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Maximum Power Point Tracking Of A Hybrid Solar-Wind Power Generation System For A Smart Grid Using Fuzzy Logic Control

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Abstract— A novel model of smart grid-connected PV/WT hybrid system is developed. Maximum power point tracking (MPPT) must usually be integrated with photovoltaic (PV) power systems so that the photovoltaic arrays are able to deliver the maximum power available. The new controller improves the hill-climbing search method by fuzzifying the rules of such techniques and eliminates their drawbacks. The proposed model and its control strategy offer a proper tool for smart grid performance optimization. The model is implemented using MATLAB/SIMULINK software package.

Index Terms—Modeling, Photovolatic power system, Wind power generation, Fuzzy logic Control, Smart grid, Control system

1 INTRODUCTION

In recent years, renewable energy sources become more significant source of energy. Among the renewable energy sources, solar energy is sustainable with less carbon emissions [1-2].The output power of a PV array varies according to the sunlight conditions such as solar irradiation, shading and temperature. To obtain maximum power from photovoltaic array, photovoltaic power system usually requires maximum power point tracking (MPPT) controller [3].
Various approaches have been reported to implement MPPT such as perturb and observe (P&O) method [4-5], the incremental conductance method, constant voltage method and short-circuit current method [6]. Using this method the maximum power point can be found for specified solar irradiation and temperature condition but they display oscillatory behaviour around the maximum power point under normal operating conditions. Moreover the system will not respond quickly to rapid changes in temperature or irradiance. On the other hand the conventional PI controllers are fixed-gain feedback controllers. Therefore they cannot compensate the parameter variations in the process and cannot adapt changes in the environment. PI-controlled system is less responsive to real and relatively fast alterations in state and so the system will be slower to reach the set point. Recently intelligent based schemes have been introduced [7-9].Among the intelligent based methods fuzzy logic controller has its own merits such that the MPPT algorithm can be easily formed. The shape of the membership function of the fuzzy logic controllers can be adjusted such that the gap between the operation point and maximum power point can be optimized. Therefore in the present paper, an intelligent control technique using fuzzy logic control associated with a MPPT controller are used to improve energy conversion efficiency of the photovoltaic system.

The proposed intelligent fuzzy logic process comprises of expert knowledge which extracts maximum power from a PV module under varying solar irradiation, temperature and load condition. Mathematical modeling of the system and the simulation results using MATLAB / SIMULINK are presented.

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- Grid optimisation: system reliability and operational efficiency.
- Distributed generation: not only traditional large power stations, but also individual PV panels, micro-wind,etc.
- Advanced metering infrastructure (AMI): smart meters.
- Grid-scale storage.
- Demand response.

This paper focuses mainly on the smart grid integration of PV/WT hybrid system (grid optimisation and distribution generation).

2 SYSTEM DESCRIPTION AND MODELING

Smart grid is a system consists of three layers: the physical power layer, the control layer and the application layer. And according to, Katherine Hamilton [1], smart grid has to be dynamic and have constant two-way communication, as shown in Fig.1. So, for example, with PV panels on the roofs, intelligent building system will generates, store and use their own energy. Hence, as active buildings they become part of the smart grid. This could save energy and increase reliability and transparency.
In this section, the dynamic simulation model is described for photovoltaic/wind turbine hybrid generation system. The developed system consists of a photovoltaic array, dc/dc converter with an isolated transformer, designed for achieving the MPP with a current reference control (I_{ref}) produced by P&O algorithm, wind turbine, asynchronous induction generator, and ac/dc thyristor controlled bridge rectifier. The block diagram of the developed system is shown in Fig. 2.

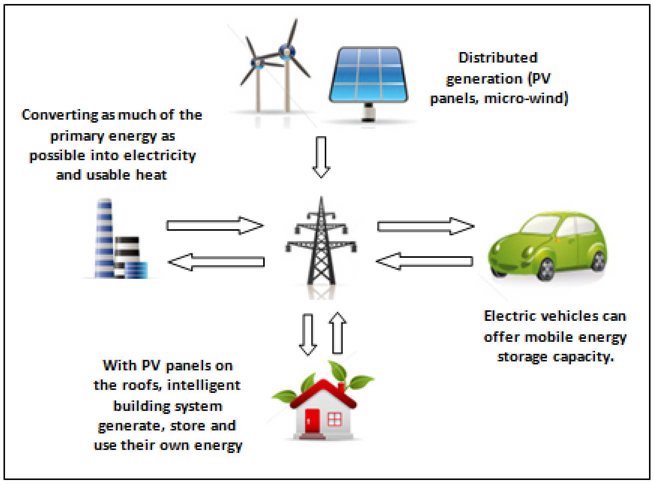


Fig. 1. General layout of the smart grid

A. *Modeling and Design of a Photovoltaic Module*

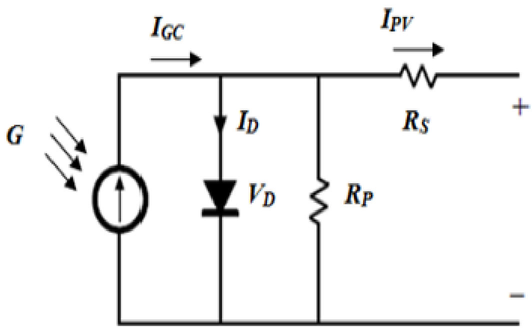


Fig. 3. Single diode PV cell equivalent circuit

The general mathematical model for the solar cell has been studied over the past three decades [12]. The circuit of the solar cell model, which consists of a photocurrent, diode, parallel resistor (leakage current) and a series resistor; is shown in Fig. 3. According to both the PV cell circuit shown in Fig. 3 and Kirchhoff's circuit laws, the photovoltaic current can be presented as follows [13]:

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

Where I_{gc} is the light generated current, I_o is the dark saturation current dependant on the cell temperature, e is the 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, T_c is the cell's absolute temperature, v_d is the diode voltage, and R_p is the parallel resistance. The photocurrent (I_{gc}) mainly depends on the solar irradiation and cell temperature, which is described as [13]

$$I_{gc} = [\mu_{sc}(T_c - T_r) + I_{sc}]G \qquad (2)$$

Where μ_{sc} is the temperature coefficient of the cell's short circuit current, T_{ref} is the cell's reference temperature, I_{sc} is the cell's short circuit current at a 25^0 C and 1kW/m2, and G is the solar irradiation in kW/m2. Furthermore, the cell's saturation current (I_o) varies with the cell temperature, which is described as [13]

$$I_o = I_{o\alpha}\left(\frac{T_c}{T_r}\right)^3 \exp^{\left[\frac{ev_g}{KF}\left(\frac{1}{T_r} - \frac{1}{T_c}\right)\right]} \qquad (3)$$

$$I_{o\alpha} = \frac{I_{sc}}{\exp^{\left(\frac{ev_{oc}}{KFT_c}\right)}} \qquad (4)$$

Where $I_{o\alpha}$ is the 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 the cells open circuit voltage. In this study, a general PV model is built and implemented using MATLAB/SIMULINK to verify the nonlinear output characteristics for the PV module. The proposed model is implemented, as shown in Fig. 4. In this model, whereas the inputs are the solar irradiation and cell temperature, the outputs are the photovoltaic voltage and current. The PV models parameters are usually extracted from the manufactures data sheet.

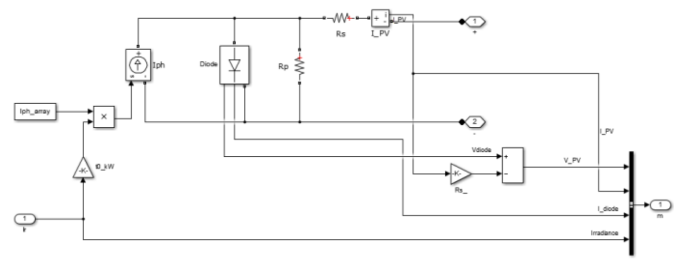


Fig. 4. Subsystem implementation of the PV model

B. Modeling and Design of a WT and Induction Generator

Several studies have been reported regarding to WT and wind generators [14]. 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 given by [15]:

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

Where P_m is the mechanical output power of the turbine, c_p is the performance coefficient of the turbine, λ is the tip speed ratio of the rotor blade, β is the blade pitch angle, ρ is the air density, A is the turbine swept area, and v_{wind} is the wind speed. The performance coefficient model c_p (λ,β) used in this paper is taken from [16] and given by:

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

Where constants c_1 to c_6 are parameters that depend on the

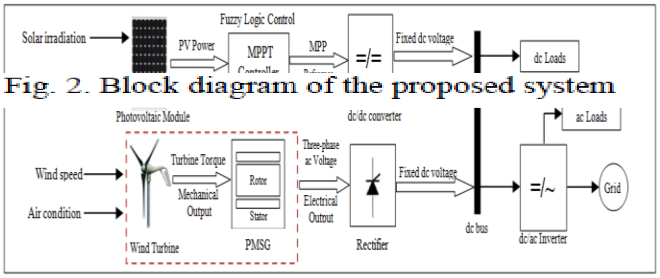


Fig. 2. Block diagram of the proposed system

wind turbine rotor and blade design, and λ_i is a parameter given in (7).

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

Furthermore, (5) can be normalized and simplified for specific values of *A* and *ρ*, as in (8):

$$P_{m-pu} = k_p c_{p-pu} v^3_{wind-pu} \quad (8)$$

Where P_{m-pu} is the power in per unit (p.u.) of nominal power for particular values of ρ and A, c_{p-pu} is the p.u. value of the performance coefficient c_p, k_p is the power gain, $v_{wind-pu}$ is the p.u. value of the base wind speed. The based wind speed is the mean value of the expected wind speed in (m/s). The modified model of the WT is implemented as shown in Fig. 5. In this model, whereas the inputs are the wind speed and generator speed, the output is the torque applied to the generator shaft. The torque of the generator is based on the generator power and speed.

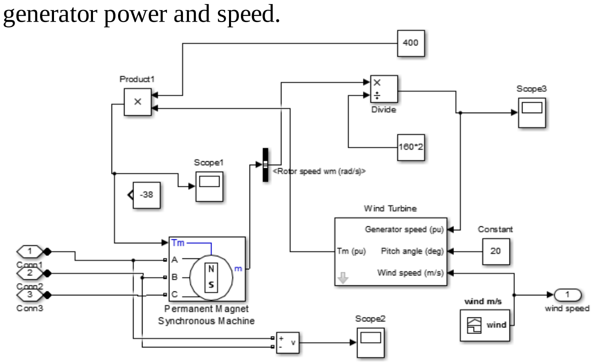


Fig. 5. Subsystem implementation of the WT model

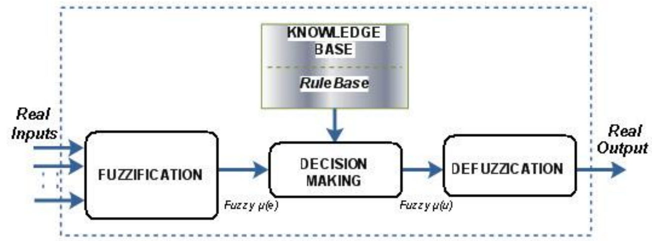
The wind turbine induction generator (WTIG) model is designed using the built-in SimPowerSystem library. The rotor shaft is driven by the WT which produces the mechanical torque according to the generator and wind speed values. The electrical power output of the generator (stator winding) is connected to the smart grid.

C. Power Control Systems

MPPT by the fuzzy logic approach

Fuzzy systems (FS) are based on fuzzy set theory and associated techniques pioneered by Lotfi Zadeh. It is a non-linear control method, which attempts to apply the expert knowledge of an experienced user to the design of a fuzzy-based controller.

Generally, as shown in figure 2, FLC contains four main components:
a) The fuzzifier that maps crisp values into input fuzzy sets to activate rules.
b) The rules which define the controller behavior by using a set of IF-THEN statements.
c) The inference engine which maps input fuzzy sets into output fuzzy sets by applying the rules, and
d) The defuzzifier that maps output fuzzy values into crisp values.



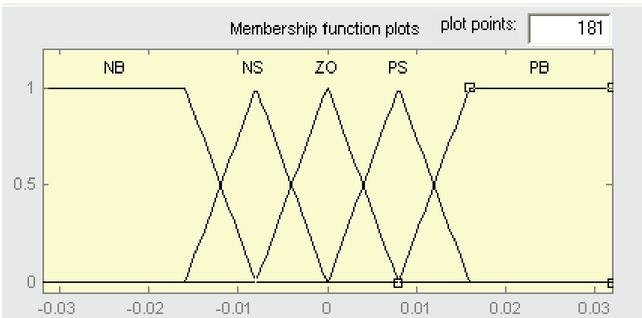
The rules describing the FLC operation are expressed as linguistic variables represented by fuzzy sets. The controller output is obtained by applying an inference mechanism. In the case of fuzzy controllers hardware implementation, which is of interest here, the shapes of the membership functions associated to the FLC linguistic variables are often piece -wise linear functions (triangular or trapezoidal). It should be noted that the number and shape of the membership functions of each fuzzy set as well as the fuzzy logic inference mechanism was initially selected based on trial-and error methods, in a manner that the region of interest is covered appropriately by the inputs data. The idea behind the chosen reasoning was ; if the last change in the control signal *(D)* caused the power to rise, keep moving in the same direction; otherwise, if it has caused the power to drop move it in the opposite direction . The MPPT using the Mamdani's FLC approach, which uses the min-max operation fuzzy combination law, is designed in a manner that the control task try to continuously move the operation point of the solar array as close as possible to the maximum power point (*MPP*). The two inputs of the fuzzy controller are the tracking error (*E*) and change of the error(ΔE), which are defined as:

$$E(n) = \frac{p(n) - p(n-1)}{V(n) - V(n-1)}$$

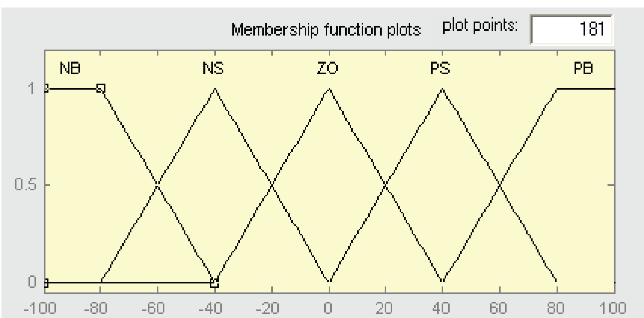
$$\Delta E(n) = E(n) - E(n-1)$$

$$D = \frac{\sum_{j=1}^{n} \mu(D_j) - D_j}{\sum_{j=1}^{n} \mu(D_j)}$$

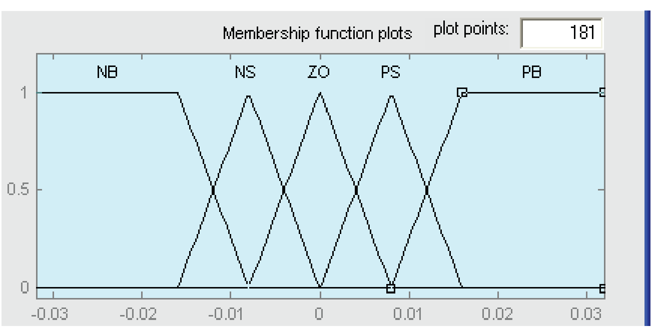
Where: *E* and ΔE are the error and change in error, *n* is the sampling time, *p(n)* is the instant power of the PV generator, and *V(n)* is the instant corresponding voltage. These inputs are chosen so that the instant valueof *E(n)* shows if the load operation power point is located on the right or in the left compared to the P_{max} actual position. While Δ *E(n)* expresses the moving direction of this operation point.The output variable is the pulse width modulation (PWM) signal called *D*, which is transmitted to the boost DC/DC converter to drive the load. After the rules have been applied, the center of area as the defuzzication method is used to find the actual value of (*D*) as a crisp output. The range of the power error is (-0.03 to 0.03 W/V) and their linguistic variables are considered as negative big (NB), negative small (NS), zero (ZE), positive small (PS) and positive big (PB) where as change of power error range is (-100 to 100 W/V) and its linguistic variables are selected as negative big (NB), negative small (NS), zero (ZE), positive small (PS) and positive big (PB). The output variable is the PWM signal driver whose range is (-0.03 to 0.03 V) and its linguistic variables are chosen as negative big (NB), negative small (NS), zero (ZE), positive small (PS) and positive big (PB).



6(a) membership functions of input variable E;



6(b) membership functions of input variable dE



6(c) membership functions of output variable D

Table 1: Fuzzy rule table

E ↓ \ CE →	NB	NS	ZE	PS	PB
NB	ZE	ZE	PB	PB	PB
NS	ZE	ZE	PS	PS	PS
ZE	PS	ZE	ZE	ZE	NS
PS	NS	NS	NS	ZE	ZE
PB	NB	NB	NB	ZE	ZE

Table 1 shows the table of fuzzy controller rules where the inputs are fuzzy sets of error (E) and the change of error (dE). The output of this rules table is the duty cycle (D).

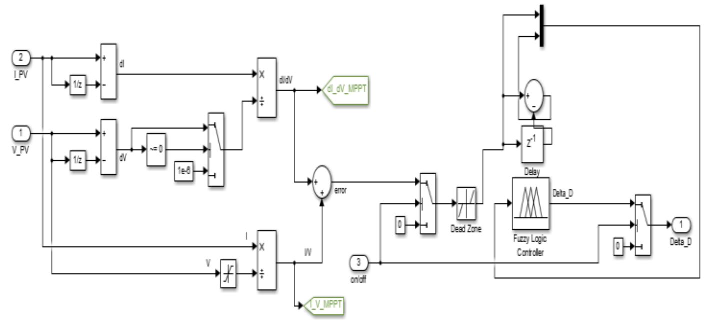


Fig 7.Control Model of fuzzy system

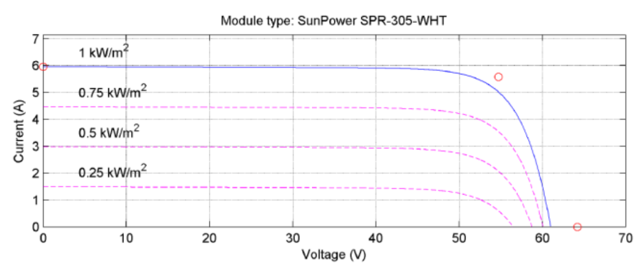
3 Simulation, Result And Discussion

The block diagram of the integrated photovoltaic/wind turbine system, and the power controllers are shown in Fig. 2.

a) The major inputs for the proposed PV model were solar irradiation, PV panel temperature and PV manufacturing data sheet information's. In this study, Sun Power SPR 305-WHT PV panel is taken as example.

Parameter	Value
Maximum power (P_m)	305.27W
Open circuit voltage (V_{oc})	64.2V
Voltage at P_m (V_{amp})	54.7V
Short circuit current (I_{sc})	5.96A
Current at P_m (I_{amp})	5.58A

The I-V and P-V output characteristics for the PV model are shown in Fig.8. The output power and current of PV module depend on the



solar irradiance and temperature, and cell's terminal operating voltage as well. It was found from Fig. 8(a) and 8(b) that with increased solar irradiance there is an increase in both the maximum power output and the short circuit current

Fig. 8.a I-V output Characterstics

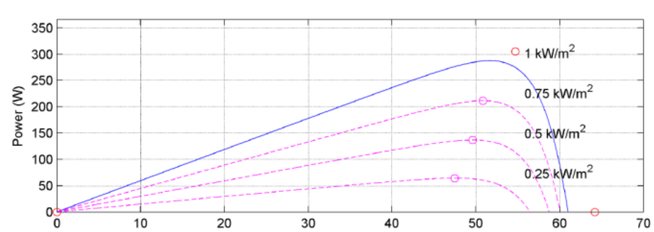


Fig. 8 b P-V output characteristics

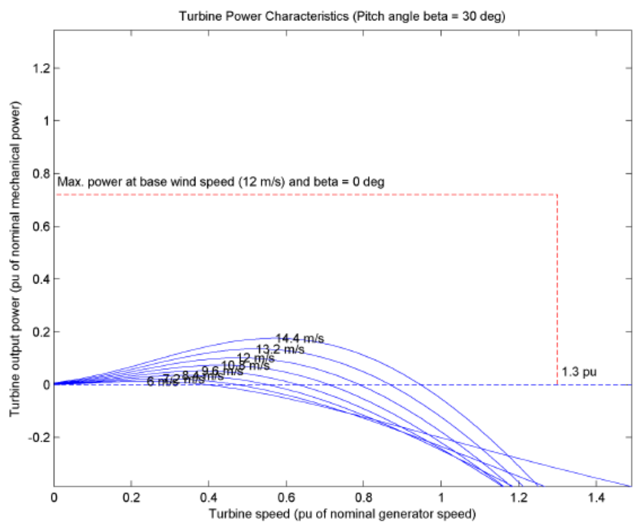
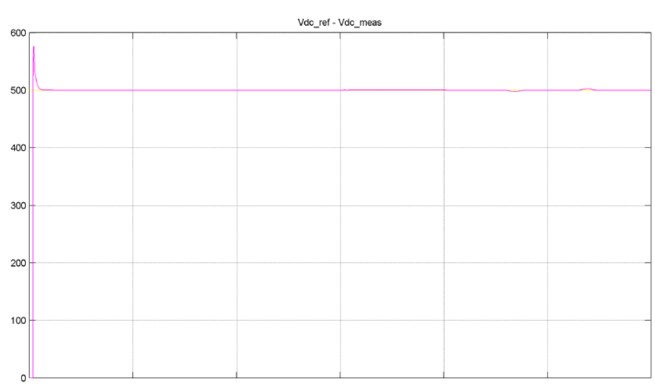


Fig .9 Wind turbine characteristics

The generator speed (rpm) and the generator power (p.u.) characteristics for the WT model are shown in Fig. 9 corresponding to various wind speed values. The output power of WT depends on the wind speed and generator speed. As depicted in Fig.9, wind speed is the most influential factor on the amount of power produced by the wind turbine. Because the power in the wind is a cubic function of wind speed, changes in speed produce a profound effect on power.

b)Wind Turbine PMS Machine parameters

Nominal mechanical output power (W)	20e3
Base power of the electrical generator (VA)	20e3
Base wind speed (m/s)	12
Maximum power at base wind speed (pu of nominal mechanical power)	0.72
Base rotational speed (p.u. of base generator speed)	1.3
Pitch angle beta to display wind-turbine power characteristics (beta >=0) (deg)	30



Although the photovoltaic voltage fluctuates due to solar radiation variations, the proposed control system of the solar power plant successfully keeps the load voltage stable at 500V. The output voltage of the dc/dc converter is depicted in Fig.10. The output voltage of the PV panel is depicted in Fig.11.

Fig. 10. Output voltage of the dc/dc converter

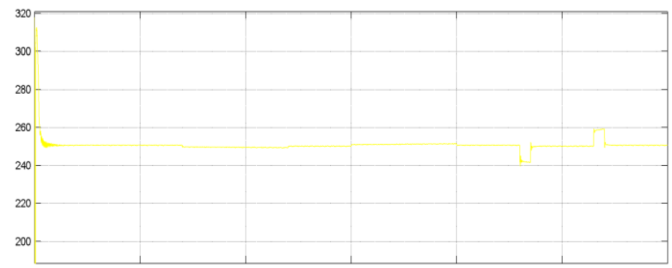


Fig. 11. Output voltage of the PV panel

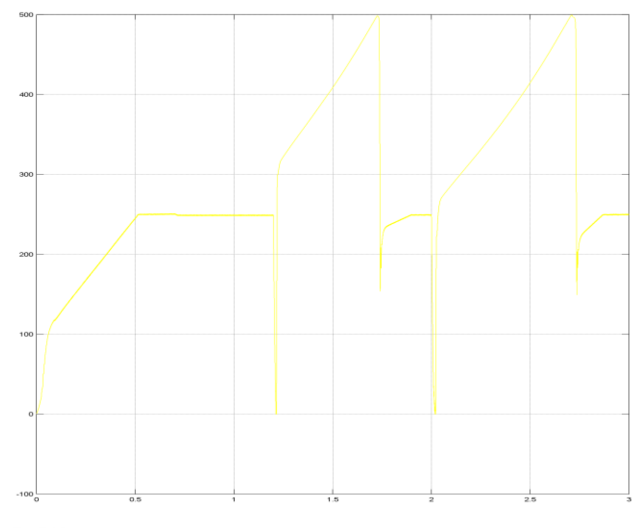
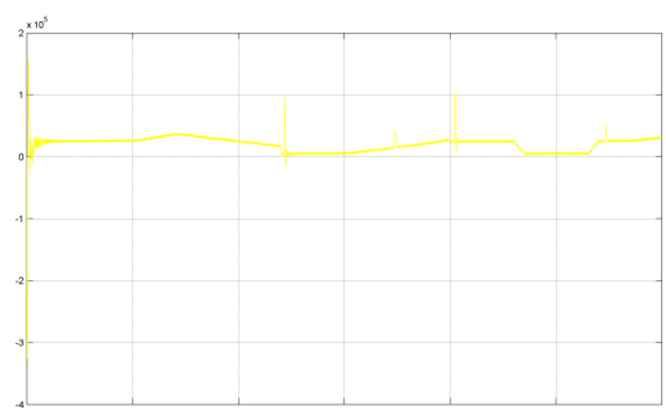


Fig .17 Power of the generator coupled to the wind turbine

Fig. 18 Power delivered to load side by the hybrid topology



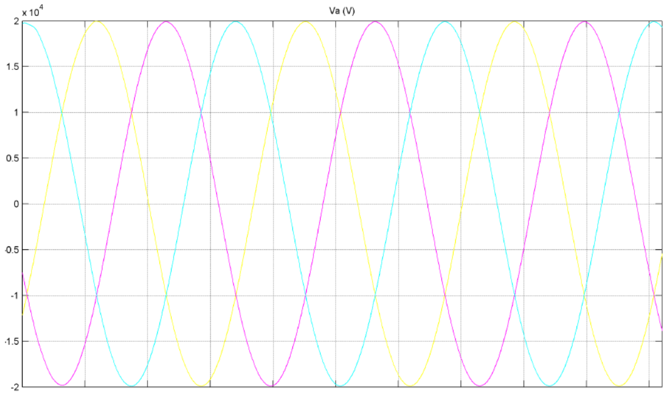


Fig .19 Grid Voltage form Hybrid topology

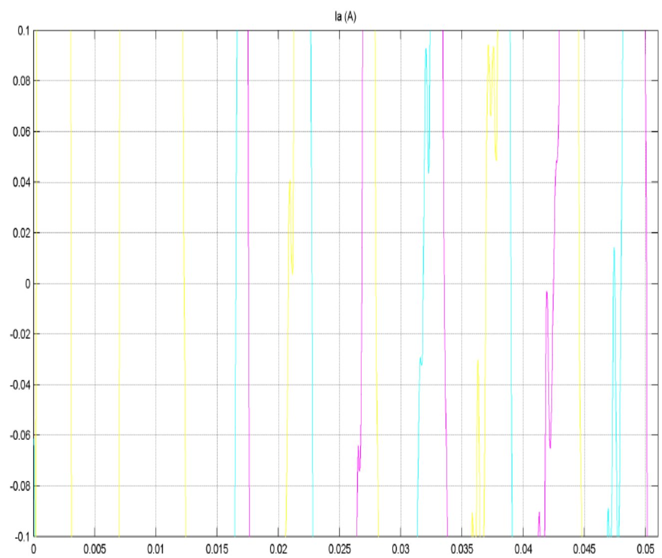


Fig .20 Grid Current from Hybrid topology

4 Conclusion

In this paper, a novel PV/WT hybrid power system is designed and modelled for smart grid applications. The developed algorithm comprises system components and an appropriate power flow controller. The model has been implemented using the MATLAB/SIMULINK software package, and designed with a dialog box like those used in the SIMULINK block libraries. The available power from the PV system is highly dependent on solar radiation. To overcome this deficiency of the PV system, the PV module was integrated with the wind turbine system. The dynamic behavior of the proposed model is examined under different operating conditions. The developed system and its control strategy exhibit excellent performance for the simulation of a complete day. The proposed model offers a proper tool for smart grid performance optimization.

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