Design, Control and Management of P-V System for Residential Applications with Weak Grid Connection

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ABSTRACT

Driven by the economical and environmental concerns, the importance of distributed renewable energy sources is increasing. In this paper, the design of a grid connected photovoltaic (PV) system for typical house will be discussed in terms of sizing of P-V units and battery storage. The sizing of the system will be determinant based on the expected loads, characteristics of the used PV module and the meteorological data of the region of installation. The system consists of PV panels, a DC-DC converter interfacing PV panels, a bi-directional DC-DC battery charger and a single phase inverter interfacing the DC bus to the loads (typical home appliances) and the main AC grid. The power conditioning unit needed to regulate the output voltage of the system across the terminals of the load and track the maximum power point (MPP) will be presented. The optimum operation of the system will be achieved based on accurate forecasting and intelligent management of the available PV power.

Keywords: Energy management, Energy storage, PV systems, renewable energy sources, residential applications, standalone systems.

1. INTRODUCTION

The global need to reduce pollutant gas emissions, rapid increase in the cost of energy and fossil fuels and inevitable energy shortage give rise to a worldwide trend to utilize renewable energy sources especially for residential applications. Among the renewable energy sources, PV recently attracts a special attention with thanks to significant jumps in power electronics technologies. However, relying on renewable energy sources associated with some concerns, such as high uncertainty, unavailability during some day periods and rapid- out of control changes. The output power fluctuation of renewable energies may cause excess variations of the system's voltage and frequency. In recent years, storage systems have been combined to photovoltaic systems, which are able to provide an energy reserve with less fluctuating output power.

In this study, a P-V system will be used to feed a typical house in rural area with weak connection to the grid. Since the connection to the grid is weak and in order to guarantee continuous power supply, an energy storage system will be connected to the system. This paper is organized as the following; general description of the system and study for load estimation will be provided in section 2. Section 3 presents the design of the P-V system, rating of the DC-DC converter interfacing the P-V system and maximum power point tracking (MPPT) algorithm. Design of the battery system along with design of the bi-directional battery charger will be provided in section 4. Forecasting algorithm to predict the available solar radiation and consequently predict the available energy from the PV system is given in section 5, finally the derived conclusions are given in section 6.

2. System General Description and Load Estimation

The system under study is grid connected-residential system, the house's owner request is less reliance on the utility and more dependence on the installed system for meeting hid demand. The nature of such a system and weak grid connectivity impose more complexity to the system design as reliability and supply continuity become crucial issues. Load curve should be analyzed carefully and the PV system should be sized and combined with the battery system in such a way to cover all the points of the load curve. On the other hand the economical aspects should be considered, it can be seen in some systems that PV modules and batteries are oversized to avoid power interruptions. Designs of these systems are not optimum and involve more –useless costs. A trade off should be done between over-sizing the system to guarantee more power continuity and system costs.

In this system, PV modules are connected to a DC bus through DC-DC converter to control the output power from the PV system and to achieve maximum power point tracking (MPPT). 12V lead acid battery is the building block of the energy storage system which is connected to the same DC bus through a bi-directional DC-DC converter to control the battery charging. Home appliances are inherently single phase AC , Most of the used devices in typical homes are operated with AC power, the interface between AC bus and DC bus is a single phase- voltage source inverter (VSI). The same inverter is used to control the power flow at the point of common coupling (PCC) and for interfacing the Ac grid. Figure 1 shows a schematic diagram for the aforementioned system.

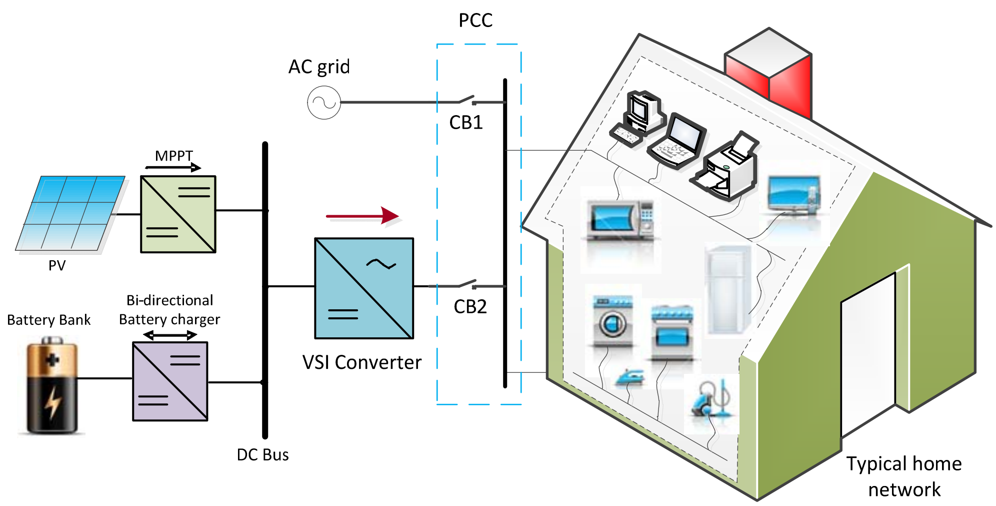

Figure 1: System schematic diagram.

The first step in design process is the load estimation, typical home appliances with its power ratings and estimated operating time per day are listed in Table 1.Its shown that the total energy consumption of the home is 25625 Wh per day, by dividing over 24 (no of hours per day), it yields ≈ 1068 W as an average load. Designing the system to supply the average load (1068 W) assumes that the load curve is uniform,which is not valid assumption especially in residential appliactions.

Table 1: Typical home appliances, power ratings and estimated operating time per day.

Appliance	Power(W)	Hours/Day	Wh/Day
Air Condition (2 units)	1800	4.5	8100
Coffee maker	600	0.2	120
Clothes Drayer	3500	0.5	1750
Computer +Monitor	160	4	640
Laptop	75	3	225
Dishwasher	1200	0.5	600
Light	80	7	560
Microwave	1100	0.5	550
Refrigrator	600	12	7200
LCD Television	200	8	1600
Vacuum Cleaner	1400	0.2	280
Stove	2000	1.5	3000
Washing machine	1000	1	1000
Total			25625

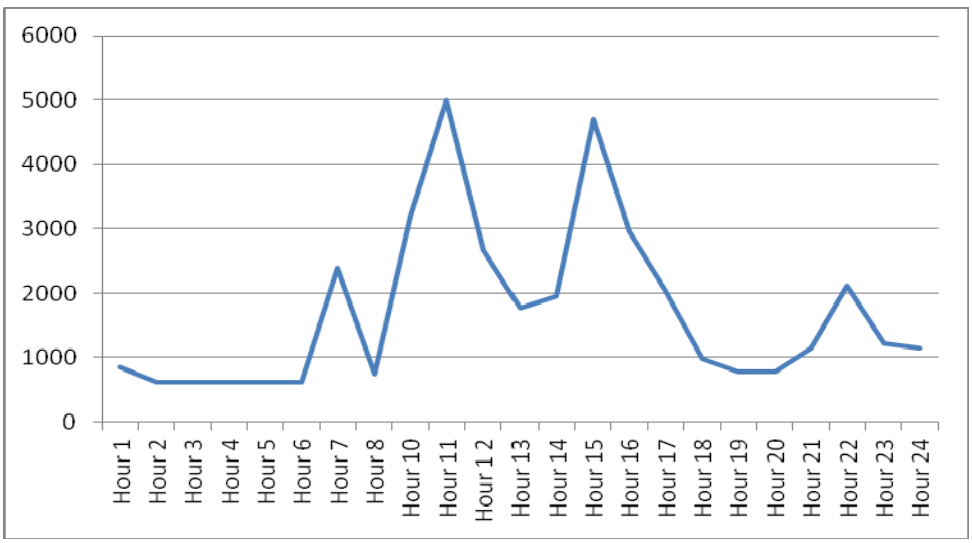

Figure 2: Investigated load profile for a typical house.

3. DESIGN OF PV ARRAY

In order to satisfy load requirements, all the components of the system (PV array can be excluded) should be rated to the maximum demand. The load profile for a typical house was investigated and its shown in Figure2. There are two peaks at 5000 & 4700 W, this is due to the operation of the clothes drayer and air condition units respectively, which are bulky loads. Since the refrigrator is connected and disconnected automatically, it was taken into account that the refrigrator is operating all the day when calculating the maximum demand. The area under the curve shown in Figure 2 should equal the total energy consumption over the day calculated in Table 1.

When designing a PV system,the location of the system should be considerded to determine the availabilty of solar radiation. Its assumed that the system is located in the southern area of Florida state, USA. It has benn noticed that there's a noticable difference between solar irradiance in winter and summer,so as a common practice, the design will be carried out based on the worst condition and lowest irradiance. In order to add reality and plausibilty to the system,the design will be based on commercially available equipments only. The parameters of the chosen PV module are given in Table 2. During daylight time, PV array should do two functions; supply the reguired power to loads and recharge the batteries. During nigth time, the batteries should have the capability of supplying the loads continously.

Table 2: Parameters of the chosen PV module.

Power	175 Watt
Area	1658mm*835mm
V(Maximum Power Point)	23.9V
V(Open Circuit)	30.02V
I (Maximum Power Point)	7.32Amp
I (Short Circuit)	7.963Amp
α	-0.0821
β	0.00318
K	-0.005
Efficiency	15%

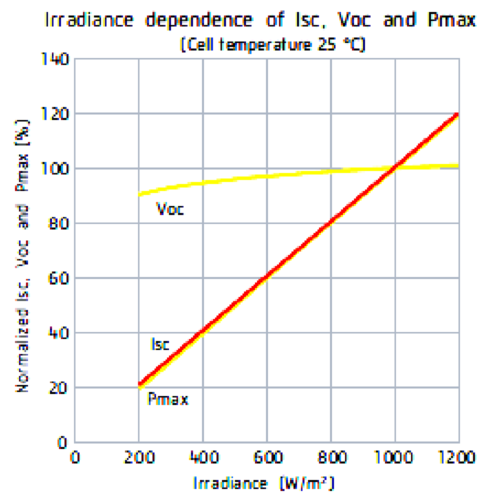

Figure 3: PV module characteristics.

To calaculte the required number of modules, we can project the available solar radiation values from the historical meterorological data to the irradiadiance-output characteristices of the selected module and calculate the output power for each module, this can be done by MATLAB lookup tables. This step yeilds an average solar radiation of 530W/m^2 ,and output power of 55% of the maximum output power- according the available data sheet from the manufacture the maximum output power of the modulre is 175 W- this step yeilds output power equals 97 W . Then after calculating the output power per each module, it's multiplied by number of hours when the solar radiatio is available to calculate the daily available energy from the module . The average number of shinning hours is 6-7 h per day.

$$E_{out} = P_{out} * N_h = 679Wh$$

The air conditioners is the affecting load in the summer which is replaced by heating system in the winter or the same system can perform both functions (HVAC), it can be assumed with accepted tolerance that the load profile is the same over the whole year, we can make calculations over one day for simplicity. Then the total number of modules is given by:

$$N_{\mathrm{mod}} = E_{required} * S.f / E_{out}$$

Where *s.f* is a safety factor accounts for system losses (such as losses in the DC-DC converter and DC-AC inverter) and the expected degradation of the PV modules' output power due to dust and environmental conditions, usually this factor is selected to be 1.1-1.2, it will be selected here as 1.15. This step gives the number of required modules as 44 PV modules. It can be connected in pairs to get the rerquired voltage level. A check has to be done here , we have to check the ability to this system to meet the maximum load, so by multiplying 44 by 97, we get 4268 W as a maximum power which enough for the most loading conditions but it is less than the two peaks 5000W, 4700 W. In this case, the VSI withdraws the required energy from the grid to cover the peak load, or another solution is to account on the batteries (if charged) to cover this energy deficit. The selection of one choice depends greatly on the consumer preferences and battery state of charge (SOC). User preferences can be implemented by giving a higher priority to one option over another while designing the controller as the consumer can't interfer each time.

PV array will consist of 44 modules, to determine how many modules will be selected in series we have to select the voltage of the DC bus. Many researchers have investeigated the the DC bus voltage selection, based on theses studies the DC voltage will be slected as 48 V to reduce the system losses. Since the maximum power point voltage of the PV module is 23.9V,we can connect two in series to get a total voltage of 47.8V and use the DC-DC converter to adjust the output voltage to 48 V. Finally the array will be 2*22 modules.

There are two common ways to select the capacity of the DC-DC converter interfacing the PV system, the first one is to select the capacity as 5%-10% higher than the maximum power rating of the whole PV array.The second one is to select the converter with rating of 5%-10% of the maximum anticipated demand. The first option is prefered in standalone systems, while the second one can be adopted in grid connected system as in our case safely.

$$P_{conv}=5000*1.05= 5250 \text{ W}$$

MAXIMUM POWER POINT TRACKING

PV systems are often operated in an MPPT mode to maximize the benefit from the solar power. The main MPPT algorithms can be classified into two main categories; direct and indirect methods. The indirect methods are based on using either a database containing the parameters and data that show the characteristics of the PV panel at different environmental conditions, such as different temperatures and irradiances or some mathematical functions achieved by experience on the estimation of the MPP. The indirect methods include "curve-fitting method", "look-up table method", "open-circuit voltage method", "short-circuit method" and "open-circuit voltage photovoltaic test cell method". Direct methods use output voltage or/and current of PV panel and the relationship of the changing of them to the changing of the output power of the PV panel to find the maximum power point. The direct methods include "differentiation method", "Perturbation and Observation P&O method", "artificial intelligence method" and so on. The most commonly used methods are the direct methods, a summary of these different algorithms is discussed as follows.

- *Differentiation method.*

This method is based on the following equation, and therefore in order to get the MPP and operate the system in real time, this equation should be solved quickly. The disadvantage of this method is that at least 8 calculations and measurements should be done to solve (1.6), which is not easy with a high sampling frequency in real time operation.

$$\frac{dP_{PV}}{dt} = V_{PV}\frac{dI_{PV}}{dt} + I_{PV}\frac{dV_{PV}}{dt}$$

- *Artificial intelligence method*

Artificial intelligence such as neural network (NN), fuzzy logic controller (FLC) and genetic algorithm (GA) play an important role in smart grid power systems. Also they can be applied in MPPT algorithms, The NN has the ability of approaching certain nonlinear functions, so this can be used to emulate the behavior of a PV array and generate its MPP lookup table. Furthermore, FLC can greatly improve the system's control robustness, and the exact mathematical model of the PV array is not required. The GA has the ability of optimizing the control of the converter system for the PV utilization during the real time operation to optimum parameter selection, and then adjusting them so that the system will have a much faster response. The system can then meet the MPP quickly.

- *Perturbation and observation (P&O) method*

The P&O algorithm is the most commonly used MPPT algorithm. It utilizes the values of the input current and voltage to calculate the power. The values of voltage and power at the k^{th} iteration (P_k) are stored. Then, the same values are measured and calculated for the $(k+1)^{th}$ iteration (P_{k+1}). The difference between P_{k+1} and P_k (ΔP) is then calculated. Inspecting the power-voltage curve, we can see that the slope of the power curve (dP/dV) at the right hand side of the MPPT is negative. Moreover, dP/dV will be positive at the left hand side of the MPPT, while this slope will be zero right at the maximum power point. Finally, depending on the observation of the sign of ΔP and ΔV, the algorithm will decide whether the duty cycle is to be increased or decreased.

4. DESIGN OF BATTERY SYSTEM

In this section the size of the battery bank will be selected and the design of the battery charger will be provided. The battery bank will be built with the commercially available lead-acid 12V batteries. For battery sizing there's a procedure which was presented in literature, with the necessary modifications and improvements, it can be adopted to suit the system understudy. The first step is to choose the minimum and maximum voltage for the proper operation if the loads, for most of the home appliances the voltage range is ±10%. The second step is to calculate the voltage drop between the battery and the load, which Can be given as:

In DC side:

$$\Delta V_{DC} = I_{DC} * R$$

In AC side:

$$\Delta V_{AC} = VDF * I_{AC} * D$$

Where ΔV_{DC} is the voltage drop in the DC side, I_{DC} is the DC current, R is the cable resistance, ΔV_{AC} is the voltage drop in the AC side, VDF is a drop voltage factor which is given by the cable manufacturer, I_{AC} is the AC current and D is the distance between the battery and load (cable length).

$$\Delta V = \Delta V_{DC} + \Delta V_{AC}$$

This step yields a total voltage drop of 0.87 V. The number of the cells connected in series:

$$n = \frac{V_{\max} + \Delta V}{V_Z}$$

Where V_{max} is the maximum permitted continous (110% here), ΔV is the voltage drop, V_Z maximum trickle-charge voltage per cell. Trickle charging voltage refers to the voltage required to charge a fully charged battery under no-load at rate equal to its self discharging rate. This value ranges from 2.15-2.23 V per cell. By subsitituting with 2.23V as a trickle-charge voltage, we get the number of cells to be connected in series equals 24, given that each battery has 6 cells, so the number of batteries connected in series is 4 batteries.

The choice of the battery type depends on the discharge time and cutoff voltage, the selected battery chould be capable of providing current -at the the discharge time and cutoff voltage- higher than the total load current. The battery chosen here has 12 V and capacity of 17Ah. The discharge characteristics of the chosen battery are given in Figure 4.

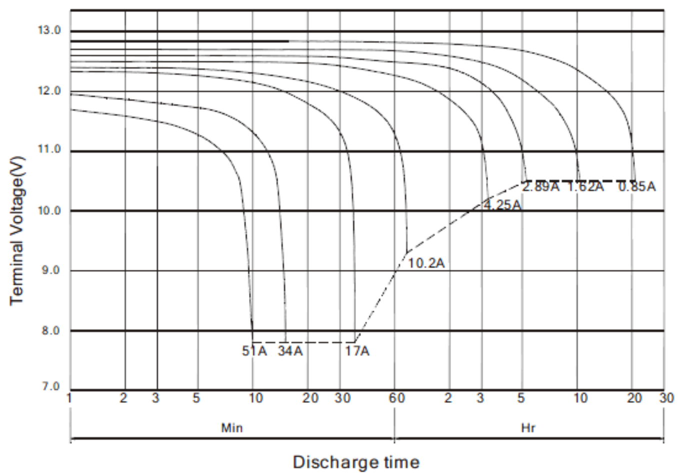

Figure 4: Battery discharge characteristics

It can be seen from figure 5 that the battery can provide current of 0.85A continously for 20 hours with final voltage drop 1 Volt. Then number of batteries connected in parallel can be given by:

$$N_P = \frac{S.f * L_{avg}}{V_n * I_{Batt}}$$

Where $S.f$ is a safety factor which is selected here as 1.15, L_{avg} is the average demand, V_n is the nominal voltage, I_{Batt} is the battery discharging current.This gives 30 batteries, the total number of batteries is 120 battery. For the battery charger, it was selected form the available chargers in the market (data sheets and websites are listed in reference section). The charger is capable of chraging lead-acid battery banks with 48 V and current up to 30 Amps and it's DC-DC, so it's suitable for this application.

5. ENERGY MANAGEMENT SYSTEM

Integrating PV systems to the utility through inverters or with energy storage systems gives rise to imperative necessity towards using more efficient energy management systems (EMS). Better utilization of renewable energy sources can be achieved if the available power from these sources can be accurately predicted over futuristic periods. EMS can be developed based on forecasting of the next hour solar radiation depending on historical data. This can be done easily using artificial neural networks (ANN). Based on the historical records of solar radiation the available power from the solar panels for next period of time can be calculated, then it can be used to optimize the control of the inverter. An artificial neural network (ANN) is an information processing model that is inspired by the biological nervous systems, it processes information in the same way as the human brain. In general neural networks can be expressed as a mathematical model designed to accomplish a variety of tasks. Untrained ANN is like a new born child, it has to learn by example and it does what it is trained to do. So, the training process should be done very carefully because it has a significant impact on the output.

Good training of ANN requires large amounts of historical data sets to help the network to recognize different data patterns. Increasing the training data sets increases the probability of containing noisy data. This may result into not only a bigger network model and longer training time but also more forecasting inaccuracy, as the network may fail to capture the true features in the data. These reasons give rise to the need of robust data filtering, wavelet transform can be a powerful tool for this application.

Wavelet transforms has gained much attention recently as it has been adopted in many applications. Its impressive frequency isolation features become good incentives for researchers to use them in the area of electric power systems. In this work, wavelet filter is used to smooth the training data, which is used to train the artificial neural network (ANN) to forecast the solar radiation. This means that the wavelet filter is introduced as a preliminary stage to filter the data fed into the training stage.

Time series (indices) are created to let the network capture weather trends, the first index is for the hour of the day, second one is for the day of the month and the third is for the month of the year. The gathered data used for training the hourly records for two years (2008 & 2009) and it's desired to forecast the load for the first five days of 2010 (120 hours). After all, the training matrix will be [3×17544]. Analysis of historical solar data showed that each day hour has its own distinct characteristics. For example, the hour 7:00 PM in summer, the sun still in the sky and there's a value for solar radiation but in winter it's completely dark and the solar radiation will equal to zero. Hence, one ANN will be used to forecast the load for each hour i.e. 18 neural networks will be required for predicting the solar radiation. There are six hours at night which have zero solar radiation all the year, so they are excluded from the forecasting process. This procedure is called "separate hour forecasting" . The forecasting results are shown in figure 5. It is shown that the neural network can track the sudden and rapid changes in the solar radiation, the forecasted wind curve is very close to the actual wind curve, which confirms the high predictability of the system. It is clear that the neural network forecasts the solar radiation with high accuracy and follows closely the solar profile.

An exception will be at the marked point, at these days the solar radiation was very low for unexpected reason. The most reasonable explanation for the decreased solar radiation is a temporary dense cloud cover.

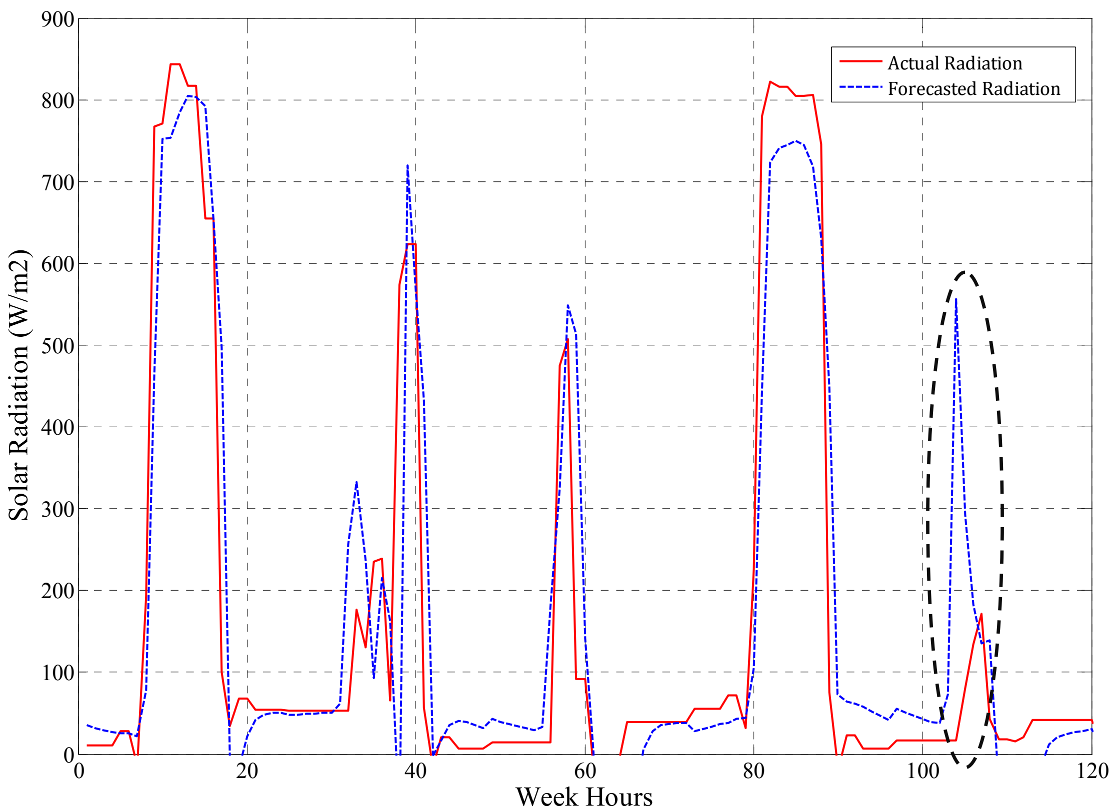

Fig. 5. Forecasted versus measured solar radiation.

The main purpose of the forecasting in this work is to serve the energy management system, so obtained forecasts will be integrated to the system control to achieve better system management. The VSI has the capability of receiving reference values for active as well as reactive power and hence will play a role in the control of the power flow. The available power from PV will be calculated based on the forecasted solar radiation, then it will be passed with the forecasted load value to the supervisory controller. The controller will calculate the suitable reference signal and send it to the bi-directional VSI. In turn, the VSI will control the amount and direction of power flow from the main grid to the house or vice versa.

6. CONCLUSION

In this paper, the design and energy management of a grid-connected PV system for redential applications were presented. Firstly, a comprehensive and simple procedure for designing the PV system was provided. The design was based on commercially available equipments. The total consumption of a typical house was estimated. The number of required PV modules was calculated based on load eastimation. A battery bank was used to supply the load at night. The number of batteries connected in series and in parallel were determeined. The design was carried out with taking into consideration the minimization of the total cost. Secondly, an energy management scheme was developed to optimize the energy utilization in the system. This management scheme was based on an ANN forecasting element that was used to quantify the estmited available energy from the PV.

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