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Modeling and simulation of stand-alone hybrid power system with fuzzy MPPT for remote load application

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Abstract: Many parts of remote locations in the world are not electrified even in this Advanced Technology Era. To provide electricity in such remote places renewable hybrid energy systems are very much suitable. In this paper PV/Wind/Battery Hybrid Power System (HPS) is considered to provide an economical and sustainable power to a remote load. HPS can supply the maximum power to the load at a particular operating point which is generally called as Maximum Power Point (MPP). Fuzzy Logic based MPPT (FLMPPT) control method has been implemented for both Solar and Wind Power Systems. FLMPPT control technique is implemented to generate the optimal reference voltage for the first stage of DC-DC Boost converter in both the PV and Wind energy system. The HPS is tested with variable solar irradiation, temperature, and wind speed. The FLMPPT method is compared with P&O MPPT method. The proposed method provides a good maximum power operation of the hybrid system at all operating conditions. In order to combine both sources, the DC bus voltage is made constant by employing PI Controllers for the second stage of DC-DC Buck-Boost converter in both Solar and Wind Power Systems. Battery Bank is used to store excess power from Renewable Energy Sources (RES) and to provide continuous power to load when the RES power is less than load power. A SPWM inverter is designed to convert DC power into AC to supply three phase load. An LC filter is also used at the output of inverter to get sinusoidal current from the PWM inverter. The entire system was modeled and simulated in Matlab/Simulink Environment. The results presented show the validation of the HPS design.

Key words: Solar PV system, Wind energy conversion system, Hybrid power system, DC-DC converters, Fuzzy logic based MPPT, Three phase PWM inverter

1. Introduction

Environmental effects such as global warming and pollution due to fossil fuel based electricity production systems are become huge issues in the International Agenda in the last two decades. Researchers are trying to meet the ever increasing energy demands with inexaustible, enviromentally friendly Renewable Energy Sources (RES) [1]. RES are clean, pollution free and abundantly available in nature. Recently, Solar PV and Wind energy sources have been proved as more promising, technically matured, and cost effective energy sources. They are being used in many places of world as a single source are combinely as HPS [1-4]. These sources are used in stand-alone or grid connected mode. PV-Wind hybrid power system with storage device can provide reliable power for stand alone loads [1-3].

The renewable energy sources are producing energy using natural resources like solar irradiation, natural wind, tides or waves etc. These natural resources are varying in nature with respect to time. So the power production from renewable energy sources also varying from time to time. Maximum power from the sources can be obtained by using MPPT Controller [1, 5-10]. In order to obtain maximum power from these sources, many maximum power tracking techniques can be found in the literature. For extracting maximum power from solar PV, techniques like Perturb & Observe (Hill Climbing) Incremental Conductance, Current Control, Voltage Control, Pilot Cell, Current Compensated Voltage Control, Fuzzy Logic Control, Neural Network Control etc. have been proposed in the literature [1, 5, 6, 9]. For wind system many techniques such as Tip speed ratio cotrol, Hill Climbing search, Fuzzy Logic Control, Neural Network Control etc. has been proposed in the literature [1, 10, 11].

2. Hybrid power system configuration

In this paper a PV/Wind/Battery Hybrid power system with a 3-phase load is considered. The configuration of the system is shown in Figure 1 [2, 3]. This centralized DC bus HPS structure provides some advantages such as robust control, economics and easiness of control [1]. The PV modules considered are generating peak power of 100 kW. TitanS6_60 solar panels are modeled for 100 kW output power at nominal operating cell temperature and solar irradiation. 24 solar panels are connected in series and 20 such strings are connected in parallel. Totally 480 panels are used for constructing the solar PV system. A PMSG type generator rated for 200 kW is considered for wind turbine. The connected load to the system is 80 kW maximum considered as 40 kW base load and two additional loads of 20 kW each. The load is variable because it is considered as a village electricity load. The Battery Energy Storage System (BESS) are rated for 300 kWh. One string consists of 72 batteries of 120 Ah connected in series, which can store 100 kWh of energy. Three such strings are connected in parallel to provide 300 kWh of energy ie. the BESS can supply 3 h 45 minutes for the maximum load of 80 kW. The system components and controllers are modeled in MATLAB/Simulink.

Generally, the DC bus voltage regulated by adjusting the amplitude of the injected current into AC side. An increase in the injected AC current will cause a decrease in the DC bus voltage and vice versa, but this approach may cause significant deterioration of the power quality on AC side. In order to achieve MPP operation and DC voltage stabilization two stages of DC-DC converters are employed [1] in the proposed scheme of HPS as in Figure 1. The first stage is Boost converter, which is employed for MPP operation. The second converter is Buck-Boost converter, which can regulate the DC bus voltage.

In this paper a Fuzzy Logic based MPPT is proposed [5-10] for the HPS, which can electrify a village load or an industrial load of 80 kW Peak. The output voltage from solar PV system varies from 150 V to 850 V according to solar irradiation level and temperature. The output voltage from wind generator is 120 V to 925 V depends on the wind speed. These voltages are boosted by changing the duty cycle of the Boost converter in each case. The duty cycles are obtained from respective Fuzzy Logic Controllers. The DC Bus voltage is maintained at 850 V, by the use respective DC-DC Buck-Boost converters with PI controller for both Solar and Wind Generator as shown in Figure 1.

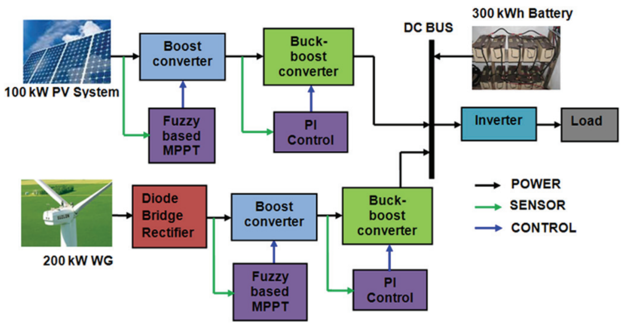

Fig. 1. PV/wind/battery hybrid power system

3. Energy management algorithm

It is important to utilize the available RES power and the load should be met without more interruptions. For this purpose an energy management algorithm is necessary in the HPS. The main decision making factors in the proposed energy management algorithm are the level of the power provided by the RES (solar, wind), load power and the state of charge (SOC) of the battery bank [2]. The power management algorithm utilised in this paper is shown in Figure 2. The algorithm has the following steps [2, 3]:

i) Receive solar PV power, wind power, battery power, load power and SOC of the battery.

ii) Calculate RES power $P_{available} = P_{solar} + P_{wind}$ and $P_{excess} = P_{available} - P_{Load}$.

iii) Check whether P_{excess} is greater than or equal to zero.

iv) If P_{excess} is equal to zero then meet the load only without battery.

v) If P_{excess} is greater than zero and SOC is ≥ 80% then meet the load and connect dump load.

vi) If P_{excess} is positive and SOC is not ≥ 80% then meet the load and charge the battery bank.

vii) If P_{excess} is negative and SOC is less than 40% disconnect all loads.

viii) If P_{excess} is negative and SOC is between 40% and 80% then check $P_{excess} + P_{Battery} \geq 80$ kW.

ix) If $P_{excess} + P_{Battery} \geq 80$ kW then meet the load with battery bank.

x) If $P_{excess} + P_{Battery} < 80$ kW then disconnect load3 and check $P_{excess} + P_{battery} \geq 60$ kW.

xi) If $P_{excess} + P_{Battery} \geq 60$ kW then meet the load with battery bank.

xii) If $P_{excess} + P_{Battery} < 60$ kW then disconnect load2 and check $P_{excess} + P_{battery} \geq 40$ kW.
xiii) If $P_{excess}+P_{Battery} \geq 40$ kW then meet the load with battery bank.
xiv) If $P_{excess}+P_{Battery} < 40$ kW then disconnect load1.
xv) Repeat the sequence.

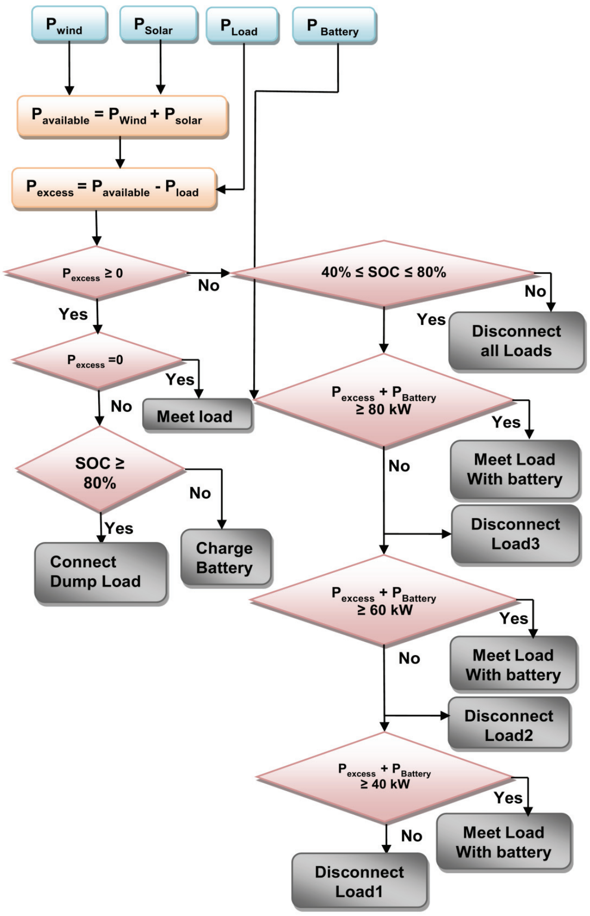

Fig. 2. Algorithm for Power management in HPS

This algorithm checks all conditions in the HPS and taking decision according to difference power between RES power and load power, SOC of the battery.

4. Model for solar PV system and principle of MPPT

The model of the PV cell can be developed by using equivalent circuit of PV Cell. The basic equation that describes I-V characteristic of the ideal photovoltaic cell shown in Figure 3 is [5-7, 9, 11]:

$$I = I_{pV,cell} - I_{0,cell}\left[\exp\left(\frac{qV}{akT}\right) - 1\right], \tag{1}$$

where $I_{pv,cell}$ is the current generated by the incident light, I_d is the Shockley diode equation, $I_{o,cell}$ is the reverse saturation or leakage current of the diode, q is the electron charge ($1.60217646 \times 10^{-19}$ C), k is the Boltzmann constant ($1.3806503 \times 10^{-23}$ J/K), T (in Kelvin) is the temperature of the p-n junction, and a is the diode ideality constant. Practical arrays are composed of several photovoltaic cells that are connected in series and parallel. Cells connected in parallel increase the output current and cells connected in series provide greater output voltages.

The observation of the characteristics at the terminals of the photovoltaic array requires additional parameters to (1). So it can be expressed as

$$I = I_{pV} - I_0\left[\exp\left(\frac{V + R_s I}{aV_t}\right) - 1\right] - \frac{V + R_s I}{R_p}, \tag{2}$$

where I_{pv} and I_o are the photovoltaic (PV) and saturation currents, respectively, of the array and $Vt = NkT/q$ is the thermal voltage of the array with N_{ss} cells connected in series. The I-V characteristic of the photovoltaic device depends on the internal characteristics of the device (R_s, R_p) and on external influences such as irradiation level and temperature.

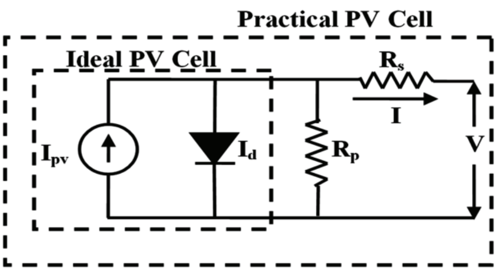

Fig. 3. Generalized model of a PV cell

A 100 kW Solar system is simulated in MATLAB/Simulink. TitanS6_60 Panel's data were used for simulation [11]. The specifications of the TitanS6_60 panel are given in Table 1. To design 100 kW PV system 24 modules are connected in series and 20 such strings are connected in parallel. Figure 4 shows the power Vs voltage characteristics of the 100 kW PV system at various voltage and current levels. For the maximum power the PV voltage is varying from 620 V to 680 V approximately for 200 W/m^2 to 1000 W/m^2 at 25°C.

The available power from solar PV system depends on irradiation and temperature. The maximum power can be extracted from solar PV system by operating the panels output to match the load resistance means that changing the level of operating voltage and current. This could be explained using the I-V characteristic and P-V characteristic of the PV system shown in Figure 5.

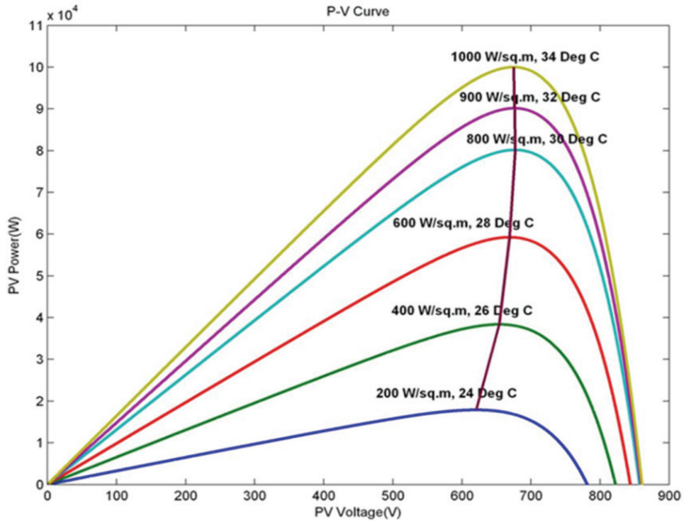

Fig. 4. P-V characteristics of 100 kW PV system at different irradiation and temperature levels

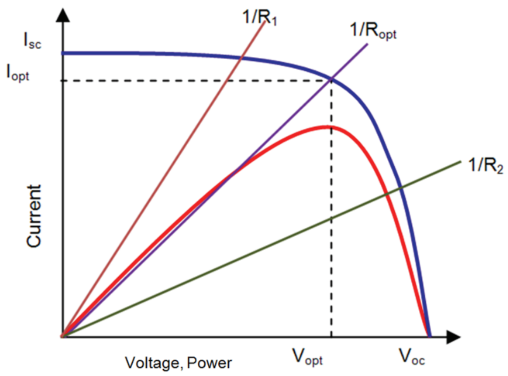

Fig. 5. I-V and P-V characteristics of PV system

Table 1. Parameters of the TITANS6_60 PV Module at 25° C and 1000 W/m^2

Parameter	Symbol	Value
Peak power	P_{MPP}	215.015 W
Peak power voltage	V_{MPP}	28.9 V
Peak power current	I_{MPP}	7.44 A
Open circuit voltage	V_{OC}	37 V
Short circuit current	I_{SC}	8.21 A
Temperature coefficient of current	K_i	3.183 mA/°C
Temperature coefficient of voltage	K_v	−0.123 mV/°C
Number of series cells	N_s	60

For varying loads, irradiation and temperature, the maximum power tracking is nothing but adjustment of load line. To adapt the load resistance to the solar PV system and extract maximum power, the duty cycle is set to its optimal value which corresponds to its optimal operating point (V_{opt}, I_{opt}). R_1 and R_2 are load resistances for two different load conditions. If the PV system is operated at either of these points, could not produce maximum power. Instead it will produce lesser power than maximum power. To increase the efficiency of the solar PV system it is necessary to employ maximum power tracking techniques.

5. Model for wind energy system and principle of MPPT

Wind power varies throughout the day as wind speed varies. Power produced by a wind turbine is given by [1-3, 10, 11]

$$P = 0.5\pi\rho Cp(\lambda,\beta)R^2V_w^3, \tag{3}$$

where, R is the turbine radius, V_w is the wind speed, ρ is the air density, Cp is the power coefficient, λ is the tip speed ratio and β is the pitch angle. In this work β is taken as zero. The tip speed ratio is given by:

$$\lambda = \frac{\Omega R}{V_w}, \tag{4}$$

where Ω is the turbine angular speed. The dynamic equation for the wind turbine is written as

$$\frac{d\Omega}{dt} = \frac{1}{J[T_m - T_L - F\omega_r]}, \tag{5}$$

where, J is the system inertia, F is the viscous friction coefficient, T_m is the torque developed by the turbine, T_L is the torque due to load which in this case is the generator torque and ω_r is the turbine rotor speed.

The turbine power coefficient $Cp(\lambda, \beta)$ is a non-linear function and given by [11]

$$Cp(\alpha,\beta) = 0.5176\left(\frac{116}{\delta} - 0.4\beta - 5\right)e^{\frac{-21}{\delta}}, \tag{6}$$

where

$$\frac{1}{\delta} = \frac{1}{\lambda + 0.08\beta} - 0.\frac{035}{1+\beta^3}.$$

The simulation for $Cp(\lambda, \beta) Vs\lambda$ was carried out in MATLAB and is given in Figure 6 [11]. It is observed that one value of Cp which provides maximum power for each value of β. For $\beta = 0$, the maximum value of Cp is 0.42.

The optimum power obtained from a wind turbine is given in (7)

$$P_{opt} = K_{opt}\Omega_{opt}^{3}, \tag{7}$$

where,

$$K_{opt} = \frac{0.5\pi\rho Cp_{\max}(\lambda,\beta)R^{5}}{\lambda_{opt}^{3}}, \tag{8}$$

$$\Omega_{opt} = \frac{\lambda_{opt}V_{w}}{R}. \tag{9}$$

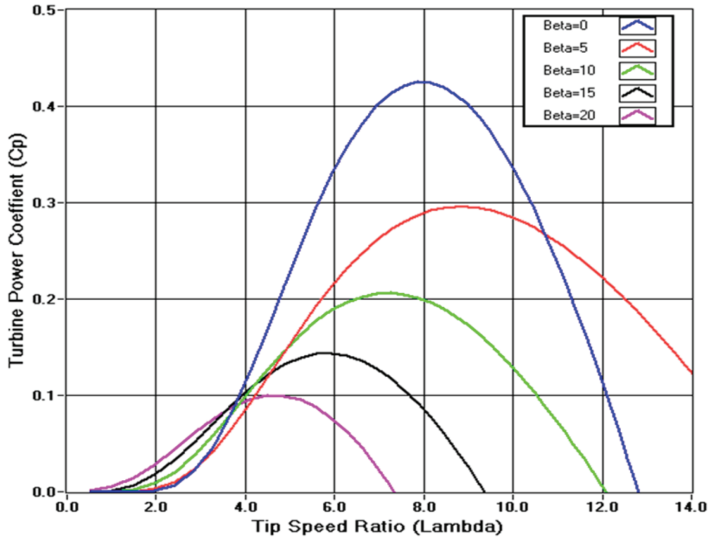

Fig. 6. Power Coefficient Vs Tip Speed Ratio characteristic of Wind Turbine for different Pitch angle

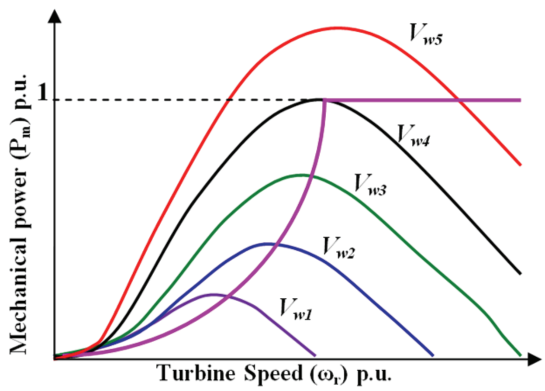

Fig. 7. Mechanical power Vs rotor speed characteristics of wind turbine

Figure 7. shows turbine mechanical power as a function of rotor speed at various wind speeds V_{w1}, V_{w2}, V_{w3}, V_{w4}, and V_{w5}. The power for a certain wind speed is maximum at a certain value

of rotor speed called optimum rotor speed Ω_{opt}. This is the speed which corresponds to optimum tip speed ratio Ω_{opt} λ_{opt} The turbine should be always operated at λ_{opt} in order to achieve maximum possible power. This is possible by controlling the rotational speed of the turbine so that it always rotates at the optimum speed of rotation. The specifications of wind turbine and PMSG are given in Table 2 and 3 respectively.

Table 2. Parameters of 210 kW wind turbine

Parameter	**Symbol**	**Value**
Mechanical output power	P_m	210 kW
Base wind speed	V_w	11 m/s
Maximum power at base wind speed	P_{max}	0.9 pu
Pitch angle	β	0°

Table 3. Parameters of 200 kW PMSG generator

Parameter	**Symbol**	**Value**
Stator Resistance	R_s	0.005 Ω
Armature Inductance	L_a	0.000835 H
Static friction	T_f	0.54 N-m
Flux Linkage	ϕ	0.283 Wb
Moment of Inertia	J	0.1197 kg.m^2
Viscous damping	F	0.1189 N-m
Pole Pairs	P	24

6. Model of the battery energy storage system

The power generated from RES consists of sharp and transient variations. To meet the load smoothly it is necessary to provide an energy storage system in the HPS. A Battery Energy Storage System (BESS) with the specifications given in Table 4 is considered with RES. The BESS consists of 3 parallel strings with 72 batteries in each string. The discharge current characteristics of the BESS are shown in Figure 8.

Table 4. Specification of battery energy storage system

Component	**Ratings**
BESS	300 kWh
1 module	72 single batteries in series
Single battery capacity	12 V, 120Ah
Maximum working voltage	840V
Minimum working voltage	696V

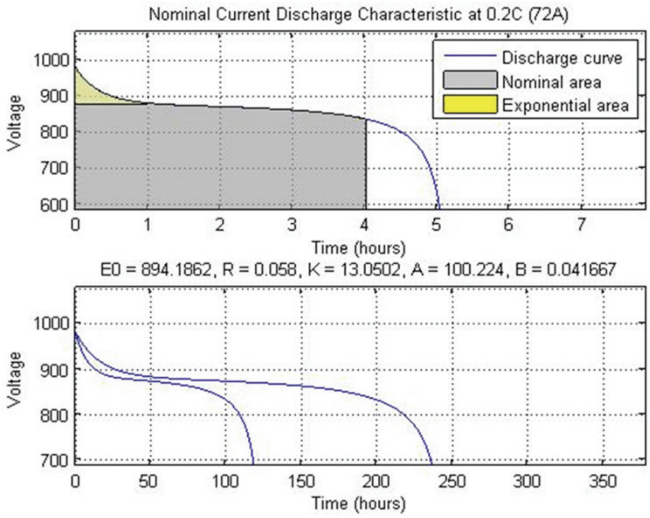

Fig. 8. Nominal discharge current characteristics of BESS

7. Fuzzy control method for MPPT

Fuzzy logic is recently employed for control of tracking the maximum power in Solar PV [5-9] and Wind Energy systems [10, 11]. This technique does not require the model of the system but necessitates the thorough knowledge about the system [2, 5-9]. The inputs for the fuzzy logic controller are power error and change in power error. They can be defined for PV system and Wind system respectively at sampled time k by,

$$\left.\begin{aligned} PE_{PV}(k) &= \frac{P_{PV}(k)-P_{PV}(k+1)}{V_{PV}(k)-V_{PV}(k+1)}, \\ CPE_{PV}(k) &= PE_{PV}(k)-PE_{PV}(k+1) \end{aligned}\right\} \tag{10}$$

$$\left.\begin{aligned} PE_{W}(k) &= \frac{P_{W}(k)-P_{W}(k+1)}{\omega(k)-\omega(k+1)}, \\ CPE_{W}(k) &= PE_{W}(k)-PE_{W}(k+1) \end{aligned}\right\} \tag{11}$$

The inputs $PE_{PV}(k)$, $PE_W(k)$ represents the location of the operation point on the left or right side of maximum power point on the Power Vs Voltage characteristic of the solar PV system and Power Vs Wind velocity characteristic of wind Turbine respectively. The inputs $CPE_{PV}(k)$, $CPE_W(k)$, are representing the direction of movement of the operating point towards the maximum power point on the Power Vs Voltage Characteristic of PV system and Power Vs Wind velocity characteristic of wind Turbine respectively.

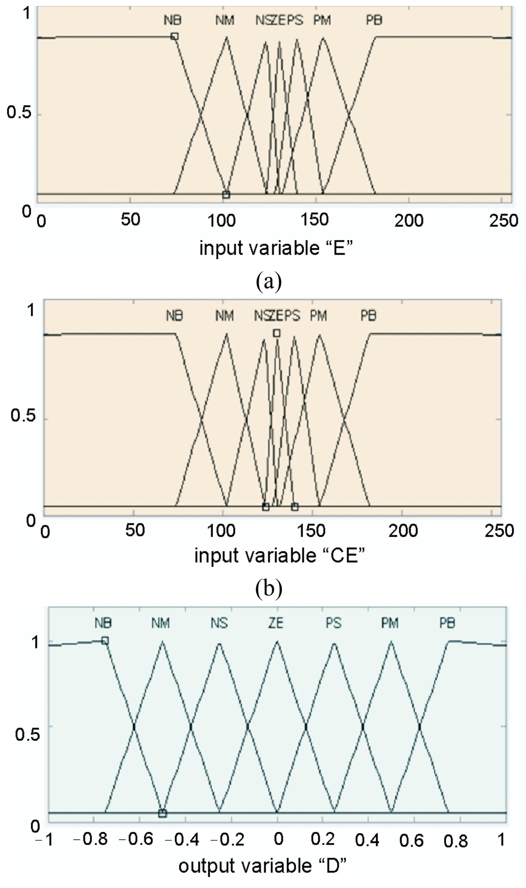

Fig. 9. Membership function of (a) Error E (b) Change in Error CE (c) Duty cycle

Table 5. Fuzzy rule table

E \ CE	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	ZE	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

The membership functions and fuzzy inference rules are defined based on Mamdani's method. The membership functions of two input variables $PE_{PV}(k)$, $CPE_{PV}(k)$, and the output variable duty cycle are shown in Figure 9. The fuzzy rules for the DC-DC Boost MPPT control are given in Table 5. The Membership functions for the Power Error (PE) and Change in Power Error (CPE) and Duty Cycle (D) are chosen such as NB-Negative Big, NM- Negative Medium, NS- Negative small, ZE-Zero, PS-Positive Small, PM-Positive Medium, and PB-Positive Big. The duty cycle for the DC-DC Boost converter D is obtained using center of gravity method and is calculated using (13) [7, 8].

$$D = \frac{\sum_{j=0}^{n} (\mu(D)_j) \cdot D_j}{\sum_{j=0}^{n} (\mu(D)_j)}, \tag{12}$$

where $(\mu(D)_j)$ is the aggregated membership function of the duty cycle and D_j is the output variable.

8. Boost converter and fuzzy control

DC-DC converter is designed [12, 13] to use as MPPT in both PV [1-3, 5-9] and Wind Energy systems [4]. The MPPT control logic for the solar PV system is shown in Figure 10.

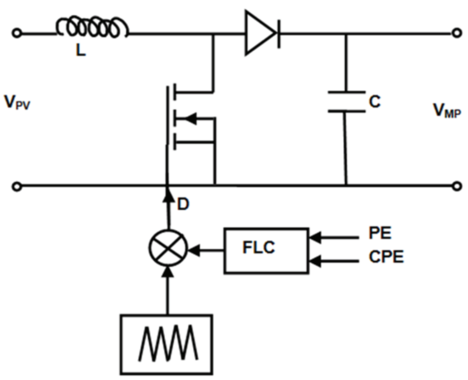

Fig. 10. Control of *D* using FLC for boost converter

The Fuzzy controller produces the duty cycle for the DC-DC Boost converter based on the Power Error and Change in Power Error, which are defined in (10) and (11) respectively. The parameters of the Boost converters for Solar PV and Wind systems are given in Table 6 and 7 respectively.

Table 6. Parameters of boost converter for solar PV system

Parameter	Symbol	Value
input voltage	Vs	150-850 V
output voltage	V_0	230-1100 V
switching frequency	F_s	20 kHz
inductance	L	8.9 mH
capacitance	C	57 µF

Table 7. Parameters of boost converter for wind energy system

Parameter	Symbol	Value
input voltage	Vs	120-925 V
output voltage	V_0	400-1000 V
switching frequency	F_s	20 kHz
inductance	L	7.4 mH
capacitance	C	86 µF

9. Buck-Boost converter and PI control

A Buck-Boost converter with PI Control is designed [12, 13] to modulate the duty cycle to make the output DC bus voltage constant for both PV and Wind systems [1]. The output voltage from the first stage Boost converter is the input to the second stage Buck-Boost converter. The control scheme is shown in Figure 11. The output of the Buck-Boost Converter is maintained constant by the control of duty cycle to the Buck-Boost Converter. The duty cycle is obtained using PI Control. The parameters of the systems are given in Table 8 and 9 respectively.

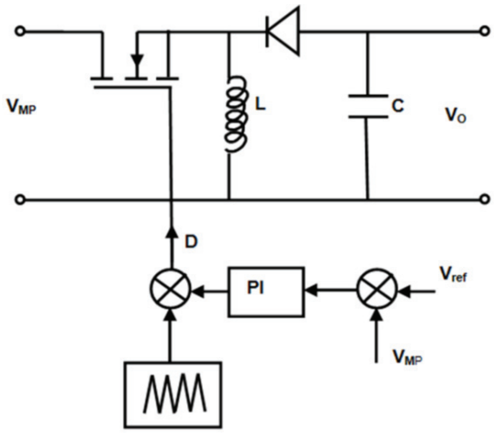

Fig. 11. Control of D in Buck-Boost Converter

Table 8. Parameters of Buck-Boost Converter and PI Controller for PV system

Parameter	Symbol	Value
input voltage	Vs	230-1100 V
output voltage	V_0	850 V
switching frequency	F_s	20 kHz
inductance	L	8 mH
capacitance	C	85 µF
proportional gain	K_p	2
integral gain	K_i	50

Table 9. Parameters of Buck-Boost Converter and PI Controller for Wind system

Parameter	Symbol	Value
Input voltage	Vs	400-1000 V
Output voltage	V_0	850 V
Switching frequency	F_s	20 kHz
Inductance	L	9 mH
Capacitance	C	57 µF
Proportional gain	K_p	3.86
Integral gain	K_i	500

10. Inverter and filter model

Table 10. Operating Values of Three Phase PWM Inverter

Parameter	Symbol	Value
DC input voltage	V_s	850 V
AC input voltage	V_0	415 V
carrier frequency	F_c	20 kHz
modulation index	m	0.9
filter inductance	L	53 mH
filter capacitance	C	87 µF

A sine PWM inverter is used [12, 13] at the output stage to convert the DC Voltage into 3-phase AC Voltage. The low harmonic distortion of the voltage and current at the output of the inverter is achieved by using an inductive, capacitive filter. The operating values of three phase PWM inverter and filter are tabulated in Table 10.

11. Simulation results and discussion

A hybrid power system has been simulated in Matlab/Simulink environment with MPPT control and power flow control. The output of PV and Wind system are simulated under variable environmental conditions. The results of fuzzy logic based MPPT is shown in Figure 12 and 13 respectively for Solar PV and WECS systems. The fuzzy controller tracks the MPPT very closely and is effective under all varying environmental conditions. When compare to P&O method the output power with fuzzy control is approximately 3 to 8% higher. Also the oscillations are reduced by the proposed Fuzzy controller. This shows the rigidness of the Fuzzy MPPT Control. The output of MPPT controller voltage is made constant by the buck boost converter with the help of PI controllers which is shown in Figure 14.

The Peak Voltage of Three Phase PWM Inverter is 586 V and it is shown in Figure 15. The three phase RMS output voltage is 415 V which is shown in Figure 16.

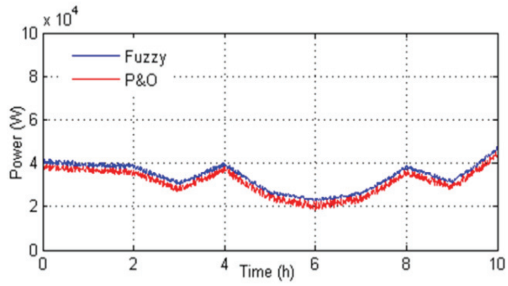

Fig. 12. Maximum power of solar PV system

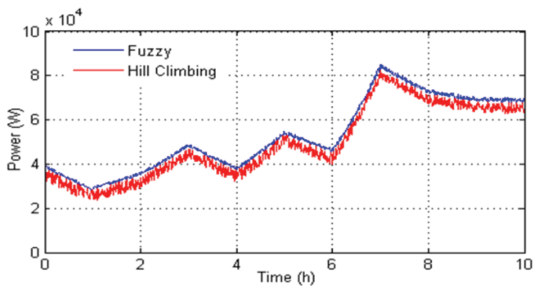

Fig. 13. Maximum power of WECS system

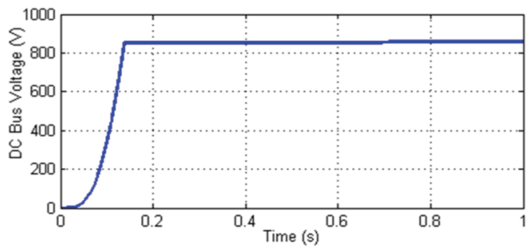

Fig. 14. DC bus voltage

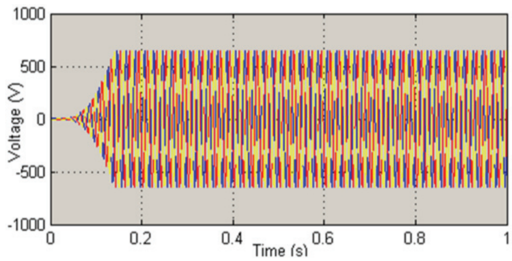

Fig. 15. Output voltage of three phase inverter

The THD spectrums for output current without and with filter are shown in Figure 17 and Figure 18 respectively.

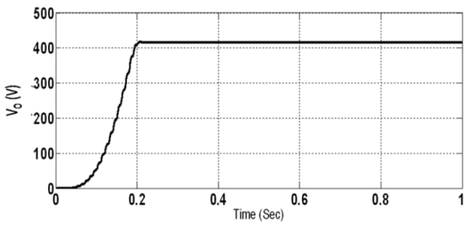

Fig. 16. RMS voltage of three phase inverter

The output current of three phase inverter without filter has 83% of THD, which is shown in Fig. 17. By using LC-filter, the current harmonic is reduced to 0.97% of THD as shown in Fig. 18.

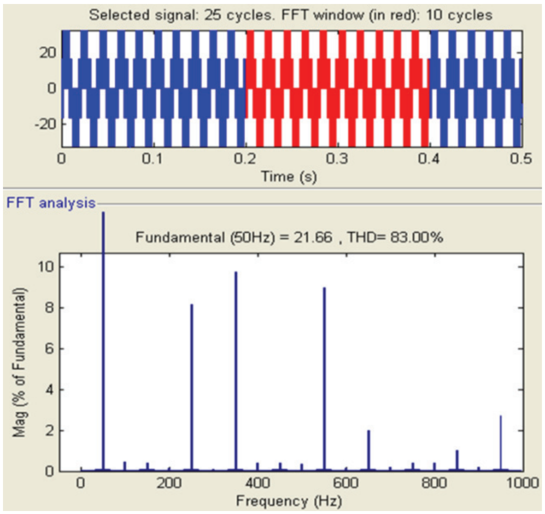

Fig. 17. THD spectrum for output current without filter

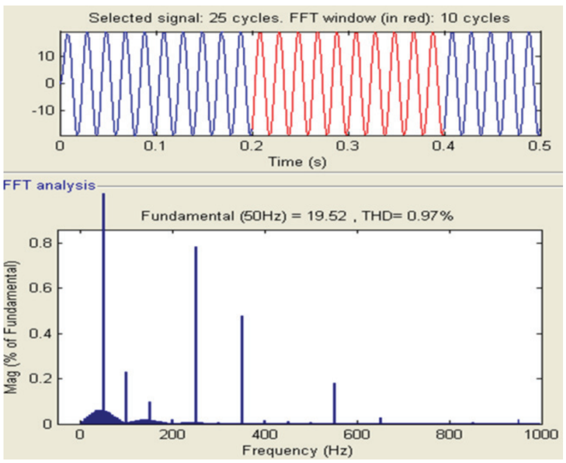

Fig. 18. THD spectrum for output current with filter

12. Conclusion

The stand-alone 100 kW Solar PV and 200 kW Wind Energy Systems with Battery Bank of 300 kWh capacity are designed, simulated for a load of 80 kW peak. The proposed fuzzy logic based MPPT technique can track the maximum power point faster than the conventional controller. It has the ability of reducing the voltage fluctuation after MPP has been recognised. The Solar PV and wind energy system not only boosts up the voltage but also produce a signal, free from transient noise. Hence the performance of the closed loop system has been improved by using FLC.

The synchronized hybrid Solar and Wind energy systems are simulated in MATLAB/ Simulink. After obtaining the constant output voltage, from both Wind and Solar energy systems, they are connected in parallel. The DC source from hybrid power system is converted to AC by using PWM inverter. In order to produce a pure sine wave output with low harmonics, an LC filter is used. The output current of the inverter has 0.97% of THD which is lower than the IEEE-519-1992 standard. The hybrid power system can be utilized either for remote generation plants or it can be utilized for grid integration.

Future Work

The proposed system can be further tested with other renewable energy sources such as Hydro power plants and Bio-gas plants and storage devices such as Fuel cell, Double layer capacitors. This will improve reliability and robustness of the HPS system in supplying continuous power to load and power quality. The three phase inverter output voltage is 415 V, 50 Hz AC supply with lesser harmonic content can be synchronized with the grid. More fractions in the load could be considered in order to utilize the maximum available renewable energy effectively with new load management strategies. Many hilly regions, remote places in India are not having electricity. In such places the proposed system can be implemented in real time.

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