Different control schemes have been developed to increase the performance and efficiency of wind-sourced DFIG systems, including those for weak area electric power system, distorted grid conditions etc. [6] - [10]. Liu *et al*. [9] and Xu *et al*. [10] came out with probable solutions for harmonic suppression in stator circuits using rotor-side converter control. In 2014, Nian and Song [11] propounded a modified control scheme to level out the overall active and reactive power output of DFIG under distorted grid voltage conditions.In the last a few decades, solar PV-based power generation has also raised as a strong and favorable option as it is pollution free, noise free, and maintenance free source of energy with no additional mechanical or rotating assembly. In same context many significant advancements and refined control strategies have been reported in the recent past for large capacity grid-connected PV systems [12], [13]. These systems are generally either two power or single power stage and most of the configurations employ a grid-side voltage-source inverter (VSI). Over recent years some prominent work has been carried out in hybrid power system which recommends an optimal design model for hybrid solar–wind system where battery banks are employed to calculate the system's optimum configurations in China [14]. In 2008, Reichling and Kulacki [15] modeled a hybrid solar wind power plant in south western Minnesota for a two year period, utilizing hourly solar irradiation and wind speed data. Later in 2010, Dihrab and Sopian [16] presented a hybrid solar-wind system as a renewable source of power generation for grid connected application in three cities of Iraq.

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Ekren *et al.* [17] demonstrated an optimum sizing procedure of PV/wind hybrid system in Turkey. Among several modeling studies on PV/WT power system, Kim *et al.* [18] developed a grid-connected photovoltaic model using PSCAD/EMTDC for electromagnetic transient analysis. An insulation-oriented PV model using MATLAB/SIMULINK software package was implemented by Tsai [19]. Gow and Manning [20] came out with a general PV model which can be implemented on simulation platforms such as PSPICE or SABER. Khan and Iqbal [21], presented the model of a small wind-fuel cell hybrid energy system and analyzed life cycle of a wind-fuel cell integrated system. In 2009, Chayawatto *et al.* [22] developed a mathematical model of a dc/ac full-bridge switching converter with current control for PV grid connected system under islanding phenomena occurring at the time when grid system is disconnected for any reason and the distributed generation still supplies to any section of local loads. Onara *et al.* [23], presented a hybrid wind/FC/ ultra-capacitor (UC) power system for a grid-independent user with appropriate power flow controllers.

The present study proposes a detailed dynamic model, control and simulation of a smart grid-connected PV/WT hybrid power generation system. Modeling and simulation have been implemented using MATLAB/SIMULINK and Sim Power Systems software packages to verify the effectiveness of the proposed system. The ingrained advantage of hybrid solar PV-wind energy system is reduction in overall variation in the power output.

II. SYSTEM DESCRIPTION

Smart grid consists of three layers namely; physical power layer, control layer and the application layer. Smart grid (Fig.1) needs to be dynamic and have constant two-way communication [5] for example, with PV panels on the roofs, intelligent building system will generate, store and use their own energy. Therefore, as an active building, they become part of the smart grid which can help in saving energy and increasing reliability as well as transparency [2].

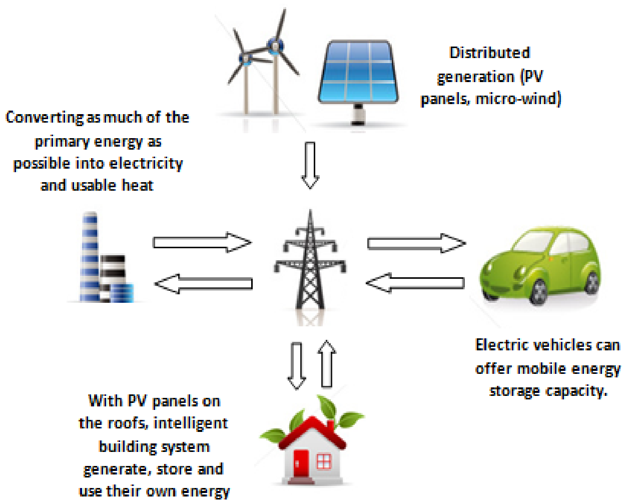

Fig. 1 General layout of the smart grid

In this section, dynamic simulation model has been described for photovoltaic/wind turbine hybrid generation system which consists of a photovoltaic array, dc/dc boost converter, MPP produced by P&O algorithm, doubly fed induction generator and dc/ac IGBT PWM inverter. The block diagram of the developed system is shown in Fig. 2.

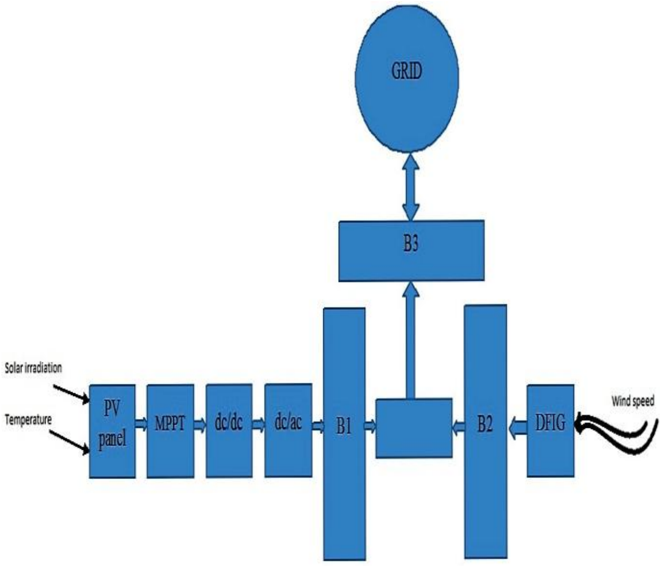

Fig. 2 Block diagram of the proposed system

A. Photovoltaic Module

General mathematical model proposed for solar cells have been studied over the past three decades [24]. The circuit of the solar cell model comprises of a photocurrent, diode, parallel resistor (leakage current) and a series resistor (Fig. 3). According to Kirchhoff's circuit laws and Fig. 3, the photovoltaic current can be presented as follows:

$$I_{pv} = I_{gc} - I_o\left[\exp^{\left(\frac{v_d}{KFT_c}\right)} - 1\right] - \frac{v_d}{R_p} \quad \text{.........} (1)$$

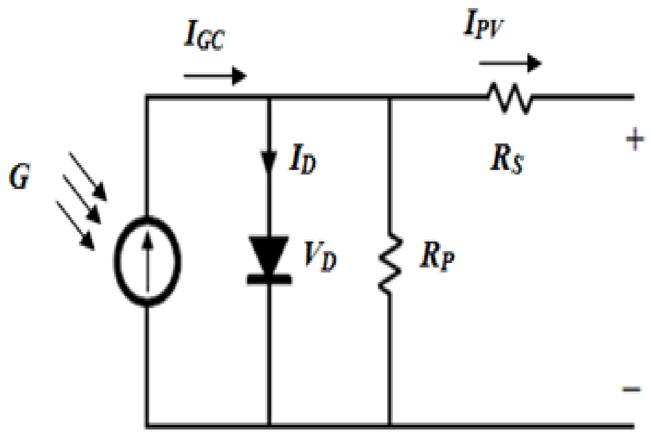

Fig. 3 Single diode PV cell equivalent circuit

Where I_{gc} is light generated current, I_o is the dark saturation current dependant on the cell temperature, *e* is electric charge = 1.6 x 10^{-19} Coulombs, *K* is Boltzmann's constant = 1.38 x 10^{-23} J/K, *F* is the cell idealizing factor, *Tc* is the cell's absolute temperature, v_d is the diode voltage, and R_p is the parallel resistance [25]. The photocurrent (I_{gc}) mainly depends on the solar irradiation and cell temperature, which is described as

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$$I_{gc} = [\mu_{sc}(T_c - T_r) + I_{sc}]\,G \quad \text{.............. (2)}$$

Where μ_{sc} is the temperature coefficient of cell's short circuit current, T_{ref} is cell's reference temperature, I_{sc} is the cell's short circuit current at 25°C and 1kW/m^2, and G is the solar irradiation in kW/m^2. Furthermore, the cell's saturation current (I_o) varies with the cell temperature, which is described as [25]

$$I_o = I_{o\alpha}\left(\frac{T_c}{T_r}\right)^3 \exp^{\left[\frac{\varepsilon v_g}{KF}\left(\frac{1}{T_r}-\frac{1}{T_c}\right)\right]} \quad \text{................. (3)}$$

$$I_{o\alpha} = \frac{I_{sc}}{\exp\left(\frac{\varepsilon v_{oc}}{KFT_c}\right)} \quad \text{..................................... (4)}$$

Where $I o\alpha$ is cell's reverse saturation current at a solar radiation and reference temperature, V_g is the band-gap energy of the semiconductor used in the cell, and V_{oc} is cell's open circuit voltage. In this study, a general PV model has been built and implemented using MATLAB/SIMULINK to verify the nonlinear output characteristics for the PV module.

B. Wind Turbine

Several studies have been reported regarding WT and wind generators [26]. In this study, the proposed WT model is based on the wind speed versus WT output power characteristics. The output power of the wind turbine is based on the study by Muljadi and Butterfield [27]:

$$P_m = c_p(\lambda,\beta)\,\frac{\rho A}{2}\,v_{wind}^3 \quad \text{......................... (5)}$$

Where P_m is mechanical output power of the turbine, c_p is the performance coefficient of turbine, λ is the tip speed ratio of rotor blade, β is the blade pitch angle, ρ is the air density, A is turbine swept area, and v_{wind} is the wind speed.

The performance coefficient model c_p (λ, β) given by:

$$c_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\left(\frac{-c_5}{\lambda_i}\right)} + c_6\lambda \quad \text{.............. (6)}$$

Where constants c_1 to c_6 are parameters that depend on the wind turbine rotor and blade design, and λ_i is given by:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad \text{...................... (7)}$$

Furthermore, (5) can be simplified for specific values of A and ρ, as:

$$P_{m-pu} = k_p c_{p-pu}\, v_{wind-pu}^3 \quad \text{................. (8)}$$

Where $P_{m\text{-}pu}$ is the power in per unit (p.u.) of nominal power for particular values of ρ and A, $c_{p\text{-}pu}$ is the p.u. value of performance coefficient c_p, k_p is the power gain, $v_{wind\text{-}pu}$ is the p.u. value of base wind speed. The base wind speed is mean value of the expected wind speed in (m/s).

C. Power Control Systems

1) Photovoltaic Control System

The output characteristics of the PV model with different solar irradiance and cell temperature are nonlinear. The solar irradiation is unpredictable, leading to continuous change in maximum power point (MPP) of the PV module. Hence, a maximum power point tracker (MPPT) technique is needed to operate the PV module at its maximum power point (MPP). Perturb and observe (P&O) algorithm, a maximum power point tracker (MPPT) control algorithm is used in this model. The algorithm operates by periodically increasing or decreasing the PV array operating current, and comparing the PV output power with previous one. If it is positive, the control system moves the PV array operating point in the same direction, otherwise moves towards opposite direction [2].

The two measurements required for P&O algorithm are: measurement of the current (I_{pv}) and voltage (V_{pv}). In addition to this a dc averaged switched model converter with input current control (I_{ref}) is also built and implemented using MATLAB/SIMULINK, in order to minimize the switching harmonics and steps-up the PV voltage to a higher dc voltage (e.g. 500V). However, when the PV system with a MPPT is connected to the power electronic converters (PEC), an automatic feedback controller will be required to balance power and maintain the direct voltage constant; especially when the system is running under varied conditions [2].

In the present study, a 100kW PV array is connected to a 25kV grid via a DC/DC boost converter and a IGBT based three phase three level Voltage Source Converter (VSC). Maximum Power Point Tracking (MPPT) is implemented in the boost converter by means of a Simulink model using 'Perturb & Observe' technique.

2) DFIG Control System

Control system of DFIG wind turbine usually comprises of: 1) the electrical control of the DFIG and 2) the mechanical control of the wind turbine blade pitch angle [28], [29] and yaw system. Control of DFIG is achieved by controlling the rotor side converter (RSC) and grid side converter (GSC). RSC aims at regulating the stator-side active power and reactive power independently whereas; control objective of GSC is to maintain dc-link voltage constant and to regulate the reactive power that GSC exchanges with the grid.

In this study, a 9 MW (6*1.5 MW) wind turbines is connected to a 25 kV distribution system. Wind turbines using a doubly fed induction generator (DFIG) consists of a wound rotor induction generator and an AC/DC/AC IGBT based PWM converter modeled by voltage sources. The stator winding is connected directly to the 60 Hz grid while the rotor is fed at variable frequency through AC/DC/AC converter. The DFIG technology permits the extraction of maximum energy from wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind.

3) dc/ac inverters

In this study, fixed dc voltages are converted to ac voltages with IGBT PWM inverters. The inverters have fixed dc inputs, controlled to produce three-phase ac output voltage with the same specifications (such as amplitude and frequency) using an appropriate PWM generator, which provides gate signals for the inverter elements. The three-phase IGBT inverter has been shown in Fig. 4 [23].

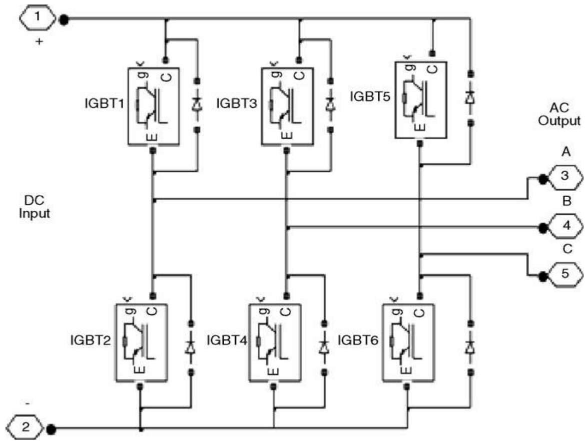

Fig. 4 DC/AC inverter

The parameters used in the voltage equations of the inverter are as follows:

m modulation index
V_{dc} dc input voltage of the inverter (V)
$V_{l\text{-}l}$ Line-to-line output voltage of the inverter (V)

III. SIMULATION RESULTS

This section deals with the evaluation of performance of complete control scheme for various stages of the proposed hybrid PV/DFIG system. The block diagram of integrated photovoltaic/DFIG system and the power controllers are shown in Fig. 2. The complete system described in Section II has been modeled in MATLAB-Simulink software for validation of the proposed PV-wind hybrid system. The parameters listed in Table I and II have been used for the simulations.

The major inputs for the proposed PV model were solar irradiation, PV panel temperature and PV manufacturing data sheet informations. SunPower SPR-305E-WHT-D PV panel has been taken as example for the present case. The SunPower SPR-305E-WHT-D key specification is listed in Table I.

Table I: Sun Power SPR-305E-WHT-D specifications

Parameter	Value
Maximum Power (P_m)	305 (W)
Open circuit voltage (*Voc*)	64.2 (V)
Voltage at *Pm* (*Vamp*)	54.7 (V)
Short circuit current (*Isc*)	5.95 (A)
Current at *Pm* (*Iamp*)	5.58 (A)
Temp coefficient for *Voc*	-0.27269 (% / oC)
Temp coefficient for *Isc*	0.061745 (% / oC)
No. of cells	96

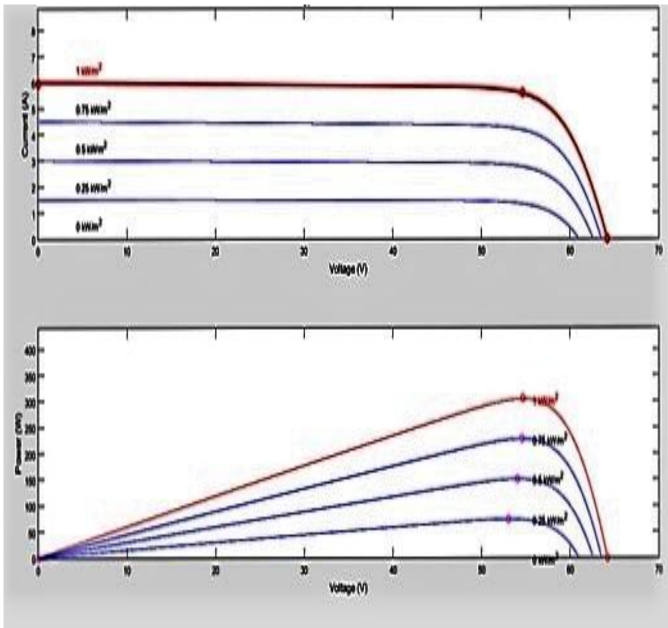

Fig. 5 I-V and P-V output characteristics with different irradiation

The I-V and P-V output characteristics for the PV model have been shown in Fig.5 and Fig. 6. The output power and current of PV module depends on the solar irradiance, temperature, and cell's terminal operating voltage. With increased solar irradiance there is an increase in both the maximum power output and the short circuit current (Fig. 5). On the other hand, with an increase in the cell temperature, the maximum power output decreases whilst the short circuit current increases (Fig. 6).

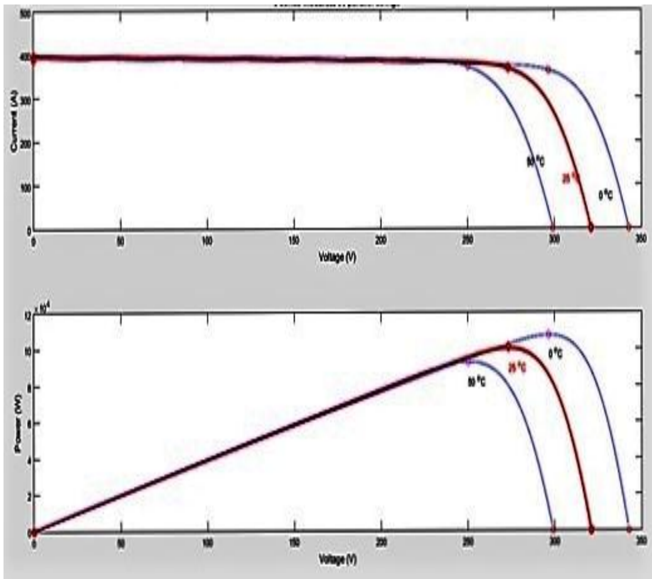

Fig. 6 I-V and P-V output characteristics with different temperature

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The parameters of the wind turbine induction generator are given in Table II.

Table II: Parameters of one 1.5 MW DFIG

Parameter	Value
Nominal Power	1.5 MW
Variable wind speed(w)	11-15 (m/s)
Line to Line voltage(V_{rms})	575 V
Rated Frequency (f_n)	60 H_z
Number of poles pair	3
Stator resistance (R_s)	0.023 p.u.
Rotor resistance (R_r)	0.016 p.u.
Stator leakage inductance (L_{ls})	0.18 p.u.
Rotor leakage inductance (L_{lr})	0.16 p.u.
Magnetizing inductance (L_m)	2.9 p.u.
Nominal DC voltage	1150 V

The generator speed power characteristics for the WT model are shown in Fig. 7 corresponding to different wind speed values. The output power of WT depends on both, the wind speed and generator speed. As evident from Fig. 7, wind speed is the most influential factor on the amount of power produced by a wind turbine. Since, the power in the wind is a cubic function of wind speed therefore; changes in speed produces a profound effect on power.

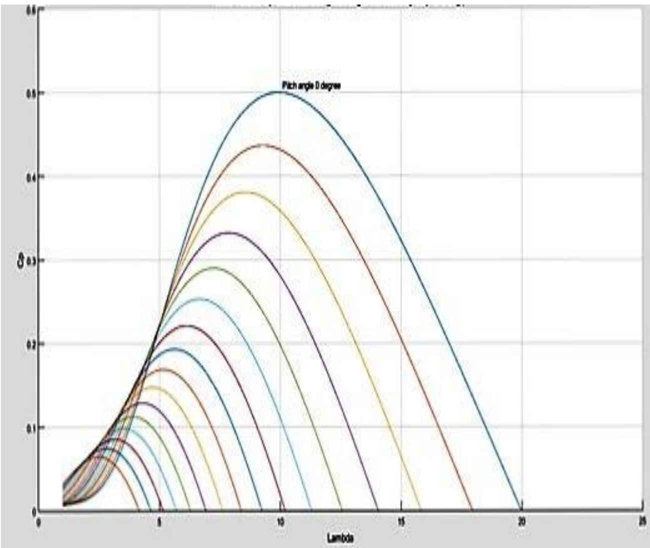

Fig. 7 Wind turbine characteristics

Proposed model behavior was observed during simulation process. The solar irradiation, panel temperature and variable wind speed profiles have been used to test the performance of the proposed hybrid system model, as shown in Fig. 8, Fig. 9 and Fig. 10 respectively.

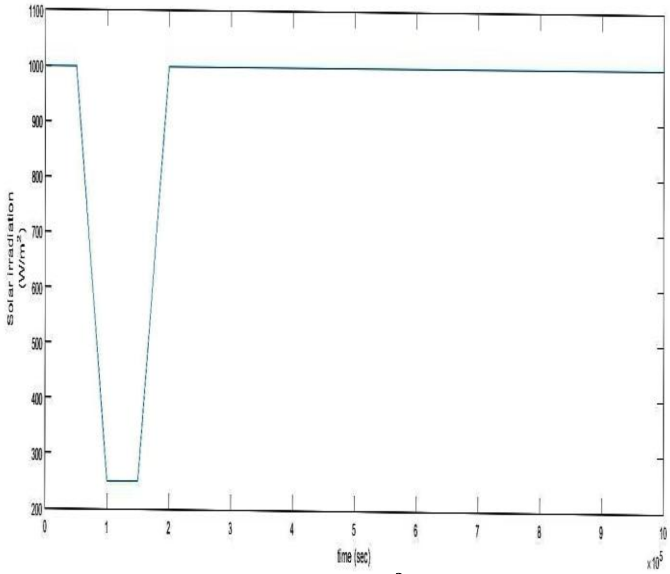

Fig. 8. Solar irradiation(W/m^2) verses time(sec)

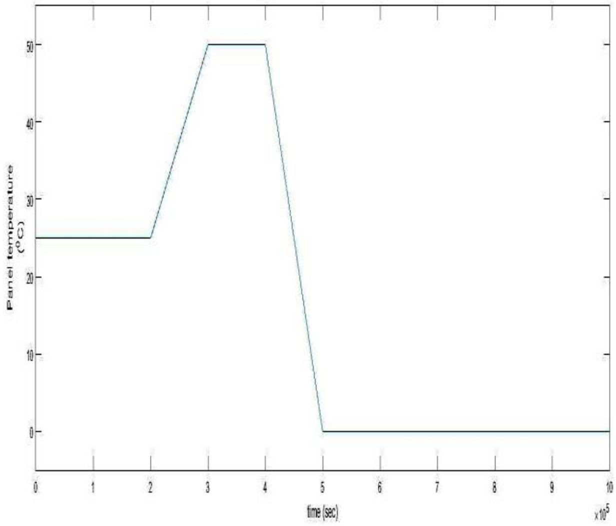

Fig. 9 Panel temperature (^{0}C) verses time(sec)

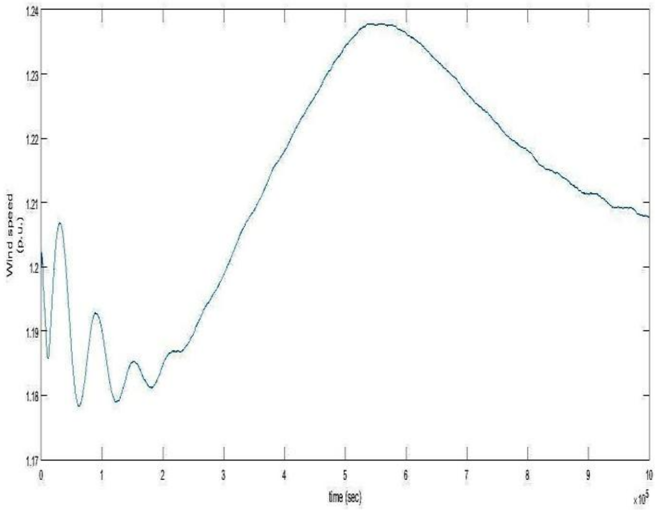

Fig. 10 Variable wind speed (p.u.) verses time(sec)

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Despite of the photovoltaic voltage fluctuation caused due to solar radiation variations, the proposed control system of the solar power plant successfully kept the load voltage stable at 500V. The output voltage of the dc/dc converter and the output voltage of the PV panel have been represented in Fig. 11 and Fig.12 respectively.

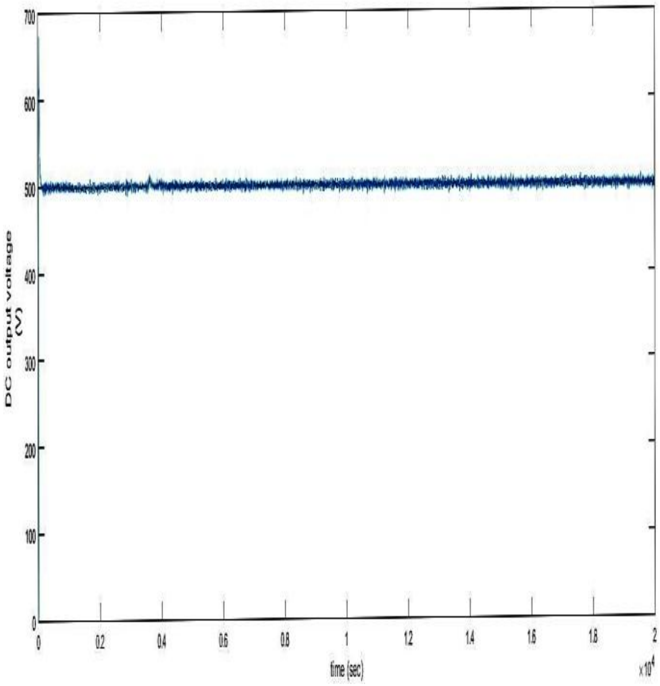

Fig. 11 Output voltage of the DC/DC boost converter (V) verses time (sec)

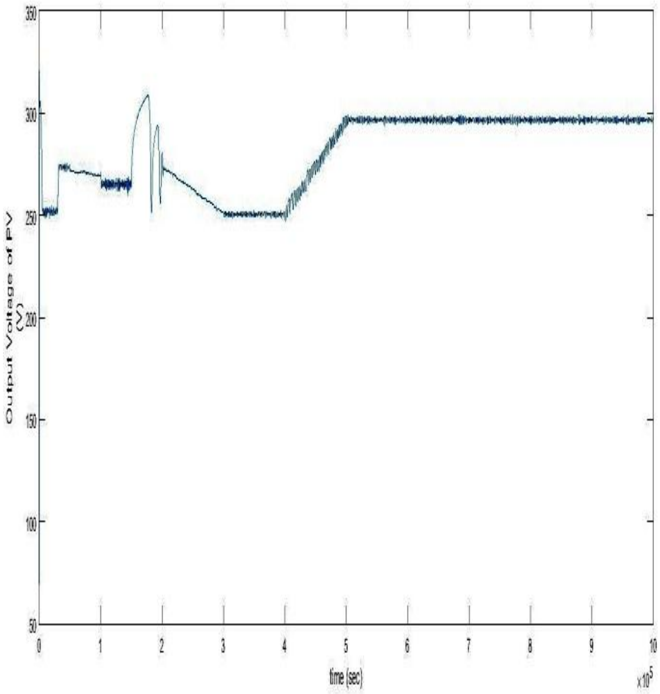

Fig. 12 Output voltage of PV panel (V) verses time(sec)

The objective of P&O algorithm is to adjust the dc/dc boost control variable, so that PV array operates at the maximum power point (MPP). PV array operating current (*Ipv*), as shown in Fig. 13. Total power output of PV (kW) has been represented in Fig. 14.

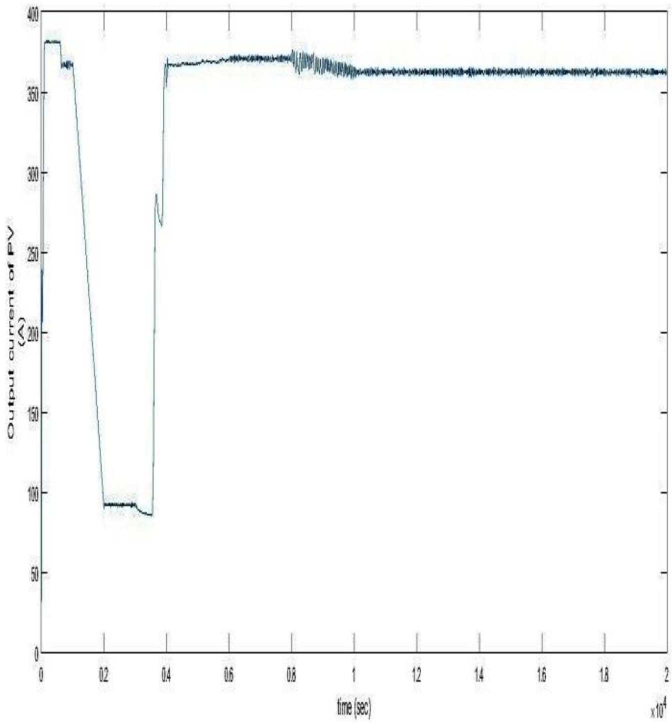

Fig. 13 Output current of PV panel (A) verses time (sec)

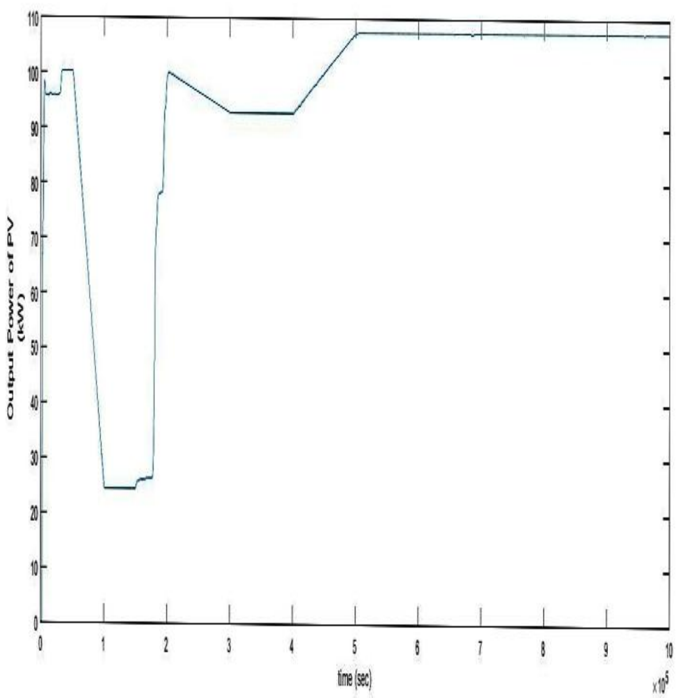

Fig. 14 Total power output of PV (kW) verses time (sec)

The solar power is unavailable during early morning before 8:30am and in the evening after 19:00pm, due to nonexistence of solar radiation. To overcome this unavailability of solar power leading to deficiency of the PV system, and to increase the amount of power, the DFIG wind turbine system was added to the solar power plant. Stator winding is connected directly to 60 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter.

The active power P (kW), reactive power Q (Mvar) and the

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dc voltage of DFIG system is shown in Fig. 15, Fig. 16 and Fig. 17.

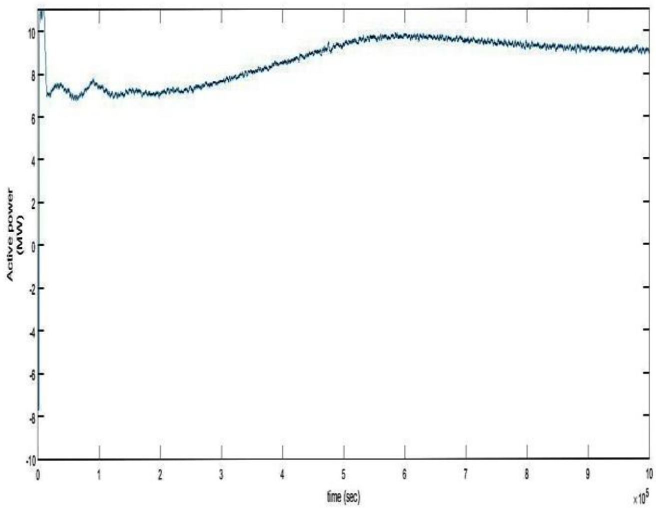

Fig. 15 Active power (P in MW) verses time(sec)

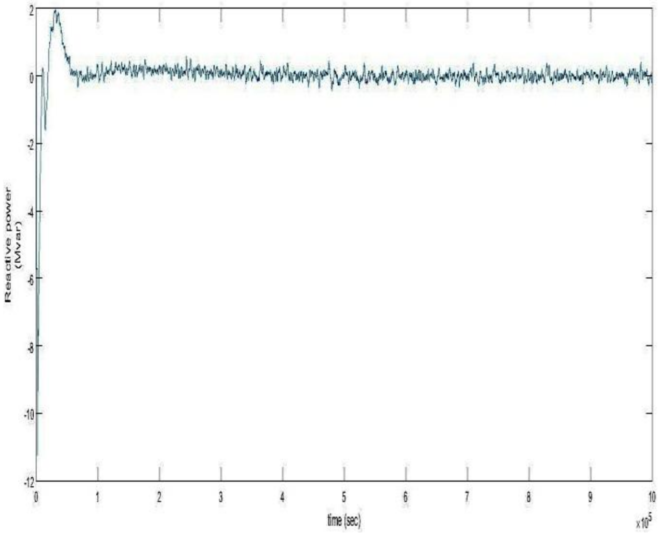

Fig. 16 Reactive power (Q in Mvar verses time(sec)

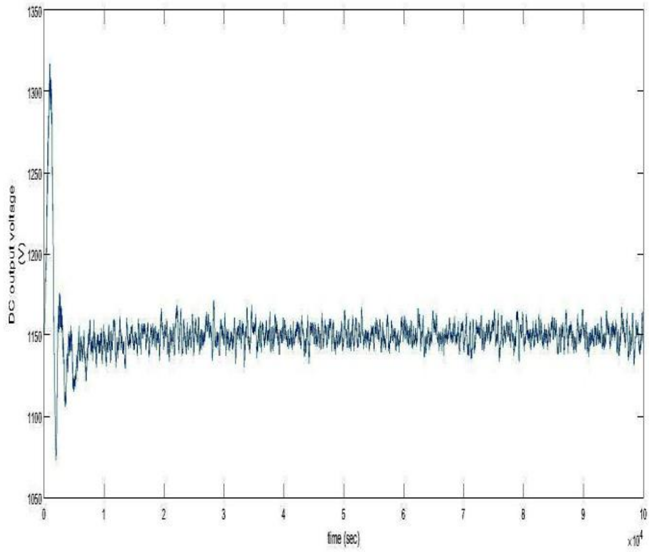

Fig. 17 DC output voltage (V) verses time (sec)

The PV power plant and the wind energy power plant delivered the power to the grid. The power delivered to the grid by PV power plant and the wind energy power plant is shown in Fig. 18 and Fig. 19 respectively. The total power of the integrated system is shown in the Fig. 20.

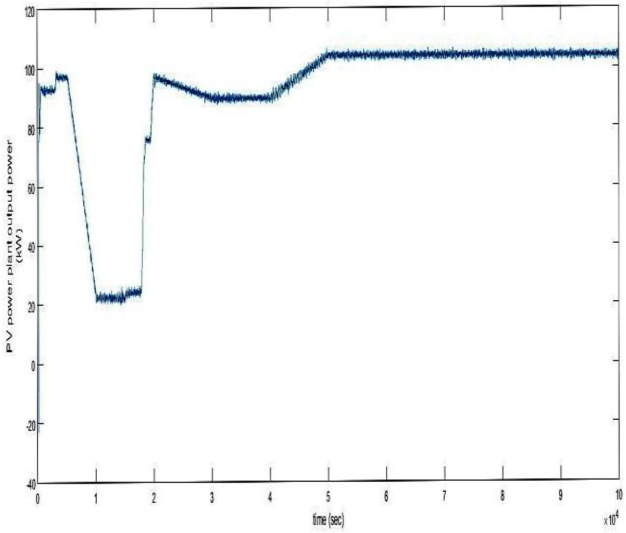

Fig. 18 PV power plant output power (kW) verses time(sec)

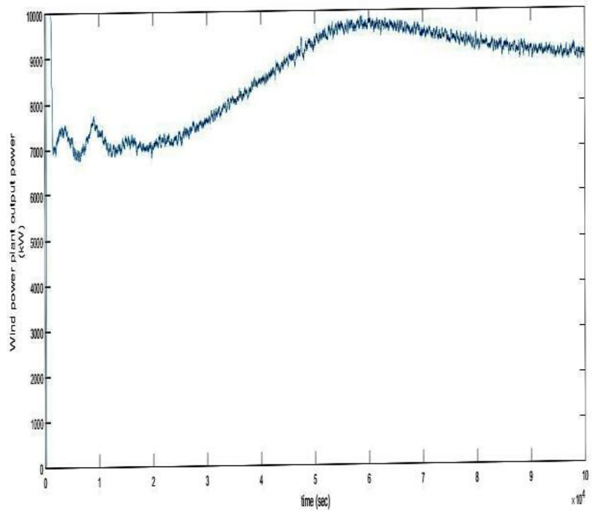

Fig. 19 Wind power plant output power (kW) verses time (sec)

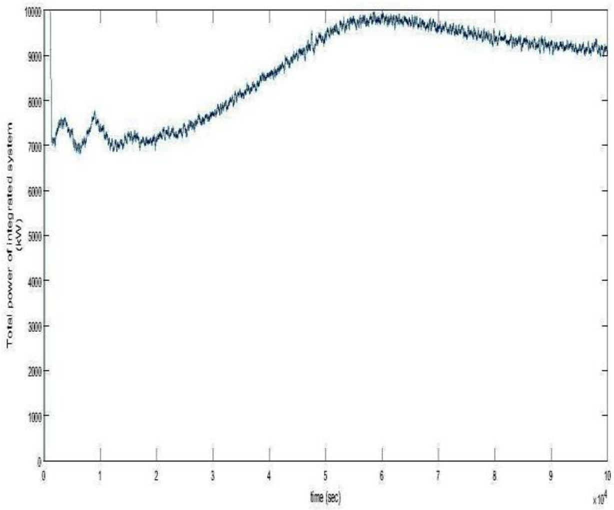

Fig. 20 Total power output of integrated system (kW) verses time (sec)

IV. CONCLUSION

In this paper, a novel PV/DFIG hybrid power system has been designed and modeled for smart grid applications. The developed technique comprises of system components and an apposite power flow controller. The model has been executed using the MATLAB/SIMULINK software package. The proposed hybrid PV/DFIG energy conversion system provides a sophisticated integration of the solar PV and wind turbine to extract optimum energy from both sources. The available power from the PV system is highly dependent on solar radiation which remains unavailable at various time and situation. To overwhelmed this deficiency of PV system, the PV module was integrated with the DFIG wind turbine system. The developed system and its control strategy showed excellent performance for the simulation. Overall, the proposed system makes decent use of the nature's complementary behavior for wind velocity and solar radiation.

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