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Electric Vehicle as an Energy Storage for Grid Connected Solar Power System

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ABSTRACT

In the past few years the growing demand for electricity and serious concern for the environment have given rise to the growth of sustainable sources like wind, solar, tidal, biomass etc. The technological advancement in power electronics has led to the extensive usage of solar power. Solar power output varies with the weather conditions and under shading conditions. With the increasing concerns of the impacts of the high penetration of Photovoltaic (PV) systems, a technical study about their effects on the power quality of the utility grid is required. This paper investigates the functioning of a grid-tied PV system along with maximum power point tracking (MPPT) algorithm. The effects of varying atmospheric conditions like solar irradiance and temperature are also taken into account. It is proposed in this work that an Electric Vehicle (EV) can be used as an energy storage to stabilize the power supplied to the grid from the photovoltaic resources. A coordinated control is necessary for the EV to obtain desired outcome. The modeling of the PV and EV system is carried out in PSCAD and the proposed idea is verified through simulation results utilizing real field data for solar irradiance and temperature.

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1. INTRODUCTION

Energy crisis is an ongoing social issue which needs to be addressed worldwide. Recently many developing countries have even decommissioned the nuclear power plants after the Fukushima disaster. This has led to the growing need for generating energy in an alternative manner and microgrid technology started becoming more popular. The microgrid can be defined as a power system which has limited geographic extent and contains embedded generation or storage resources or both which may operate parallel to the grid or in isolation mode [1, 2]. Microgrid technology is one of the viable solutions for electrification where the expansion of the main grid is either not possible or has no economic justification. The microgrid offers decentralized operation and control which helps to reduce the transmission burden on power utility systems.

Distributed energy resources (DER) are a part of the microgrid which includes photovoltaic (PV), small wind turbines (WT), heat or electricity storage, combined heat and power (CHP), and controllable loads. Among the various DERs the PV resource is more appealing as it is not having any moving parts and the losses associated with motion are nonexistent. Also solar power systems are used in applications similar to a generator to supply remote loads [3]. But the main disadvantage of solar power is its intermittent nature. Energy storage is generally recommended in the case of an intermittent source [4].

It has been shown before that plug-in vehicle parking lots (SmartParks) can be used to absorb the variations caused due to the intermittency in wind power [4-5]. The idea of using an electric vehicle (EV) as an external energy storage [6] can be extended to a solar powered system also. In the near future the rising penetration of PV system may also lead to important impacts on power distribution systems, particularly due to the intermittent nature of its output caused by cloud cover [7]. Therefore, a coordinated use of solar powered system with EVs will be a possible solution which can help to maintain a flat power profile to the grid.

EVs can be coordinated with PV systems in many ways. For example, a dc-dc converter inserted between an EV and the dc bus voltage of a PV system can improve grid integration of PV systems by reducing the ramp rate of the PV inverter output power [8] [9]. To reduce the fluctuations in the grid, only slowly changing power can be exported by the use of a high pass filter in the network, which directs rapid power fluctuations to the EV battery [10]. Not only that, to regulate the energy imbalance in the system, the day time solar generated power can effectively be converted into night time consumption using the vehicle to grid and grid to vehicle concept [11]. Also as more and more PV generation is pumped into the existing power system, the need for an energy storage which is cost effective is emphasized [12, 13, 14].

However, in order to generate more confidence on this technology, the system has to be exposed to realistic field data. This is the most important objective of this paper, where, a grid connected combined PV and EV system is thoroughly modeled and studied by incorporating the real field data in PSCAD/EMTDC environment. In order to verify the performance of the PV-EV combined microgrid, field data (solar irradiance and temperature) obtained from Centre for Wind Energy Technology (CWET), Chennai, Tamilnadu, India has been used. The results obtained shows that this Electric Vehicle technology in coordination with the solar PV generating unit gives a smooth power output to the grid. This paper is organized as follows: In section II, modeling and control of grid connected PV-EV combined system is discussed. The simulation results are shown in Section III and conclusions are drawn in Section IV.

2. PROPOSED MODEL AND CONTROL OF GRID CONNECTED PV-EV COMBINED MICROGRID

2.1. Modeling and Control of Grid Connected PV System

The pictorial representation of a grid connected PV system is represented in Figure 1. The input to the PV module is nothing but the solar irradiance and the temperature. The DC-DC converter is used to boost the output of the PV module. The firing pulse of the DC-DC converter is generated through the MPPT control logic. The output of the converter is connected to the grid through a three phase current controlled PWM inverter.

2.1.1. Modelling of the Solar Farm

In this paper, a 100 kW solar farm is modeled in PSCAD/EMTDC platform. The parameter values of all the passive components are obtained from the Matlab demo model of a 100 kW solar PV system. Ten numbers of modules are connected in series and eight numbers of modules are connected in parallel. There are 216 cells connected in series per module and eight cells in each string per module in series. The series resistance per cell is 0.02 ohm and the shunt resistance is 1000ohm. The output voltage of the solar panel is obtained across a capacitor (C in Figure 1).

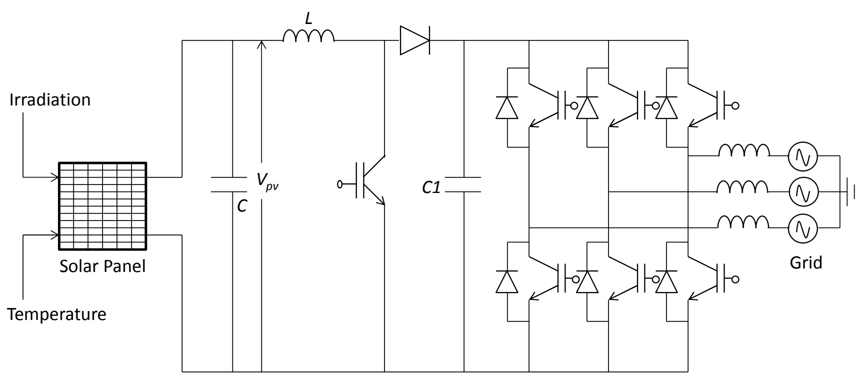

Figure 1. Schematic diagram of the grid connected PV system

2.1.2. Modelling of the Boost Converter

It is also very important to extract the maximum possible power from the panel using Maximum Power Point Tracking (MPPT) algorithm. The algorithm is embedded inside the control of the boost converter. The implementation of MPPT based boost converter control in this paper is presented in Figure 2. Fig. 2 shows that the output current (I_{pv}) and output voltage (V_{pv}) of the PV module are passed through first order low pass filters. The MPPT block uses the Incremental Conductance Algorithm for tracking the required point. The algorithm is based on the fact that the slope of the PV array power curve is zero at the Maximum Power Point (MPP), positive on the left of the MPP, and negative on the right. The MPP can thus be tracked by comparing the instantaneous conductance (I/V) to the incremental conductance ($\Delta I/\Delta V$).

The output of the MPPT block is the MPP voltage (V_{mpp}). This is the voltage at which the PV module has to operate to extract maximum power. The algorithm decrements or increments V_{mpp} to track the maximum power point when operating under varying climatic conditions and passing clouds. This voltage (V_{mpp}) is then compared with the measured PV panel output voltage (V_{pv}) and is fed as the input to PI controller. The output of the PI controller is used to generate the switching pulses for the boost converter.

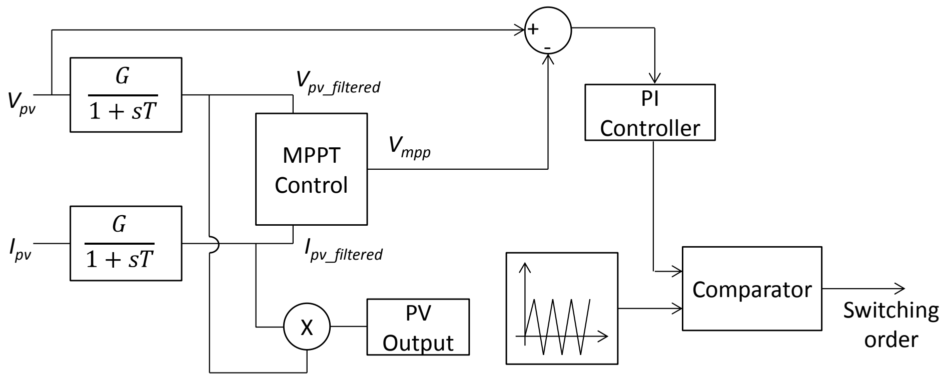

Figure 2. MPPT and the control of boost converter

2.1.3. Control of the Inverter

The output of the DC-DC converter is connected to the inverter, which converts it into AC and then connects it to the utility grid. The inverter is a two-level voltage source converter (VSC) using IGBT switches along with anti-parallel diodes as shown in Figure 1. Current controlled PWM technique is used to generate the switching order for the IGBTs. In order to explain the control of the grid-connected VSC, a simplified diagram is shown in Figure 3. The complex phasor representation of Figure 3 is again shown in Figure 4.

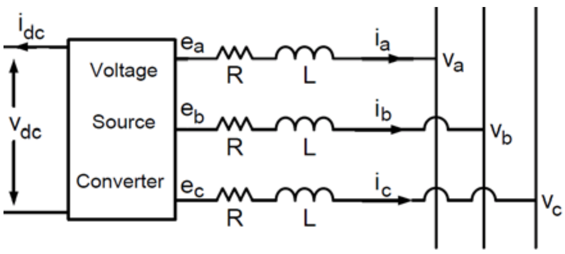

Figure 3. Schematic diagram of a grid connected VSC

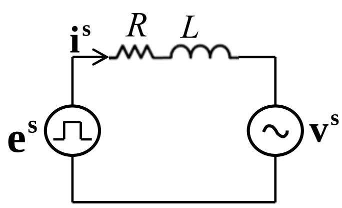

Figure 4. Complex phasor representation of grid connected VSC

From Figure 4, it appears that $\mathbf{e}^s = R\mathbf{i}^s + L\frac{d\mathbf{i}^s}{dt} + \mathbf{v}^s$ (1)

Here, $\mathbf{e}^{s}$ is the converter voltage, $\mathbf{v}^{s}$ is the grid voltage and $\mathbf{i}^{s}$ is the current flowing from converter to the grid. All these variables are represented in stationary reference frame. Converting them into synchronous (d-q) reference frame yields

$$
\begin{aligned}
& e^{-j\theta}\mathbf{e}^{s} = e^{-j\theta}R\mathbf{i}^{s} + e^{-j\theta}L\frac{d\mathbf{i}^{s}}{dt} + e^{-j\theta}\mathbf{v}^{s} \\
& \Rightarrow \mathbf{e} = R\mathbf{i} + e^{-j\theta}L\{e^{j\theta}(j\omega\mathbf{i} + \frac{d\mathbf{i}}{dt})\} + \mathbf{v} \\
& \Rightarrow \mathbf{e} = R\mathbf{i} + L(j\omega\mathbf{i} + \frac{d\mathbf{i}}{dt}) + \mathbf{v}
\end{aligned}
\tag{2}
$$

The PLL is used to generate the value of theta θ. This theta is used to turn on and off the IGBT's which in turn controls the flow of real and reactive power.
Putting $\mathbf{e} = e_d + je_q, \mathbf{v} = v_d + jv_q, \mathbf{i} = i_d + ji_q$ and separating real and imaginary parts

$$
\begin{bmatrix} e_d \\ e_q \end{bmatrix} = R\begin{bmatrix} i_d \\ i_q \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega L\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} v_d \\ v_q \end{bmatrix} \tag{3}
$$

Aligning the *d*-axis of the reference frame on the voltage space vector, we obtain

$$
v_d = |\mathbf{v}| \qquad v_q = 0 \tag{4}
$$

With this new reference frame orientation we obtain complete decoupling of active and reactive power. The power equations become

$$
P = v_d i_d \qquad Q = -v_d i_q \tag{5}
$$

Equation (3) now changes to

$$
\begin{bmatrix} e_d \\ e_q \end{bmatrix} = R\begin{bmatrix} i_d \\ i_q \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} -\omega L i_q \\ \omega L i_d \end{bmatrix} + \begin{bmatrix} v_d \\ 0 \end{bmatrix} \tag{6}
$$

In equation (6), the terms $\omega L i_q$ and $\omega L i_d$ are the speed/frequency induced terms that gives raise to the cross coupling between the two axes. These terms are considered as disturbances in the system and hence eliminating them will yield better results. If we define our commanded converter *d* and *q* voltages as e_d^* and e_q^* and commanded currents to be $i_{d(ref)}$ and $i_{q(ref)}$, then with a PI type current controller along with cross-coupling compensation, following equations hold

$$
e_d^* = L\left(K_p + \frac{K_i}{s}\right)(i_{d(ref)} - i_d) - \omega L i_q + v_d \; ; \; e_q^* = L\left(K_p + \frac{K_i}{s}\right)(i_{q(ref)} - i_q) + \omega L i_d \tag{7}
$$

Here, since i_d is directly proportional to active power (5), then it is reasonable to control the DC voltage by controlling the i_d. Therefore, $i_{d(ref)}$ can be generated as an output of the DC voltage controller.

$$
i_{d(ref)} = \left(K_{pdc} + \frac{K_{idc}}{s}\right)(v_{dc}^* - v_{dc}) \tag{8}
$$

The overall control of the inverter for the grid connected PV system is shown in Figure 5.

2.2. Modelling and Control of Grid Connected Electric Vehicle

The electric vehicle is modeled as a DC voltage source with a three-phase two-level inverter through which it connects to the grid (Figure 6). The control of the electric vehicle inverter system is almost the same as the PV inverter. The only difference between the two is that since it is connected to a constant DC voltage source, the DC voltage control is not necessary. Instead, it can directly control the active power commanded (P_{EV}^*) from the electric vehicle. However, here the active power order comes from the coordinating controller which controls the overall power injection (PV+EV) into the utility grid.

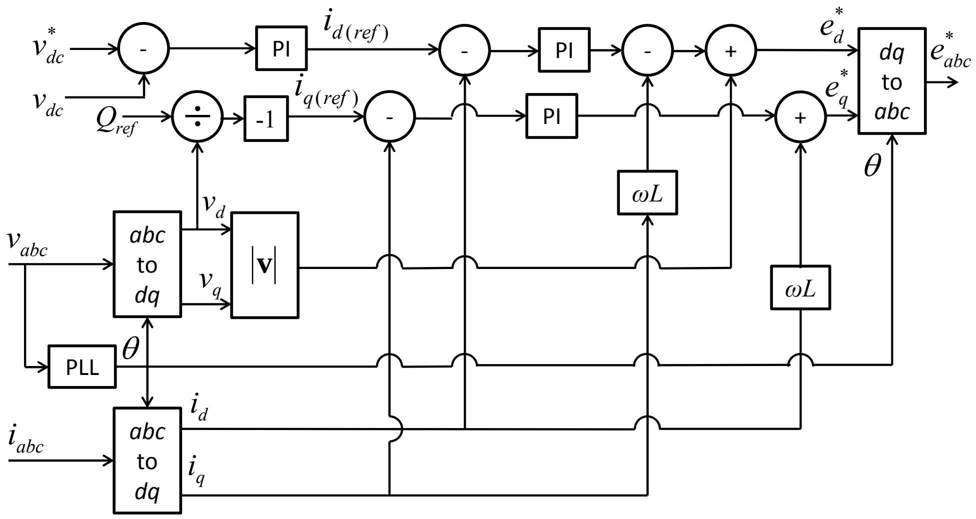

Figure 5. Overall control schematic of the grid connected PV inverter

2.3. Coordinated Control of the PV-EV Combined Microgrid

In order to smooth out the power fluctuations from the PV inverter and to make sure that the power injection to the utility grid is absolutely constant, a coordinating controller is necessary. The desired power to the utility grid is given as an input to the coordinating controller. It also tracks the output power from the PV system. Then the difference between these two powers, which is the output of the coordinating controller, can be used as the commanded power for the EV system. Mathematically,

$$P_{utility}^* - P_{PV} = P_{EV}^* \quad (10)$$

where, $P_{utility}^*$ represents the desired power output of the utility grid, P_{PV} represents the output power from the solar generating plant and P_{EV}^* represents the commanded power to the electric vehicle.

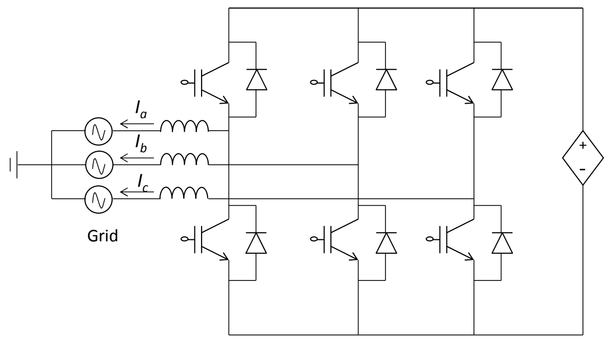

Figure 6. Schematic representation of grid connected EV

3. SIMULATION RESULTS AND DISCUSSION

3.1 Performance of the Solar PV System

In order to verify the performance of the PV-EV combined microgrid, field data obtained from Centre for Wind Energy Technology (CWET), Chennai, Tamilnadu, India has been used in this paper. The organization provides site data for both solar PV and wind systems. In this paper one minute data is taken into consideration, as it is meaningful to interpolate the same. The inverters in the electric vehicle should be very fast to mitigate power unbalance, but they are not supposed to work for a long time. Therefore if ten minutes data is used then the interpolation will not be realistic. Hence the solar irradiance and temperature data with one minute interval on 1st January, 2013 at a site location in Chennai, Tamil Nadu is used. The site description is shown in the below table 1.

Table 1. Site Description

Station Name/ID	Chennai/1791
Latitude	12 ° 57'21.79" N
Longitude	80°12'59.75" E
Elevation / Altitude	1m amsl / 0 m agl
Site Address	National Institute of Wind Energy, Chennai, Tamilnadu.

The data sheet specified the Sun height angle, Sun azimuth angle, Global horizontal irradiance "W/m^2", Direct normal irradiance "W/m^2", Diffuse horizontal irradiance "W/m^2", Horizontal wind speed (10m) "m/s", Wind direction, Air temperature "°C", Relative humidity "%", Barometric pressure "hPa", Precipitation "mm", Dew point temperature "°C", Wet bulb temperature "°C".

All the simulations are carried out with a 100 minutes' data set starting from 10:00 AM. However, in PSCAD, it is quite time consuming to actually run a 100 minutes' data set when the simulation time-step is 50 µs. Such a small time-step has to be used in order to achieve the high frequency switching of the power electronic converters which are modeled in quite detail in this paper. In order to obtain a realistic solution to this problem, the 100 minutes' data set is used in the PSCAD model. All the simulation results are obtained with respect to time (100 minutes) in the x-axis.

Figure 7 (a) shows, how the irradiance and temperature has varied during the time interval mentioned before. Due to that variation, the output of the solar PV system changes, which is shown in Figure 7 (b). The output of the PV array varies within the range of 80 kW to 130 kW. This power is captured using the MPPT algorithm discussed before.

Figure 7 (a) Solar irradiance and temperature variation with time as per the field data

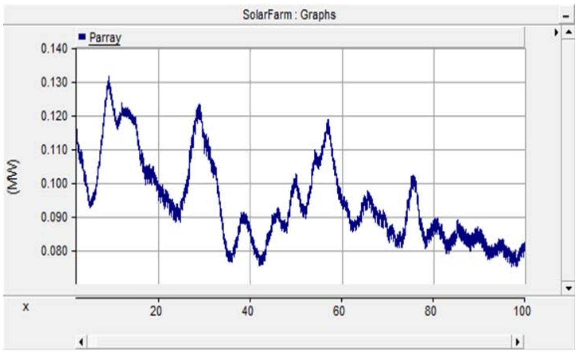

Figure 7 (b) Variation of PV array output power due to the variation of irradiance and temperature

Now, in order to send this power to the utility grid, it is required to hold the DC link voltage of the solar PV inverter to a constant value by the DC voltage controller. The performance of the DC voltage controller in such a varying power scenario is therefore important for the correct operation of the solar PV system. In Figure 8, the reference and the actual DC voltage of the DC link is shown. It is observed that even in this varying power scenario, the DC link voltage is successfully maintained at the commanded value.

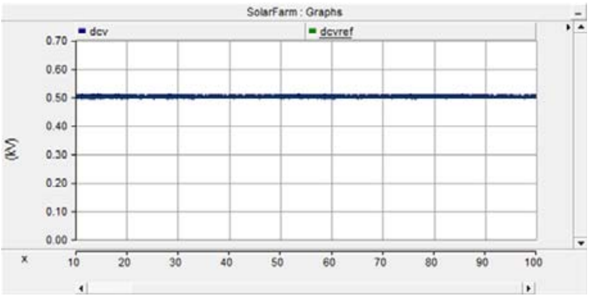

Figure 8. Reference and actual DC voltage of the inverter DC link

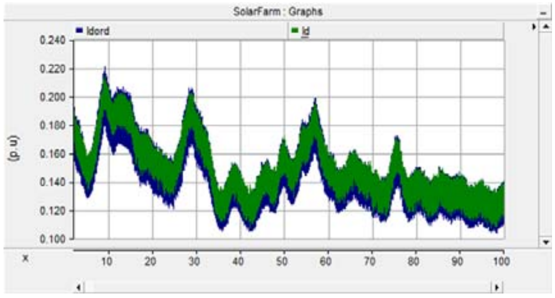

Figure 9. Reference and actual d-axis current of the solar inverter

Another important component of the solar PV inverter is the current controller. The current controller in the *d*-axis has to be fast enough to track the current reference generated by the DC voltage controller. At the same time the current controller has to be able to limit the current in case of transient events so that the converter valves does not experience high unwanted current beyond its rating. In Figure 9, the tracking of the d-axis current controller is shown. Here I_{dord} is the reference current and I_d is the actual current waveforms. From the reference and actual current, the successful operation of the current controller is established.

3.2 Performance of the Electric Vehicle

In this case an electric vehicle is used in order to absorb the power variations caused due to the variation in irradiation and temperature. In figure 7, these variations are simulated using the real time field data obtained from Centre for Wind Energy Technology, Chennai, Tamilnadu, India. The Control circuit of the electric vehicle tracks the P_{ord} and the vehicle power follows the same satisfactorily. The vehicle power varies in the range of +/- 30kW. The vehicle power tracks the reference power which is shown in figure 10. In this model a constant dc source of 5kV is used as reference.

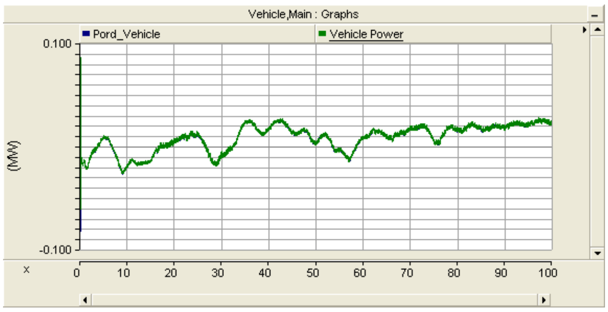

Figure 10 Reference and actual vehicle power

As mentioned earlier in section B, the control of the electric vehicle inverter system is similar to that of the PV inverter. Since a constant DC source is used, DC voltage control is not required. Instead, it can directly control the active power commanded (P_{EV}^*) from the electric vehicle. However, here the active power order comes from the coordinating controller which controls the overall power injection (PV+EV) into the utility grid. Then, the reference current for the current controller is calculated directly from the following equation

$$i_{d(ref)\_EV} = \frac{P_{EV}^*}{v_d}$$

Following the above equation, the reference current is tracked by the actual d-axis current of the electric vehicle successfully.

3.3 Performance of the PV-EV Combined Microgrid

Now, with an objective to obtain a flat power profile injected to the utility grid, a power reference of 100 kW is set in the coordinating controller. It means that, if the PV system produces more power than 100 kW, then the EV will absorb the excess power. Similarly, if the PV system produces less power than 100 kW, the EV system will supply the deficit. Obviously, the EV system cannot supply or absorb power for indefinitely long period. It will be determined by the available state of charge of the EV batteries which are taking part in this V2G and G2V transactions. In this case, it was assumed that the EV system which constitutes the PV-EV combined microgrid, is capable of supporting the PV system within a range of +/- 30 kW. Figure 11 shows that with such a simple implementation of a coordinating controller, the power fed into the grid is maintained perfectly at the commanded value, which is 100 kW in this case. The solar power fluctuations are completely absorbed by the EV system, which helps the combined system to maintain a flat power profile.

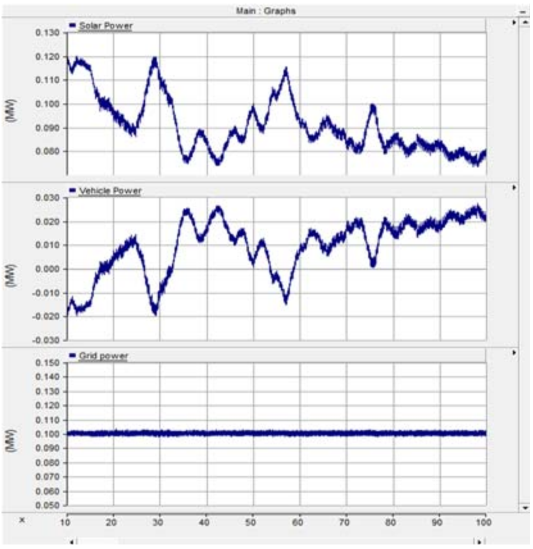

Figure 11. Performance of the PV-EV combined microgrid

It is evident from the field data obtained that renewable energy sources like solar, wind etc increases the demand for reserves and regulations in view of their intermittent nature. Asmore of these sources are injected into the grid nowadays, the electric grid needs something to bridge the gap between altering demand or supply and the response of the generally slow large generation units. This reserve/balancing capacity is is termed as ‘ancillary services’. In [6, 11] the role of EV’s is specified and the number of EV’s to be deployed in accordance to the load demand is reported but real field data has not been incorporated in these studies. In [3] the modeling of the solar PV system is carried out but the intermittency has not been addressed. In the present work the real field data of the solar irradiance and temperature has been used to validate the EV technology and the results abtained clearly shows that the power output to the grid is stable.

4. CONCLUSIONS

In this paper, it is shown that a coordinated control is capable of maintaining a flat power profile which is fed into the utility grid from a PV system by mitigating the intermittency with electric vehicles in a PV-EV combined micrigrid. A PSCAD simulation, which uses field data for solar irradiance and temperature, are carried out to verify this idea. The results shown in this paper are very promising to establish the claim that electric vehicles can be used as an external energy storage to a solar PV unit in microgrid.

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