

Design & Simulation of Power Balancing from Wind Energy with Virtual Power Plant

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ABSTRACT: Wind energy is one of the best sources of alternative energy. However, due to their inherent uncertainty, wind generators are often unable to participate in the forward electricity markets like the more predictable and controllable conventional generators. So the Virtual Power Plants (VPPs) are being advocated as a solution for increasing the reliability of such intermittent renewable sources. A VPP aggregates different types of energy generation and controls it as if it was one source. VPPs can deliver needed energy at peak usage times, and can store any surplus power, giving the energy aggregator more options than would exist in a single power plant. In this paper, to compensate the power fluctuation, different control methodology is presented by using VPP. This methodology is deliberated for real life scenarios. The performance of the designed VPP is verified by the simulation studies which have been done by using MATLAB/Simulink.

KEYWORDS: Virtual Power Plant(VPP), Grid Tie VPP System, Off-Grid VPP System, CVPP, ATS.

NOMENCLATURE

GHG	Greenhouse Gas
RES	Renewable Energy Sources
VPP	Virtual Power Plant
HAWT	Horizontal Axis Wind Turbine
CCC	Control Coordination Center
CVPP	Centralized VPP
ATS	Automatic Transfer Switch

I. INTRODUCTION

In our day to day life every kind of supporting accessories are supported by electrical energy. To complete the demand of time it is important to update this sector. Now-a-days, science is searching to find out better quality than one after another. Renewable resource is one of them. There is an increasing commitment from global leaders and policy makers to reduce GHG emissions. Efforts are being made to increase the contribution of renewable sources of energy in the energy supply mix. Several countries have already formulated policy frameworks to ensure that renewable resources play a major role in future energy scenarios. The use of renewable energy source for the transition towards a sustainable future imposes a number of new challenges for the electricity grid, one of them being the balancing of supply and demand. The flexibility in VPPs can be used within a Grid to dampen the intermittent behavior of wind energy.

Renewable energy source (RES) such as wind turbines, has opened the door to a clean and sustainable energy infrastructure. However, this particular RES has introduced a number of new challenges in order to maintain the current

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stability and reliability of the electricity supply. Its energy output fluctuates in time. This is the main difference between a typical power plant and the power we get from a wind turbine. To reduce this imbalance, a flexible virtual power plant has been introduced in the system.

The work in this paper is divided in two stages. 1) To balance the wind power fluctuation using a centralized virtual power plant. 2) To introduce diverse methods such as grid tie system, demand response system of virtual power plant to balance wind power fluctuations.

II. RELATED WORK

A VPP can be defined as “A cluster of dispersed generator units, controllable loads and storage systems, aggregated in order to operate as a unique power plant” [1]. The generators can use both fossil and RES. VPPs are designed to maximize asset owners' profits while also balancing the grid. They can match load fluctuations through forecasting [2], advance metering and computerized control, and can perform real-time optimization of energy resources [3]. Other advantages include improved power network efficiency and security, cost and risk savings in transmission systems, increased value from existing infrastructure assets and reduced emissions from peaking power plants. VPPs can also enable more efficient integration of RES into the grid by balancing their variability.

III. THEORY

Modern technology has improved the efficiency of windmills for power generation purpose. But they still depend on the vagaries of weather.

A. THEORETICAL POWER FROM WIND

The power P available in the wind is the time derivative of the kinetic energy in a parcel of air mass m , flowing at speed v in the X direction is,

$$U = \frac{1}{2}mv^2 = \frac{1}{2}(\rho Ax)v^2 \quad \text{Joules} \quad \dots(1)$$

$$\text{So, } P = \frac{dU}{dt} = \frac{1}{2}\rho Av^2 \frac{dx}{dt}$$

$$P = \frac{1}{2}\rho Av^3 \quad \text{Watts} \quad \dots(2)$$

Here, A is the cross-sectional area in m^2 , ρ is the air density in kg/m^3 and x is the thickness of the air parcel in meter. The cross-sectional area (A) can be calculated from the equation of a circle.

$$A = \pi r^2 \quad \dots(3)$$

Here, r is the rotor radius (the distance from the hub to a blade tip). The air density can be found using the equation below:

$$\rho = 3.485 \frac{p}{T} \quad \dots(4)$$

Here, p is the air pressure and T is the temperature.

From the equation (2) we can see that power is proportional to air density, cross-sectional area swept out by the wind turbine blades and to the cube of wind velocity. If the blade length is doubled the produced power will be four times than previous state. Doubling the wind speed will give eight times the power.

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B. PRACTICAL POWER FROM WIND

According to Albert Betz (a German physicist) no wind turbine can convert more than 16/27 (59.3%) of the kinetic energy of the wind into mechanical energy by turning a rotor [4]. It's called Betz Limit or Betz' Law. The theoretical maximum power efficiency of any design of wind turbine is called the maximum power co-efficient (C_p) and it is,

$$C_p = \frac{16}{27} = 0.593 \quad \dots\dots(5)$$

Which means a theoretical maximum power of 59.3% can be extracted from wind. The practical designed wind turbines can't give C_p value more than 0.35-0.45. The wind turbine converts about 30% to 35% of the available wind energy into electrical energy.

The practical power from the wind can be calculated:

$$P = \frac{1}{2} \rho A v^3 C_p \quad \text{Watt} \quad \dots\dots(6)$$

C_p varies with the tip speed ratio of the turbine. Tip speed ratio is defined as:

$$\lambda = \frac{\text{blade tip speed}}{\text{wind speed}} \quad \dots\dots(7)$$

The blade tip speed can be found from the formula below:

$$\text{blade tip speed} = \frac{\text{rotational speed} \times \pi \times D}{60} \quad \dots\dots(8)$$

Here, D is the diameter of the wind turbine. Calculating the blade tip speed and tip speed ratio we can find C_p of a particular wind turbine. Thus the actual power from the wind can be calculated.

C. WIND SPEED DISTRIBUTION

In practical scenario wind speed varies frequently. Anemometer is commonly used for measuring the wind speed. An empirical formula developed by D.L. Elliott of Pacific Northwest Laboratory [5], gives the wind speed V at a height H above ground level as:

$$V = V_{ref} \left(\frac{H}{H_{ref}} \right)^\alpha \quad \dots\dots(9)$$

IV. WIND POWER GENERATION

Bangladesh is situated between 20.34-26.38 degrees north latitude and 88.01-92.41 degrees east. In Bangladesh, wind speeds appear to be higher in the eastern region than the western region. Wind speeds in the coastal areas appear to be higher than inland. In the winter, the wind speed is very low but higher in the summer. Wind speed is peaking at noon and weakest at night [6].

Table 1: Average Wind Speed (in m/s) for different sites in Bangladesh from January 2016 to December 2016

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Chittagong	2.54	3.27	5.03	7.54	7.44	8.77	8.87	7.92	5.56	3.06	2.14	2.11	5.37
Hatiya	2.33	2.53	3.57	5.14	5.02	5.81	5.64	4.67	3.38	2.06	1.63	1.65	3.63
Cox's Bazar	3.60	3.85	4.30	4.84	5.36	6.15	6.41	5.75	4.20	3.15	2.93	3.13	4.48
Kutubdia	2.52	2.64	3.38	3.88	4.02	5.40	5.40	4.78	3.13	2.19	1.72	1.93	3.43
Khepupara	1.75	2.19	3.63	5.64	5.92	5.72	5.58	4.96	3.36	1.77	1.36	1.37	3.62

The wind speed for five different sites has shown in Table 1 from January to December 2016 [7]. From the average wind speed data (table 1) it is observed that average wind speed from the month of January to February and October to December is relatively low, which is not sufficient enough for the installment of wind power plant. Wind speed of five different sites from the month March to September has been plotted in figure 1.

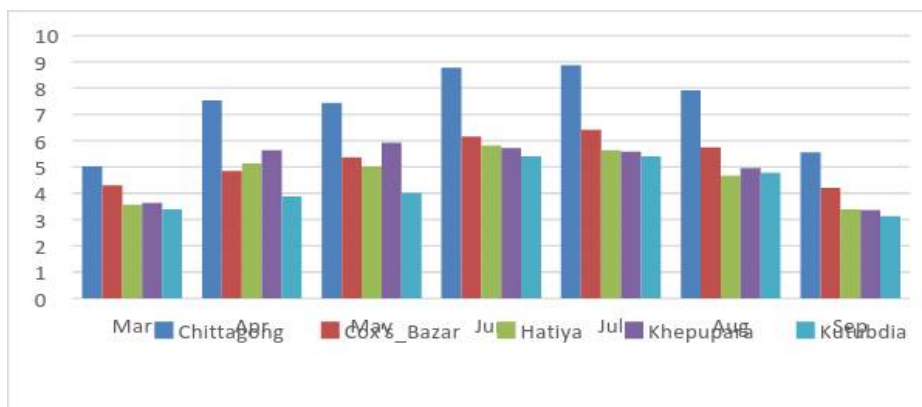


Fig. 1: Adequate wind speed (in m/s)for different sites during proposed time duration.

A. SELECTION OF WIND SPEED

The wind speed data used to calculate the power extracted from wind turbine is hourly wind speed data of Chittagong in April of the year 2016 [8]. The power calculated from the collected data impart us the idea of power fluctuation of a wind turbine, which is our primary concern.

B. SELECTION OF WIND TURBINE

The Evoco 10 kW HAWT is used as wind turbine to generate power for the house. Evoco 10kW turbine can generate 21706kWh at 5 m/s which can easily cover a typical home [9]. And also Evoco 10kW has better power coefficient (C_p) than other similar rated turbine. That's why this turbine is chose. For simplicity every home is using the chosen turbine.

C. GENERATED POWER FROM WIND TURBINE

Fig. 2 shows the generated power from selected wind turbine (Evoco 10 kW turbine). For month April we have collected the wind speed data then using the theories that were described earlier, we've calculated the power which has been extracted from the wind. As we can see the power is not consistent because air is not available all the time which varies the wind speed. Fluctuation is clearly visible here.

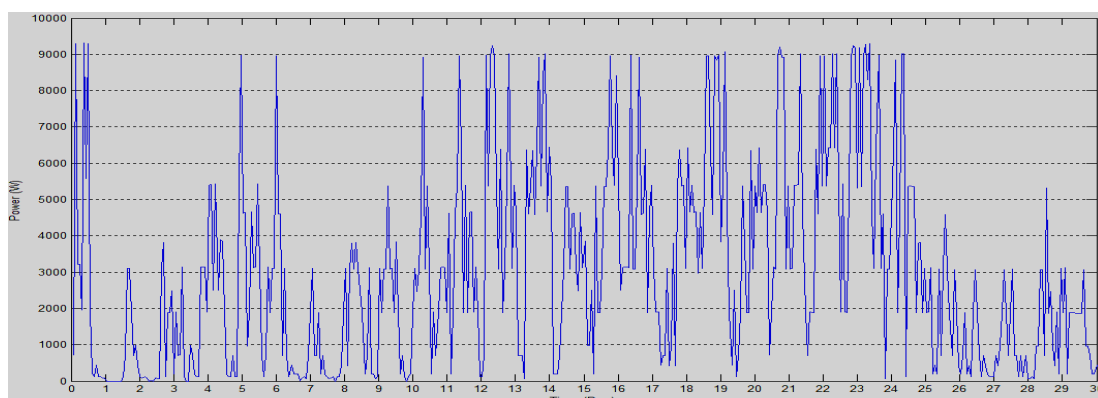


Fig. 2: Generated Powers from wind turbine in April.

V. MODELING VIRTUAL POWER PLANT

A simple demonstration is given here how a VPP's model can be made, controlled and used to balance wind power fluctuation. For simplicity only three houses have been chosen but for every house different scenario is considered. For creating the power consumption, different appliances are taken with different power rating for three different houses which has been collected from a govt. website [10].

A. GRID TIE SYSTEM

In this model every home is connected with a Centralized Virtual Power Plant or CVPP [11]. In Grid-Tie VPP system (Fig. 3) CVPP is connected with grid and wind turbine as well. The power extracted from wind turbine is integrated with CVPP.

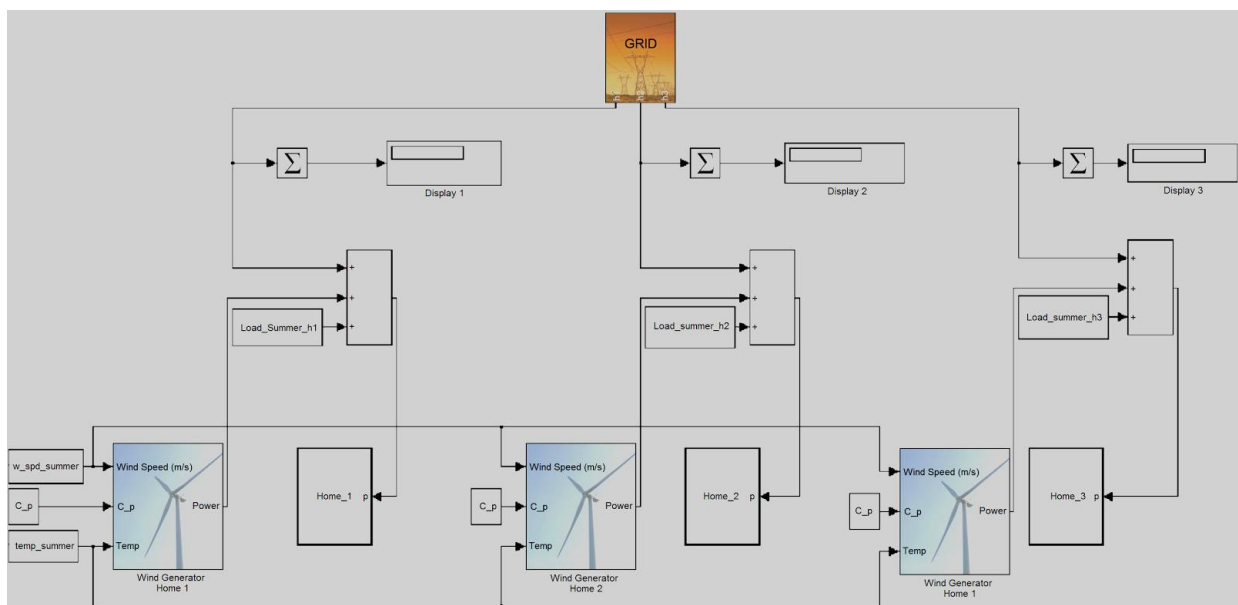


Fig. 3: Model of Grid Tie Virtual Power Plant.

In this system the power demanded by home or user first serves from power generated from renewable sources, here which is wind power. And if there is a mismatch in demand and produced power VPP operates to match the demand. When there is a shortage of power supply than demand VPP takes required power from grid and if there is a surplus VPP integrate extra power to grid. VPP monitors the total power consumed from grid and delivered to grid. Finally for a whole month the extra power is considered as energy by multiplying with time (hours) and required cost is paid to user if power delivered to grid is greater than power consumed and for vice-versa.

B. OFF GRID VIRTUAL POWER PLANT (DEMAND RESPONSE)

This model is for remote areas where grid connection is not available or when a user does not tend to connect with grid-tie system. Like the grid-tie system here all the wind turbines are connected to VPP (Fig. 4). But there is no grid or extra power supply to provide extra power when needed. But this does not mean all home will be in load shedding due to power shortage. In this system all homes using renewable energy sources are connected with each other through CVPP [11]. When one home is demanding or consuming more power than the produced power, it can be collected through other homes extra power which is not used in that certain moment if the user want to sell it. This operation is also known as demand response. Where user tend to vary its usage upon availability of generated power [12]. During

power shortage user tend to use less power than collect it from VPP or other user. For simplicity and shortage of time we were concerned with wind power only and the total number of homes in the system is three.

In this paper we initiated three individual schemes for individual houses. Whereas the Home 1 is connected with VPP under the scheme to deliver extra power to VPP but not to collect any power. Home 2 is integrating and storing its extra power in VPP which is later used at the time of power shortage. Home 3 is under fully flexible condition with VPP. Where it delivers its extra power as well as collect the power needed from VPP at required time. As in this paper only Home 1 and Home 3 are providing extra power to VPP so Home 3 can collect its demanded power from only Home 1 if available. Here VPP controls every houses load through ATS and balance the power demand and generated power [11].

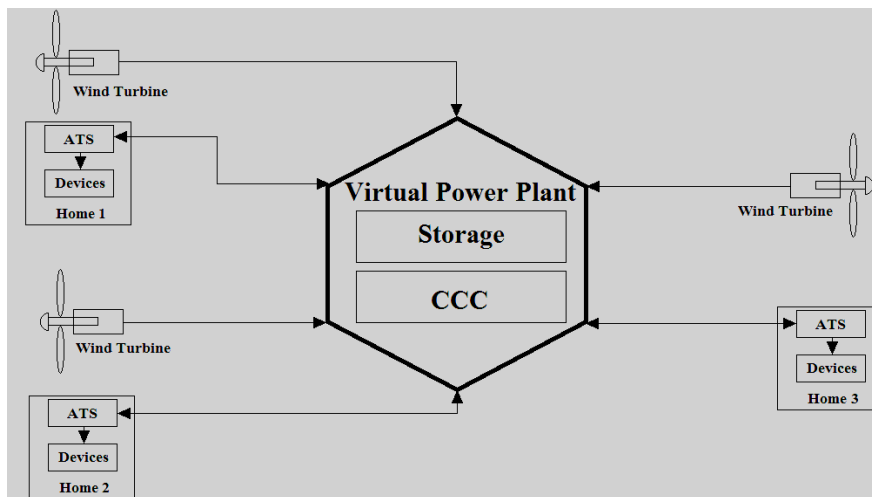


Fig. 4: Model of OFF Grid Virtual Power Plant.

VI. SIMULATION RESULTS AND DISCUSSION

The simulation of the month April for three individual houses have been shown. Results obtained from both grid-tie VPP system and off-grid VPP system are showed and described in details. From the graphs we can see how virtual power plant balances the effect of wind turbines power fluctuations.

A. POWER CONDITIONS OF VARIOUS HOMES FOR GRID-TIE VPP SYSTEM

Power conditions of different loads are demonstrated for Grid-Tie VPP system. All results are obtained by using MATLAB. The month April is depicting the effect of summer season. At an hourly data we have shown April's full power condition (whether user or home is sending power to grid or consuming power from grid) for all houses. For better understanding three different days hourly power condition of three different homes have been described and explained.

5.1.1 Power Condition at Home 1

In Fig. 5, we can see the power condition of home 1 in day 22 of April. The graph represents power vs. time curve. In X axis time (hour) has been represented. The beginning of the X-axis is 0 which represents time 12 am. So, the graph shows the three different powers throughout the day, starting from 12 am to 11pm. This graph contains three lines. The blue line represents the power generated by the wind turbine. The green line represents consumed power by various loads of home 1. And the red line represents power collected from or delivered to grid (depending on the available power condition). The red line is positive when power is drawing from the grid by the user or home 1. And negative when the extra power of home is integrated into the grid. As we can see at 4 am in the morning power generated by the wind turbine is 0 kW. Power consumed by various loads of home 1 is 0.13 kW. So produced power is less than

consumed power. So, at 4 am home 1 will receive the extra power from the grid. Power received from the grid is approximately is 0.13 kW which is shown by the red line. As at 4 am home 1 is receiving power from the grid, the red line is positive. Similarly, at 5 pm in the afternoon generated power is approximately 7.545 kW, consumed power is 0.503 kW. So at 5 pm home 1 will integrate approximately 7.042 kW saved power to the grid. As at 5 pm home 1 is sending power to the grid, the red line is negative.

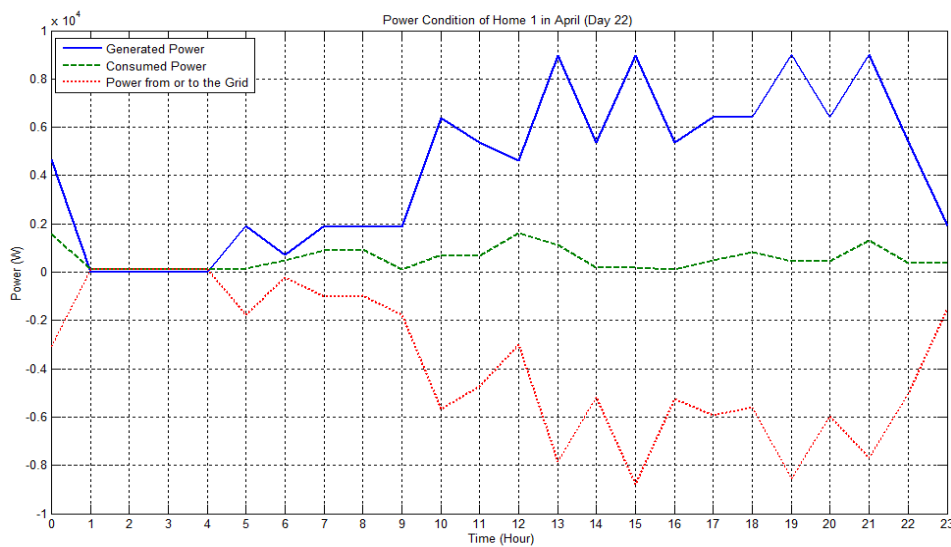


Fig. 5: Power condition at Home 1 (Day 22)

5.1.2 Power Condition at Home 2

In Fig. 6, we can see the power condition of home 2 in day 23 of April. At 12 pm in the noon generated power by the wind turbine is approximately 9 kW. Power consumed by various loads of home 2 is 1.615 kW. So produced power is greater than consumed power. So, home 2 at 12 pm will send approximately 7.385 kW saved power to the grid.

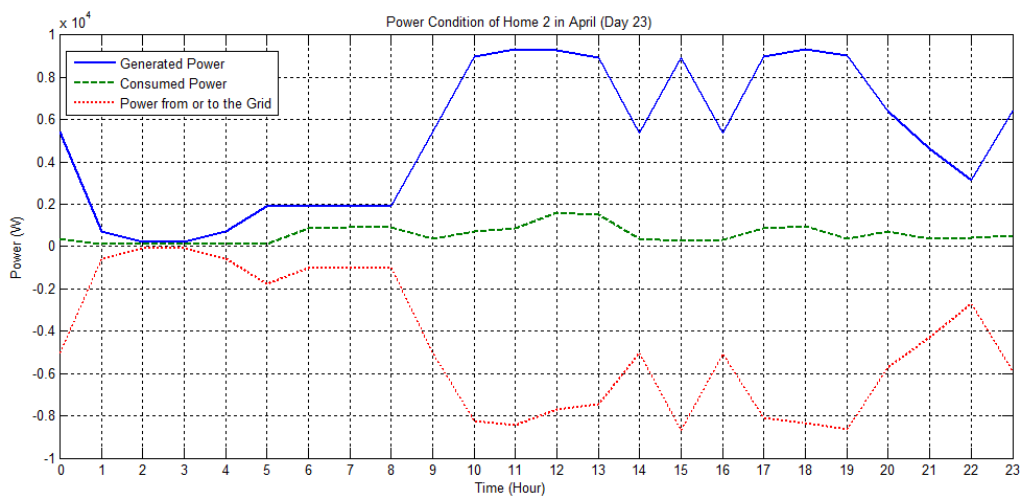


Fig. 6: Power condition at Home 2 (Day 23)

5.1.3 Power Condition at Home 3

In Fig. 7, we can see the power condition of home 3 in day 30 of April. At 1 pm in the noon generated power by the wind turbine is approximately 2.56 kW. Power consumed by various loads of home 2 is 1.91 kW. So produced power is greater than consumed power. So, home 3 at 1 pm will send approximately 0.65 kW saved power to the grid. Similarly, at 8 pm generated power by the wind turbine is approximately 70.93 W and power consumed by various loads of home 3 is 445 W. So at 8 pm home 3 will receive approximately 0.374 kW power from the grid.

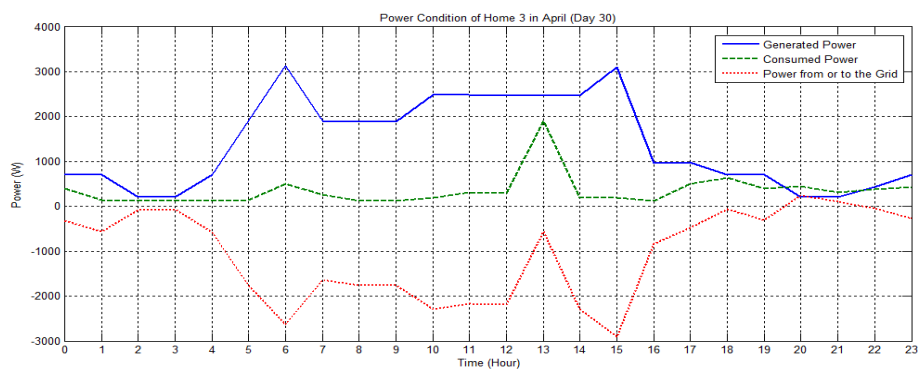


Fig. 7: Power condition at Home 3 (Day 30)

From three graphs above we can see how VPP balances the demanded power and generated power throughout the day taking or giving power from or to the grid.

B. POWER CONDITIONS OF VARIOUS HOMES OF OFF-GRID VPP SYSTEM

Here we are considering a scenario where national grid connection is not available. We considered three houses with different schemes connected with virtual power plant. Below simulations of power condition for different loads has been given which has been simulated using MATLAB.

5.2.1 Power Condition at Home 1

From earlier we already know that Home 1 is connected with off-grid VPP under the scheme where it will deliver extra power to VPP but won't consume any power from VPP. In Fig. 8, the yellow line represents generated power by the wind turbine. The blue line represents the demanded power of Home 1 which is created by us. The green line represents total power consumption after demand response which means total power used according to power available. And the fourth line or red line represents power delivered to grid after fulfilling Home 1's power consumption or the extra power after switching off the one or more flexible loads.

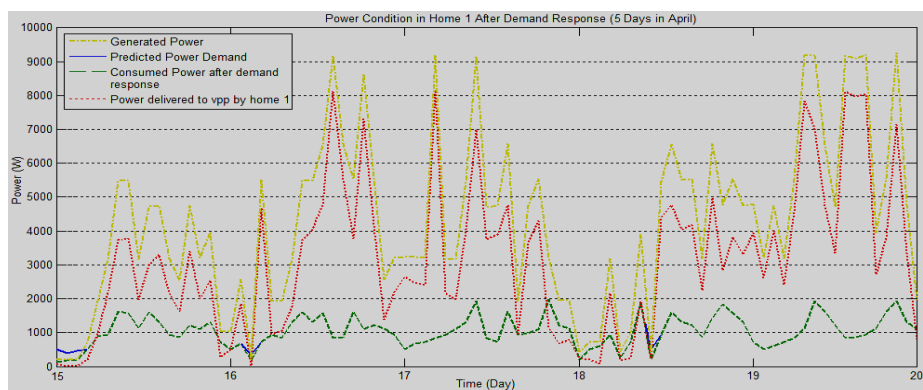


Fig. 8: Power condition in Home 1 after demand response (from April 15 to April 20)

5.2.2 Power Condition at Home 2

In Fig. 9, the orange line represents generated power by the wind turbine. The blue line represents the demanded power of Home 2. The green line represents total power consumption after demand response which means total power used according to power available. And the red line represents power delivered to VPP after fulfilling Home 2's power consumption. This power is stored for future use. When the power demand of Home 2 is greater than the generated power, Home 2 draw powers from VPP which it already stored. Thus it matches the demand response.

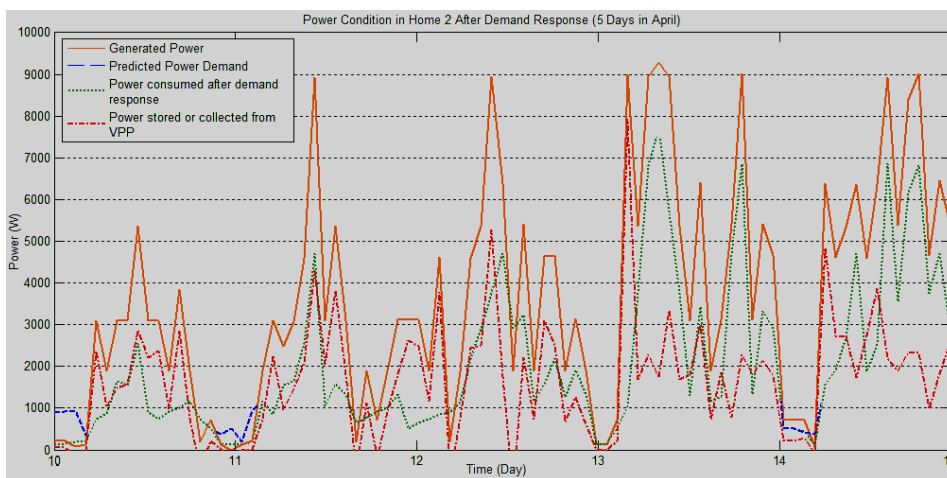


Fig. 9: Power condition in Home 2 after demand response (from April 10 to April 14)

5.2.3 Power Condition at Home 3

In Fig. 10, the orange line represents generated power by the wind turbine. The blue line represents the demanded power of Home 3. The green line represents total power consumption after demand response which means total power used according to power available. And the red line represents power delivered to or collected from grid. When generated power of Home 3 is less than demand of Home 3, it draws power from VPP. But VPP can only provide extra power of Home 1 at that time as only Home 1 is sending extra power to VPP. So, not all the loads can meet its demand. But when there is a surplus of power it integrates power to VPP. Thus it matches the demand response.

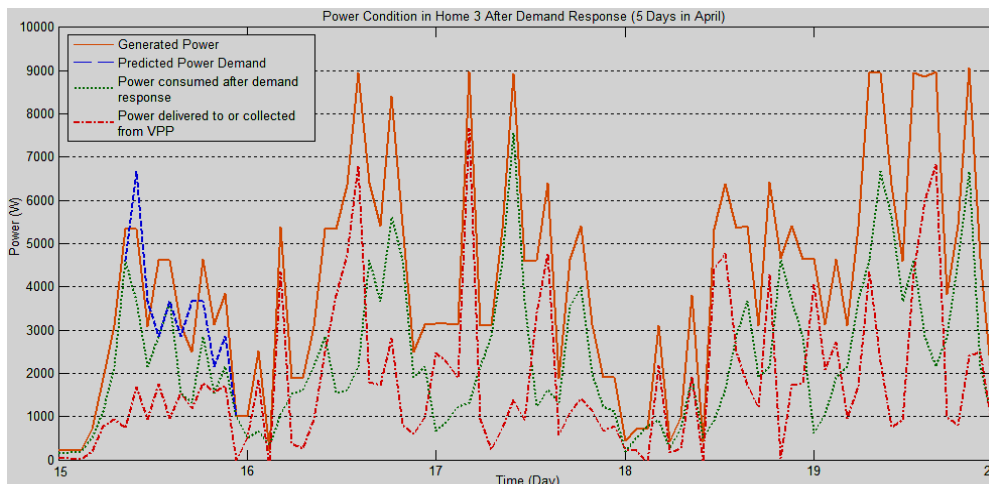


Fig. 10: Power condition in Home 3 after demand response (from April 15 to April 20)

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VII. CONCLUSION

This paper discussed the direct control of wind power fluctuation. The simulation shows various kinds of power state for different situation. If there were no VPP then there would've been a great difference between Load and Demand. So there wouldn't be any continuous power generation. So the power we got from the wind turbine would've been less reliable and less efficient. VPP increase the efficiency and maximizes the use of generated power. VPP prevents frequency mismatch, which helps the load from getting damaged. The ATS operates on flexible loads and thus VPP takes control over the load to balance the power fluctuation [11]. The simulation show the diversity of VPP in both controlling load and managing power.

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