Multi-operating Modes Based Energy Management Strategy of Virtual Power Plant

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***Abstract*—In this paper, a Virtual Power Plant (VPP) consists of a solar photovoltaic (PV) system, a wind turbine (WT) power generation system and an energy storage system (ESS) that is proposed in order to extenuate the utilization of fossil fuels on account of global warming and to cope with the increasing demand of electrical energy. These inexhaustible energy sources and the ESS are integrated to a common AC bus via double stage interfacing power converters. Multi-operating modes are generated by an Energy Management Strategy (EMS) that contingent on solar, wind and load power to control the scheduling operation of loads during dynamic weather and load conditions in order to avoid from blackout which is a primary focus of this paper. The PV and WT power generation systems are contemplated as the main sources of energy that satisfy the load demand in a regular manner whereas the battery is used only as a backup for the exigency. The modelling and the simulation of the presented VPP system are carried out under MATLAB/SIMULINK software. Simulation outcomes are shown and discussed that unveils the effectiveness and performance of the designed EMS.**

Keywords—Energy Management, Micro-grid, VPP, Simulink

I. INTRODUCTION

In recent years, the rapid increase of hybrid power generation particularly those based on renewable energy sources (RESs) is anticipated to point-black concerns on greenhouse gas emissions, energy security, energy sustainability, etc. RESs such as geothermal, biomass, tidal, solar, and wind energy are the indispensable alternative energy sources and most of them are immaculate and environment friendly. Among these assorted kinds of alternative energy sources, photovoltaic (PV) and wind power (WP) generation are the fastest growing distributed generation (DG) technologies. DG reduces the transmission cost, dependence on fossil fuels and provides the reliable and stable electrical power near to consumers.

On the contrary, the PV and wind turbine (WT) output power is variable and uncertain due to randomness of solar radiations, temperature of air and wind speed. This poses a challenging problem to manage our demand power, therefore Virtual Power Plant (VPP) is becoming more popular gradually and progressively with the integration of these renewable energy based distributed generators with Energy Storage System (ESS) and has the ability to control the aggregated units with information and communication technology (ICT) [1–3]. In a VPP, ESSs are needed for continuous operation of systems. There are many types of storage devices available such as Pumped Hydro Energy Storage (PHES), Compressed Air Energy Storage (CAES), super conducting Magnetic Energy Storage, flywheel energy storage, super capacitor energy storage and battery energy storage are used for different purposes in various applications [4]. In Ref. [5], a robust optimization tool is demonstrated by self-scheduling of VPPs with power markets uncertainty. In Ref. [6], optimum operation of a wind-hydro VPP considering the day-ahead scheduling of VPP components using mixed integer linear programming (MILP) is presented. In Ref. [7], an energy management method is investigated for VPPs and the cost and emission impacts of VPPs formation and electric vehicle penetration are also analysed. A microgrid composed of various kinds of RESs to manage the whole system, is considered in [8]. The computational intelligence methods and classical algorithms for energy management of microgrids are discussed in [9]. A multi-agent system based energy management system for implementing a PV-small hydro hybrid microgrid is discussed in [10]. A novel operation and control strategy for energy management using green energy sources are proposed in [11]. There are several approaches for the development of management of the energy in renewable energy system [12, 13]. Late studies on hybrid power systems focus on power management strategies [14–18]. In [19], author presents the design and implementation of an energy management system with fuzzy control for a DC microgrid system. Advanced Energy management systems by integration of RESs were explained in [20–23]. Power management of a stand-alone Wind/Photovoltaic/Fuel Cell energy system is discussed for the winter and summer scenarios [24].

In this paper, VPP consists of PV array, wind energy conversion system (WECS), storage battery, interfacing power converters, dynamic load and main grid. The main focus of this paper is to supply the power to the load at any time without any interruption with Energy Management Strategy (EMS) in VPP. EMS generates the operating point considering the available resources and demand to ensure the proper management of power. MATLAB/SIMULINK has been exploited to simulate the components and control system of proposed model. All simulation results have verified the validity of the proposed model and effectiveness of control strategy of VPP.

The rest of paper is organized as follows. In Section II, system configuration of designed VPP model is described with

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block diagram. Section III provides the modelling of system components which is used in simulation. The proposed EMS is discussed in Section IV. In Section V, the performance of the EMS is demonstrated through simulations. Finally, Section VI summarizes the main conclusion.

II. SYSTEM CONFIGURATION

A block diagram of the designed VPP structure is shown in Fig. 1. In this model two RESs are depicted, PV array is the first source which is connected to a maximum power point tracking (MPPT) controller to elicit the output power from PV array as much as possible. In order to improve the overall PV array efficiency, Perturb and Observe (P&O) algorithm is applied in this model for continuously tracking MPP. Then the DC to DC and DC to AC power converters are employed to get the stable output from PV array. Second source of energy is wind energy in which wind turbine is coupled with Permanent Magnet Synchronous Generator (PMSG) to get electrical energy and then AC to DC and DC to AC converters are exploited to achieve controllable output. Bidirectional power converter is used for charging and discharging of a battery. During charging of battery current flows from RESs to battery and in discharging duration it flows from battery to load. In this system, battery does not charge by grid, it only stores power that comes from RESs and discharge when load power is required. The energy sources and battery storage system are all eco-friendly so this system can be called as a “green” power generation. To control this system with proper energy management, all the energy sources are attached to a common AC bus through interfacing power converters and AC bus is also called as point of common coupling (PCC). When excess PV and WT energy is available, this extra energy is stored in a battery. But when there is lack of energy, battery as a backup provides energy to cover the remaining load. The VPP components selected parameters described in Table 1.

There are multifold modes to incorporate renewable energy sources together and each method has some advantages and disadvantages as well. In this paper, due to high reliability, 50Hz AC link is used. The focal point of this system is to provide uninterruptible supply to consumers, energy production and management by using these green sources with efficient way. The beauty of this proposed system is; it can be easily extendable with new energy sources in future to fulfil our increasing energy demand.

III. MODELLING OF SYSTEM COMPONENTS

A. Modelling of PV array

The PV output current (I) is obtained by applying Kirchhoff’s law.

$$I = I_L - I_o\left[\exp\left(\frac{V+IR_s}{Ak(T/q)}\right)-1\right]-\frac{V+IR_s}{R_{sh}} \tag{1}$$

where,

I_L	Photo diode current
I_o	Reverse saturation current of diode
V	Voltage of PV array
R_S	Series resistance
A	Ideality factor
k	Boltzmann constant
T	Current temperature of cell
q	Charge on an electron
R_{Sh}	Parallel resistance

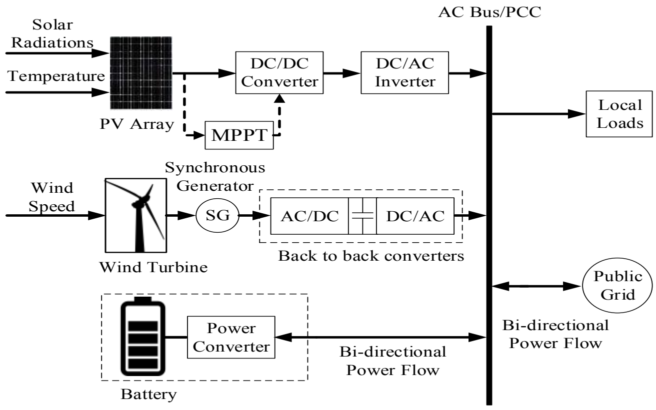


Fig. 1 System configuration of the proposed VPP structure

TABLE I. VPP COMPONENTS PARAMETERS

PV Array	Module Unit	36 Cells, 280W
	Module Number	6 × 3=18
	Power rating	18 × 280≈5 KW
Wind Turbine	Rated power	10 KW
	Cut in speed	3 m/s
	Cut out speed	16 m/s
	Rated speed	8.5 m/s
Permanent Magnet Synchronous Generator	Rated power	10 KW
	Rated voltage	650 V
	Rated frequency	50 Hz
Battery	Capacity	6 KWh
	Rated voltage	375 V
	Rated current	16 A

The reverse saturation current mainly depends upon temperature and can be calculated as

$$I_o = I_{o,ref}\left(\frac{T}{T_{ref}}\right)^3 \exp\left[\left(\frac{q\varepsilon_G}{AK}\right)\left(\frac{1}{T_{ref}}-\frac{1}{T}\right)\right] \tag{2}$$

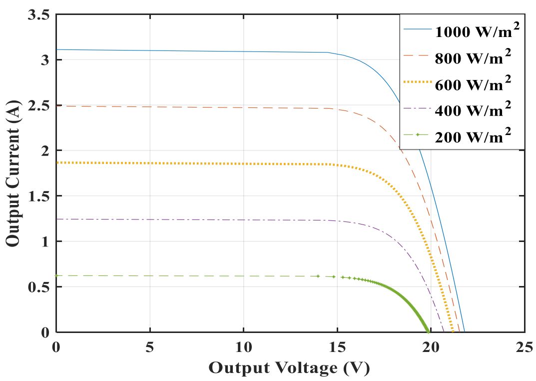


Fig. 2 PV array I-V characteristics curves

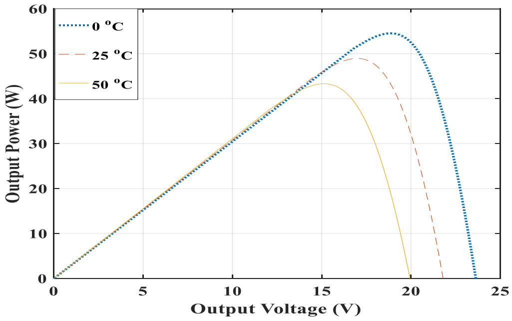


Fig. 3 PV array P-V characteristics curves

Where,

$I_{o,ref}$	Reference reverse saturation current
T_{ref}	Temperature at standard test conditions (STC)
ε_G	Band gap energy

The photo current of PV depends upon solar radiations and also varies with temperature.

$$I_L = \frac{G}{G_{ref}}\left(I_{L,ref} + \mu_{SC}\left(T - T_{ref}\right)\right) \tag{3}$$

where,

G	Current irradiance (W/m^2)
G_{ref}	Irradiance at STC
$I_{L,ref}$	Photo diode current at STC
μ_{SC}	Temperature coefficient of short circuit current

The PV array current-voltage characteristic curves employed in this study under different solar radiations and at a fixed temperature (25oC) are shown in Fig. 2. From figure it can be observed that the open circuit voltage (Voc) and the short circuit current (ISC) increases with increase in irradiance. Hence, the output PV power also increases. Temperature also has an effect in the PV output power. The temperature effects on the PV output power and voltage are shown in Fig. 3. It is worth of mention that the PV output power increases with decreases in temperature and vice versa.

B. Modelling of WT

The captured power from the wind turbine depends upon many factors and is given below

$$P = \frac{1}{2}\rho A v^3 C_p(\beta,\lambda) \tag{4}$$

Where, C_p is the wind turbine power coefficient, β is blade pitch angle, λ is tip speed ratio, ρ is density of air, A is the turbine swept area and v is wind speed. According to above formula, the output power of wind turbine is directly proportional cube of wind speed. Change in wind speed produces change in power coefficient and thus leads to change in wind power. The characteristic curves between rotor speed of generator and turbine output power is shown in Fig. 4.

C. Modelling of Battery

Among different technologies, Li-ion batteries have been very popular for commercial use due to high density, high power, light weight, faster recovery time and high efficiency. The two resistor-capacitor (RC) parallel network of a battery has high accuracy and performance and it is used in this paper.

The most important parameter of a battery is a state of charge (SOC) which shows the current energy present in a battery as a percentage of maximum energy and is given in equation (5).

$$SOC = SOC_0 - \int \frac{I \times 100}{\alpha^U \times 3600} dt \tag{5}$$

Where, SOC_0 represents initial state of charge, I is current of battery and α^U is a usable capacity.

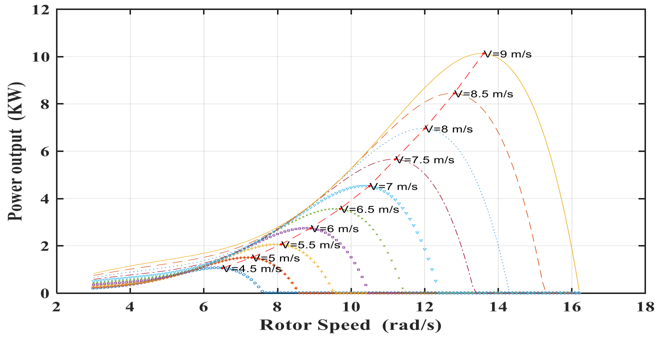


Fig. 4 Wind turbine output power versus Rotor speed

IV. Energy Management Strategy

The EMS assures the uninterrupted power supply to the demand load irrespective of the fluctuation in the power production of RESs and battery power. This EMS is designed by alternative sources for VPP, which is a new concept nowadays, to maintain power balance at all times with maximum utilization of RESs in order to mitigate transmission losses by importing less power from grid as much as possible. The EMS has two steps. In first step, it takes input of load, solar, wind, and available battery power. In second step, it determines the maximum demand that can be covered by VPP and generates operating point. According to demand load, the power from grid is imported and exported. The difference between supply and load demand power is calculated by

$$P_{pv} + P_{wt} = P_L \pm P_b \pm P_g \tag{6}$$

Where, P_{pv} represents the PV array generated power, P_{wt} is the WT power, P_L is the power deplete by load, P_b indicates the power present in battery and P_g indicates the import/export power from grid. The positive and negative sign in equation (6) indicates that power can be extracted /delivered from/to these sources respectively. The PV array is a main source in this control strategy that supplies the power to consumers, battery and grid (if any). The WT power will act as an ancillary source and it will operate only when the PV cannot satisfy the demand load. Due to fluctuations in output power of PV and WT, controllers are used to regulate power. When the generated power of RESs is excessive (high radiations and wind speed) then battery and grid receive power. First, the power will be transferred to battery, if the storage battery is full (SOC=90%) then the rest of power will be transferred to grid. According to equation (6),

$$P_{ex} = P_{gen} - P_L = -(P_b + P_g) \tag{7}$$

When there is deficiency in power then battery and grid provide power respectively according to severity of condition.

$$P_{def} = P_L - P_{gen} = P_b + P_g \tag{8}$$

Where, P_{gen} is the total output power of PV and WT. The impact of intermittent nature of RESs on load can be overcome by importing power for load and VPP will import power only when there is no radiation and absence of wind speed stay for a long time period along with the not sufficient energy preserve in a battery. To avoid from over charging and discharging of a battery a constraint is applied on a battery SOC; in a normal mode it is assumed that the maximum SOC is 90% and minimum SOC is 70% in order to increase the lifespan of this system. In an exigency mode, the minimum allowable SOC is 40%. In order to deliver the power to users, load curtailment is not used. Fig. 8 shows the block diagram of EMS in VPP. The EMS decides the dynamic operating point based on current weather and load data. In this paper, the range of SOC is selected from 40% to 90% considering the dynamic conditions and load demand. All operating conditions are summarized in Table 2 and detailed discussion is given as follows.

Mode 1: In this mode, the PV array as a principal source provides the output power to satisfy the demanded power and the surplus PV array power is stored in a battery for critical condition. Wind is not generating any power in this mode due to low wind condition.

Mode 2: In this mode, the PV array does not generate power due to absence of irradiance as PV power highly dependent on solar radiations, WT generator only produce power which is transferred to consumers. Similarly to mode 1, remaining power is supplied to battery.

Mode 3: In this condition, the PV cannot satisfy the demand alone, so PV and WT both supply the power at the same time. The surplus power is consumed by storage battery.

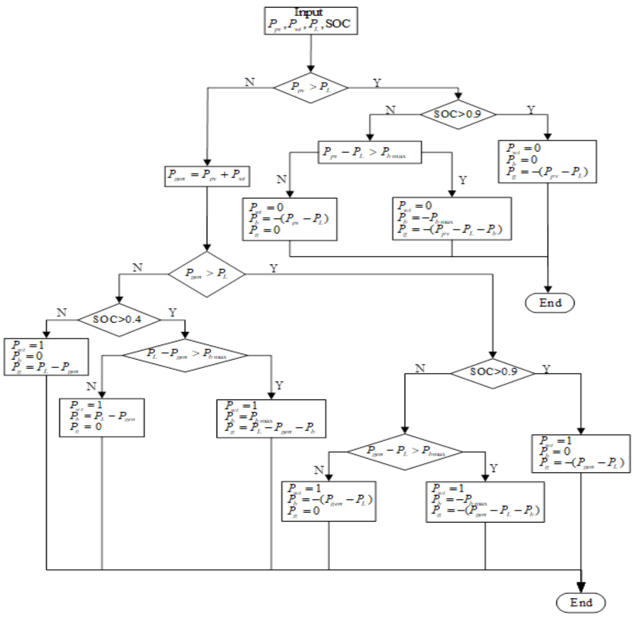


Fig. 5 Energy management strategy

Mode 4: In this mode, the PV and WT extract the maximum output power based on weather conditions but still the total generated power is less. As the demand load is increased than generation, so the battery starts supplying power in order to make system balance.

Mode 5: In this condition, load is increased more than the total generation of PV, WT and battery powers, which is worst case scenario, so the deficit power will be supplied from main grid in order to avoid system from blackout.

TABLE II. Operating points for EMS

Mode	Operating conditions
Mode 1	The output power of PV is more than the load power. ($P_{pv} > P_L$).
Mode 2	The output power of WT is enough to supply the power to demand load. ($P_{wt} > P_L$)
Mode 3	The PV output power is less than load demand and sum of PV and WT power is higher than requested power ($P_{pv} + P_{wt} > P_L$).
Mode 4	The battery supply remaining power when the load demands more power than generation.
Mode 5	The VPP needs power to fulfill the demand in case of more consumption than generation ($P_{VPP} < P_L$).

V. SIMULATION AND DISCUSSION

The performance of the presented VPP shown in Fig. 1 is investigated by considering the EMS as discoursed in Section IV. The corresponding results are exhibited and held forth in the following operating conditions.

A. Distinctive Irradiance, wind speed and load scenarios

Conjectural solar radiations and wind speed is shown in the Fig. 6(a) and 6(b). The effect of temperature is not assumed in this study therefore temperature remains constant at STC (25oC) throughout the simulation. Fig. 6(c) depicts the demand load power. Fig. 7(a) reveals the PV array power and WT power. Fig. 7(b) shows the battery and grid power. SOC of battery is shown in Fig 7(c). Operating modes decided by EMS are shown in Fig. 7(d).

In Fig. 6(a) the variations in solar radiation are as follows, from 0 to 10 s 0 W/m^2; from 10 to 20 s 565 W/m^2; from 20 to 30 s and 40 to 50 s 1000 W/m^2 and from 30 to 40 s 772 W/m^2. The fluctuation in wind speed is described below and shown in Fig. 6(b). From 0 to 10 s 7.15 m/s; from 10 to 20 s, from 30 to 40 s 6.65 m/s; from 20 to 30 s 2 m/s and from 40 to 50 s 6.25 m/s.

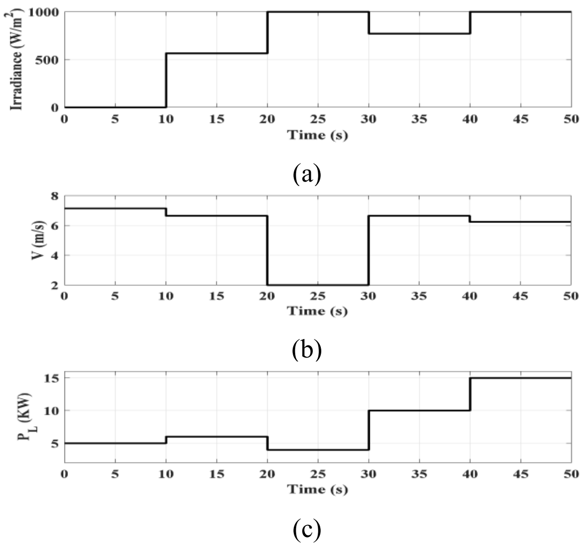
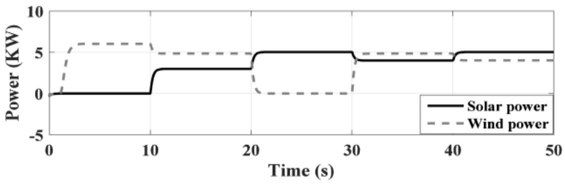
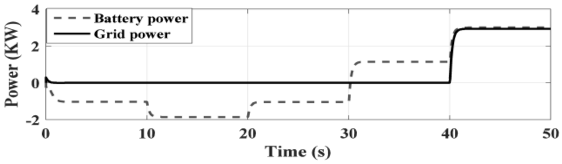


Fig. 6 (a) Solar radiations, (b) Wind speed, (c) Load power

In Fig. 6(c), initially the demand load power is 5 KW from 0 to 10 s and in Fig. 7(a), the PV and WT output powers are 0 KW and 6 KW respectively. In this condition, as PV power is zero and WT power is higher than demand load, EMS operates in mode 2 and extra power is stored in battery as shown in Fig. 7(b). At t=10 s the load is increased, WT power is reduced to 5 KW due to change in wind speed and with the increase of solar radiations, PV array also generates 3 KW power. In this condition, both PV and WT are producing power which is greater than load power so EMS operates in mode 3. In mode 3, battery is receiving more power than mode 2 due to which SOC of battery is increasing with higher rate as shown in Fig. 7(c). At t=20 s the load is decreased to 4 KW, PV output power is step up because of solar radiations and WT power is zero because the wind speed is below than cut in speed. In this condition, PV power is higher than consumed power and WT power is zero, EMS operates in mode 1. From Fig. 7(b), it is clear that excessive power is consumed by battery. At t=30 s the demand load power is 10 KW, now the PV and WT are generating 4 and 5 KW powers respectively. In this condition, EMS operates in mode 4 because power generated by these sources is not enough for consumers and battery is supplying 1 KW power At t=40 s the demand power increases up to 15 KW. It is limpid that VPP cannot cover load power. Power of PV and WT is 5 KW and 4 KW and battery can supply 3 KW which is still deficient. In this condition, VPP imports remaining power from grid in order to avoid from blackout, EMS operates in mode 5. Fig 7(b) depicts that in all modes (1, 2, 3, and 4) grid power is zero because VPP does not import/export power except mode 5.



(a)



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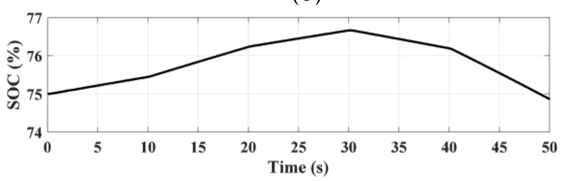

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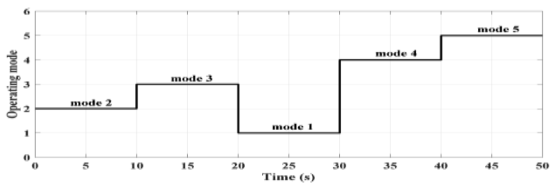
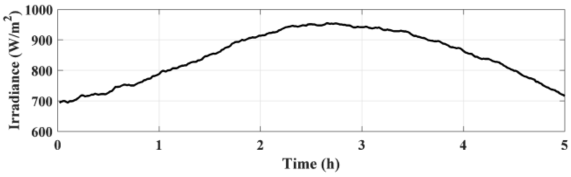


(d)

Fig. 7 (a) PV and WT output power, (b) Battery and grid power, (c) Battery SOC, (d) Different modes of operation

B. Realistic Case

The simulation study of EMS is done using real weather data (solar radiations, temperature of air, wind speed) and practical load. The weather data is collected at North China Electric Power University (NCEPU), China in order to show the good results of system. Fig. 8(a) and 8(b) show the hourly solar radiation and temperature of air profile respectively. The wind speed and load profile are shown in Fig.8(c) and 8(d) respectively.



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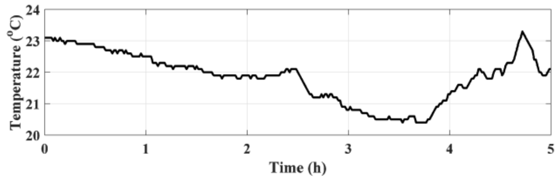

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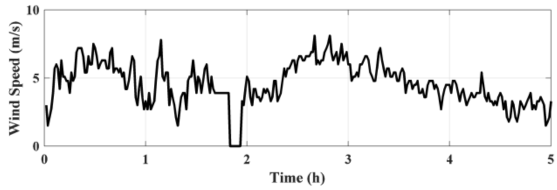

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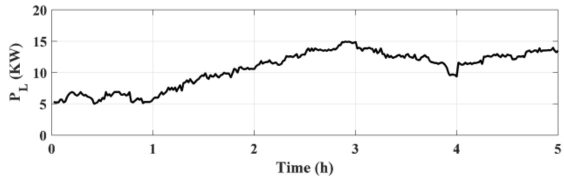
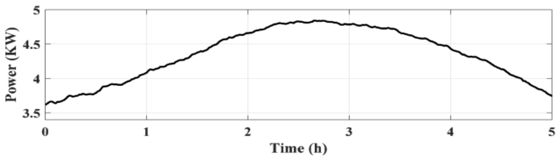


(d)

Fig. 8 (a) Solar radiations, (b) Temperature of air, (c) Wind speed, (d) Load power

The output power of PV array over the time period is shown in Fig. 9(a). The maximum output power is obtained from PV array by using MPPT controller as discussed before. It is clear from the Fig. 9(a) that the pattern of PV output power curve is same as solar radiations shown in Fig. 8(a). The wind turbine output power is shown in Fig. 9(b). When the wind speed is below than cut in speed (3 m/s) then the wind energy conversion system does not generate any power. Similarly, when the wind speed is higher than cut out speed (16 m/s), it does not produce power in order to preclude system from damage. Fig. 9(d) shows the exchange power between VPP and grid. The battery power and SOC is depicted in Fig. 9(c) and 9(e) respectively. It is clear from Fig. 7 to 9, that under different weather and load conditions, EMS is generating modes to fulfill the demand power as disclosed in section IV.

During 1 hour the total generated power is less than load power for some time and for some time it is more than load so battery is supplying and receiving power (shown in Fig. 9(c)) as per mode 4 and mode 3. From 2 to 4 hours the load power is continuously increasing but wind power is very low due to low wind speed therefore battery is continuously discharging power and during 4 hours it is fully discharged (40% SOC), it means battery cannot not supply power anymore due to imposed restriction. At last hour the load still needs more power so in order to supply power to load, VPP imports power from main grid. VPP imports power only when the RESs and battery are not enough to cover demand such as in this case. During this time if PV array and wind power transcends the load power, the VPP stops importing power and battery will be charged.



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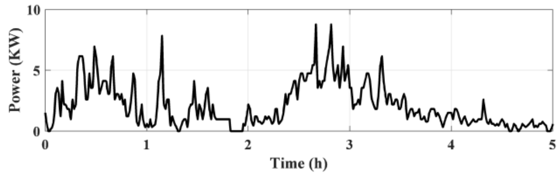

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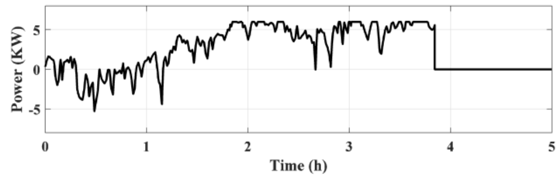

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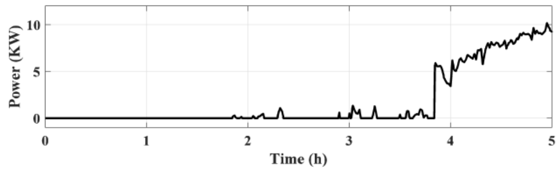

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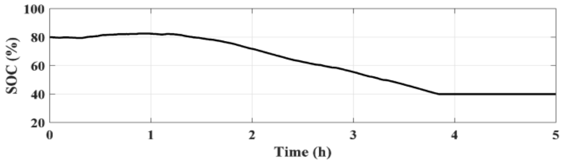

(e)

Fig. 9 (a) PV array power, (b) Wind power, (c) Battery power, (d) Grid power, (e) SOC of battery

VI. CONCLUSION

In this paper, an AC-linked PV/WT/Battery system in a VPP is explicated and modeled for dynamic loads. An EMS is developed based on different operating modes for proposed VPP structure. The purpose of this EMS is to supply the demanded power to consumers with efficient way and mitigating the power exchange from public grid. The PV is used as a primary source of energy while WT as an auxiliary source. These sources are highly weather dependent, therefore, for flexible and reliable operation of power transfer and to avoid system from blackout, battery is also used when we prevail less power from green sources. The PV and WT are controlled by converters and battery is also fully controlled by bi-directional power converter that can be seen in figures as it delivers and receives power instantly. We have achieved the main goal of this study and the feasibility of the presented VPP structure and effectiveness of this model by using real atmospheric data has been verified from MATLAB/SIMULINK.

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