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Modeling and Sizing of the Standalone PV with Battery Systems

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ABSTRACT
Photovoltaic (PV) is one of the most prime source to generate electricity without causing harm to the environment. V is used to convert the sunlight to electricity that is required in many applications. For example, to run household appliance in case of power failure, or in peak condition to reduce loads on the grid.

In this paper, off- grid PV system is modeled and designed to meet some of household appliances for a home located in Zagazig city. This system can be applied for large systems, as it is designed to supply linear and non-linear loads. The applied system is used load estimation calculations to find out the system sizing (PV array, and inverter), and with the help of Matlab-Simulink the behavior of solar PV array, Perturb and Observe (P&O) max power point algorithm, boost converter, battery, and full bridge inverter with PLL control method and linear transformer can be studied easily under different condition.

Keywords - Load Estimation, Off Grid System, PV Sizing, DC-DC Converter, DC-AC Inverter, Battery.

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I. INTRODUCTION

Electricity plays an important role in our life. It is the basic source, which is used to feed the different loads. Over time, and due to the development of technology, the use of electricity has become increasing. Hence, it was necessary to establish new power stations to meet the new and future loads.

The tradition grid is known as one way power flow, it often uses sources that adversely affect the environment in addition to its high cost. But the new outlook is heading towards the creation of smart grid (S.G). Smart grid is two way power flows; it is characterized by the possibility of establishing it near the consumers. It is also characterized as safe, clean, high efficient, and use renewable sources. The connected loads can directly supply from S.G, or from distributed generator (D.G). D.G is located near the customers, so it should use clean sources to generate electricity as solar panels and wind turbines. It is linked with the loads which can connect and disconnect from the grid [1].

Figure 1, shows the Simulink design of off grid PV system connected to supply different types of loads (linear, and non-linear). This system consists of PV arrays, perturb and observe (P&O) maximum power point algorithm, boost dc-dc converter, battery, and full bridge dc-ac inverter with a control unit phase lock loop (PLL), which tracks and determines the frequency and phase of a sinusoidal signal by using an internal frequency oscillator to adjust phase's difference to 0, and linear transformer to get pure wave to loads.

This document handles the required steps to design a perfect system, which can efficiently run under different loads and condition. This design is important especially for remote areas, which characterized by low electricity or electricity is constantly cut off. The studying case is for a house located in Zagazig city.

II. LOAD ESTIMATION CALCULATION

Load estimation is very important to evaluate the system size and find out the suitable appropriate values for voltage and current, which is required for selecting PV array and inverter.

Previously, it has been mentioned that the system that will be studied will be on a house in Zagazig, which houses two persons over 100 m2. **Table 1**, shows all household's electrical devices with their power and operating time, but the design is made for some loads that should be run at power off or at peak times. This table is considered the first step to find the exact specification for PV solar panel, inverter, and converter [2].

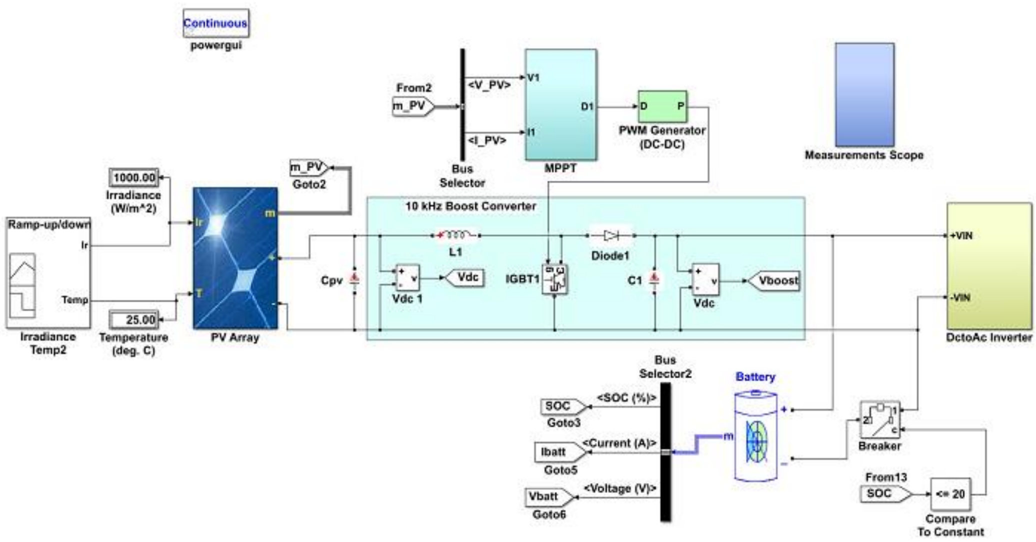

Figure 1. Simulation of Total System

Table 1: Total Home Load Estimation Data

Load	Quantity	Watt	Total Watt	Hr/Day	Watt*Hr
Ceiling Fan	4	72	288	6	1728
Lighting	12	18	216	8	1728
Led Lamps	23	12	276	3	828
Refrigerator	1	68	68	12	816
Broom	1	1800	1800	0.5	900
Television	1	128	128	3	384
Washing Machine	2	450	900	1	900
Blender	2	450	900	0.5	450
Heater	1	1800	1800	1	1800
Radio	1	4.4	4.4	3	13.2
Total			6380.4		9547.2

III. MODELING AND SIZING THE SYSTEM

II.1 Inverter Modelling and Sizing

Inverter is used to convert dc output from dc-dc converter or directly from PV panel to ac wave that is required to supply ac appliances or to back it into the grid. It should be sized according to total power, but for safety and wiring system losses [3]

$$P|_{Inverter} \geq (25-30)\%\, P|_{Total} \qquad (1)$$

Figure 2, shows single phase inverter modeling with linear transformer, which used to protect the circuit from fast response especially in case of nonlinear load, it can also filter the output from high frequency. Both of inductance (L) and capacitance (C) is used as additional filter to enhance output waves. Inductance (L) can be calculated from its relation with ripple current, and it should be selected in a range (15-25) % of the rated current, the following equations can find out the values of inductance (L) and capacitance (C) [4].

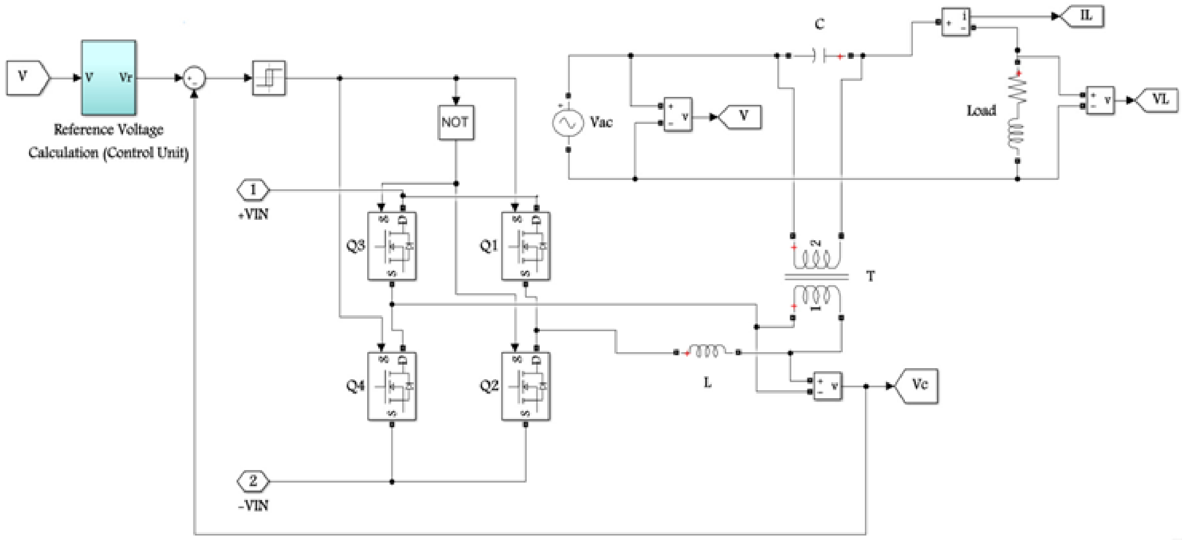

Figure 2. Inverter Simulation with Linear Transformer and Control Unit

1. Calculate ripple current as the following:

$$I_{ripple} = 1.25 \times I_{rated} \quad (2)$$

2. Calculate inductance (L) from its relation with ripple current:

$$I_{ripple} = \left(\frac{E_d}{4Lf_c}\right) \quad (3)$$

Where, Ed is the maximum input voltage, and Fc is cut off frequency.

3. Calculate capacitance (C) from its relation with cut-of frequency :

$$C = \left(\frac{1}{L(2\pi f_c)^2}\right) \quad (4)$$

However using LC filter, the output voltage may be distorted due to the transformer saturation. So a control method must be applied to ensure that the voltage values will not exceed the maximum value, and make it more stable, as shown in **Figure 3**.

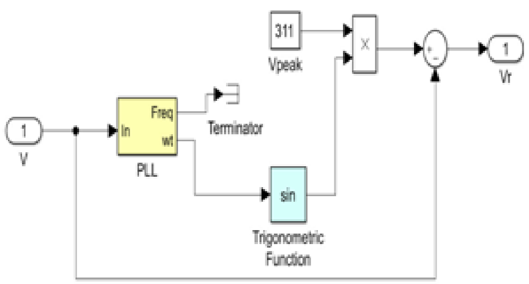

Figure 3. Simulation of Voltage Control Subsystem

II.2 PV Solar Panel Sizing and Modeling

Photovoltaic cells are used to generate electricity without environmental impact. Both of sizing and Modeling is very important to avoid under sizing and to study the characteristics and behavior of solar cell.

A. PV Mathematical Model

This section handles the equivalent equations for a single diode model with numbers of series cells NS and parallel strings NP, as shown in **Figure 4**.

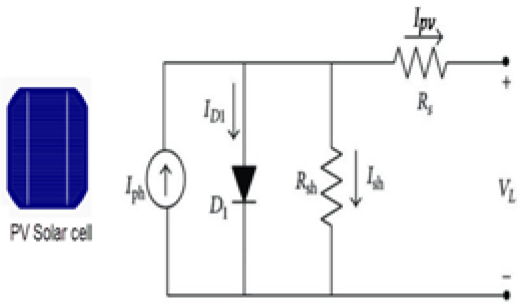

Figure 4. Equivalent Circuit for Single Diode Solar Cell

The relation between output current and output voltage can be calculated from the following equations [5]:

1. Calculate output current IPV:

$$I_{PV} = I_{Ph} - I_d \quad (5)$$

Where, IPV is the output current, I_{Ph} is photocurrent in PV module, Id is diode current.

2. Calculate the generated current from sun light:

$$I_{Ph} = \left(I_{scr} + K_i(T - Tr)\right) \times \left(\frac{G}{1000}\right) \quad (6)$$

Where, I_{SCr} is the short circuit current under Standard Test Condition, , K_i is the short circuit current coefficient, T is the operating module temperature in Kelvin, T_r is the reference Temperature in Kelvin, and G is the illumination of PV module.

3. Calculate the diode current:

(7)

Where, I_O is the saturation current in PV module, and q is the electron charge (q=1.6×10-19).

The saturation current (I_O) of PV module equation is given by:

$$I_o = I_r.\left(\frac{T}{T_r}\right)^3 . exp\left(\frac{q.E_g}{K.A}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right) \quad (8)$$

Where, Ir is the reverse saturation current, K is the boltzman constant (k=1.3805× 10-23) J/K, A is the ideality factor, and Eg is the band gap voltage.

And the reverse saturation current is given by:

$$I_r = \frac{I_{scr}}{exp\left[\frac{q.V_{oc}}{K.A.T.N_s}\right] - 1} \quad (9)$$

Where, V_{OC} is the open circuit voltage, and N_S is the numbers of series cells.

From all above equation, the PV module output current can be easily calculated from the next equation:

$$I_{PV} = N_P.I_{Ph} - N_P.I_d \quad (10)$$

Where, N_P is the number of parallel cells.

If R_{Sh} is included in the circuit, the output current will be:

$$I_{PV} = N_P.I_{Ph} - N_P.I_d - N_P.I_{Sh} \quad (11)$$

Where, I_{Sh} is the current flow through shunt resistance.

Finally the relation between output current and output voltage can be calculated from:

$$I_{PV} = N_P.I_{Ph} - N_P.I_d - N_P.\left(\frac{V - I_{PV} \times R_s}{R_{Sh}}\right) \quad (12)$$

Where, R_S and R_{Sh} are the series and the shunt resistances of solar cell respectively, and V is the output PV module voltage.

B. PV Simulation Model

There are different methods to simulate PV array. One of them is using MATLAB/ Simulink to design and simulate PV solar cell by equations (5) - (12). In this paper, a PV array block is used. This block is characterized by ease of use, as shown in **Figure 5**. By selecting number both of series and parallel string and the module type, the PV array will be ready to be used in the model.

The following equations are the steps that used to calculate PV parameters [6]:

1. Calculate Average Energy [Ea]

$$[Ea] = \frac{Daily\ Average\ Energy}{\eta_{over\ all}} \quad (13)$$

2. Calculate Peak Power [Pp]

$$[Pp] = \frac{E_r}{T_{min}(Minimum\ time\ for\ sun\ brightness)} \quad (14)$$

3. Total Current needed [Itot]

$$[Itot] = \frac{P_P}{V_{PV\ total\ System}} \quad (15)$$

4. No. of Parallel Modules [Np]

$$[Np] = \frac{I_{tot}}{I_{Module\ Rated}} \quad (16)$$

5. No. of Series Modules [NS]

$$[NS] = \frac{V_{PV\ total\ System}}{V_{Module\ Rated}} \quad (17)$$

The selecting parameters of **Figure 5**, depend on loads with total average energy ≅ 3100 Wh, overall efficiency 0.8, and 147 V for total PV system.

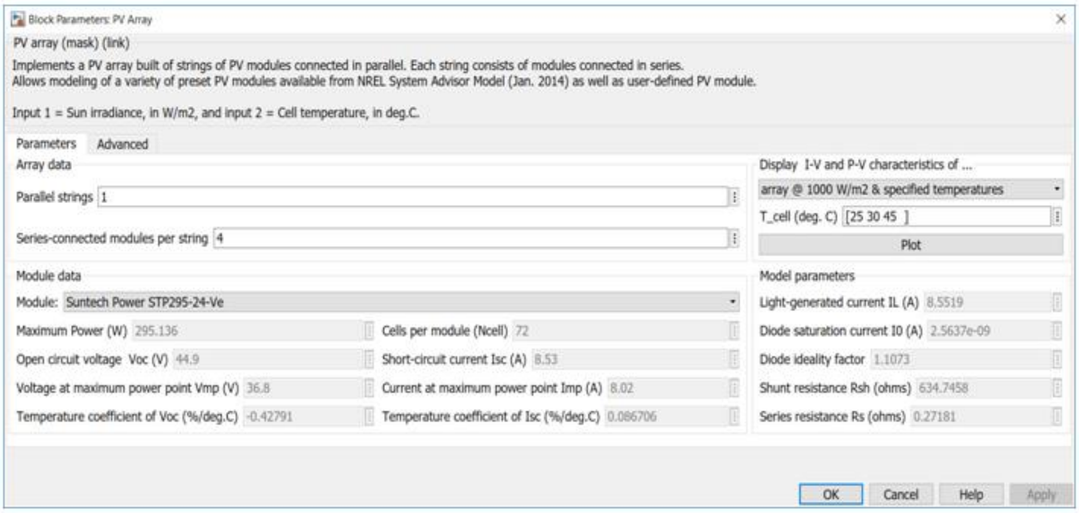

Figure 5. PV Array Block Parameters

IV. DC-DC CONVERTER PARAMETERS CALCULATION AND MODELING

Dc-Dc converter is used to converter the input dc voltage to another value output dc voltage; it is divided into buck (step-down) converter, boost (step-up) converter, buck-boost converter, and c` uk converter. In this module, a step up (boost) converter is used, which connect to Maximum Power Point Tracking (MPPT) algorithm to change the duty cycle of dc-dc converter, as shown in **Figure 6.**

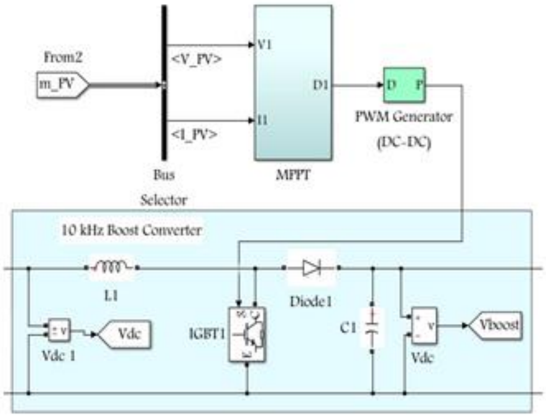

Figure 6. Simulation of Boost Converter Connected to MPPT Subsystem

To specify the values of boost converter parameter, the following equations [7]:

$$A_V = \left(\frac{V_o}{V_{in}}\right) = \left(\frac{1}{1-D}\right) = \left(\frac{240}{147}\right) \qquad (17)$$

Where, V_o is the output voltage of converter, Vin is the input voltage to converter or the output voltage of PV array, and D is the converter duty cycle.

$$L_{min} = \left(\frac{(1-D)^2 \times D\, R_L}{2 f_c}\right) \qquad (18)$$

Where, R_L is the load impedance, and Lmin is the minimum converter inductance.

$$C_{min} = \left(\frac{V_o}{V_r R_L f_c}\right) \qquad (19)$$

Where, Vr is the peak ripple of output voltage, and Cmin is the minimum converter capacitance.

V. MAXIMUM POWER POINT TRACKING (MPPT)

Figure 7, shows that PV has non-linear characteristics, so it is necessary to track the point where the PV module can operate always at its maximum value under different condition to reduce the maximum amount of wasted energy. MPPT is a control method that can track the voltage and current from solar module to compare the values with each other to detect the maximum value for voltage and current in the same moment.

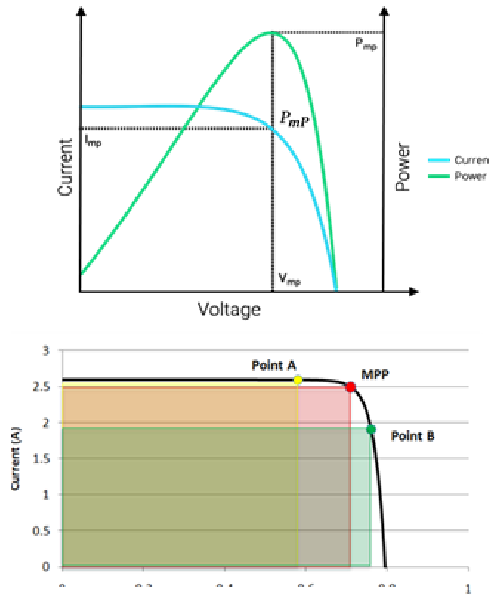

Figure 7. PV Array Characteristics

MPPT can use different algorithms, these algorithms differ in many points as effectiveness, cost, the ease of application, and sensor [8].

In this paper Perturb and Observe (P&O) technique is used. **Figure 6**, shows the connection of MPPT system. It use sensors to measure voltage and current of PV array to calculate power at a specific duty cycle, and by changing the value of duty cycle of power converter by adding and subtracting a random small values from duty cycle and detecting the value of power, then MPP can be obtained as shown in **Figure 8**. The algorithm concept of P&O is shown in **Figure 9** [9].

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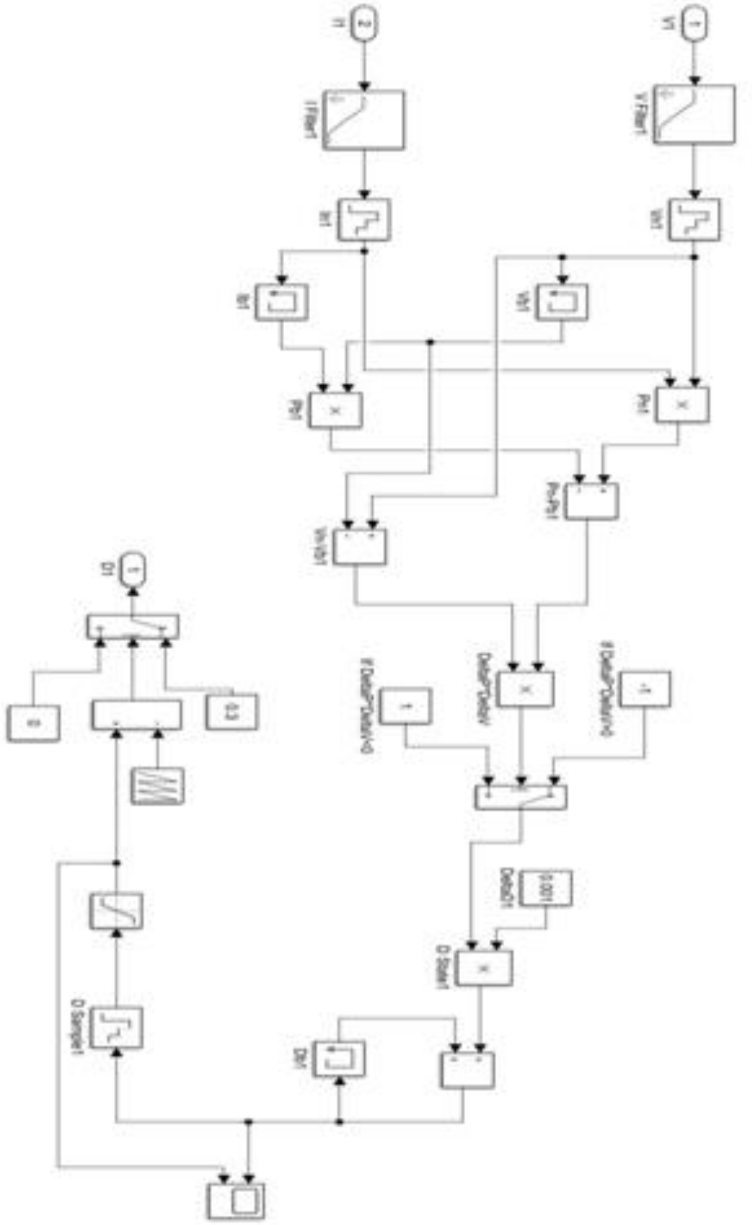

Figure 8. P&O MPPT Subsystem

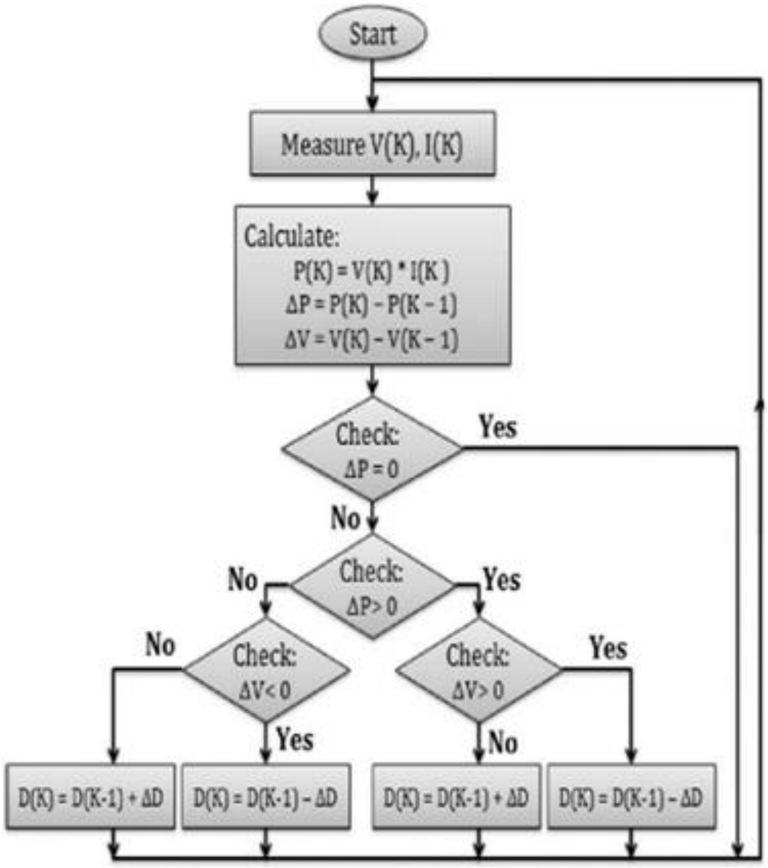

Figure 9. P&O Algorithm [9]

VI. STORAGE SYSTEM

Batteries are very important units that are used to store electric energy and use it when needed. These batteries can be used in this system to supply the connected loads in case of power outage, or in dark days, or at night, or when the sun radiation is not enough. It work as a backup power source during night or during difficult weather conditions. It is charging from the PV array and discharge while there is no power from PV. It should be sized to store energy for specified days or for one night at least [10].

There are some factors should be considered during battery selection, as the following:

1. Long life time.
2. Low cost.
3. High efficiency.
4. Low discharge.
5. Low maintenance.

V.1 Batteries Types

There are many kinds of batteries, but most commonly types that are used in PV system are shown in **Table 2**, this table also shows the main differences between them.

From **Table 2**, lead-acid batteries are the convenient type that can be used in stand-alone PV system.

V.2 Battery Parameters

The battery selection depends on some parameters, which includes nominal voltage (V), rated capacity (Ah), initial state of charge (%), and battery response time. **Figure 10**, shows a lithium-ion battery type which is connected to boost converter. This battery uses a breaker to disconnect when state of charge (SOC) is less than 20% to separate from supplying the loads.

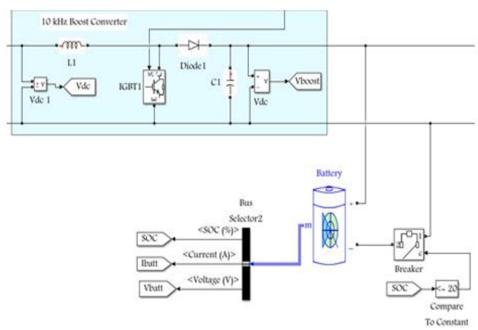

Figure 10. DC Battery Connection Simulation

VII. SYSTEM DESIGN ANALYSIS AND RESULTS

In this section, the parameters selection and the simulation results are discussed. This simulation involves the stability of the stand-alone PV system under different conditions, which is designed to meet linear and non-linear loads.

Table 2: Comparison between Different Types of Batteries

Battery Type	Advantage	Disadvantage
Lead-Acid	1. Low cost 2. Easy transfer 3. High efficiency 4. Low maintenance	Short life time
Nickel-Cadmium (Ni-Cd)	1. Long life time 2. High efficiency 3. High energy 4. Low self-discharge	High cost
Nickel-Metal Hydride (Ni-MH)	1. Long life time 2. High energy	1. High cost 2. Low efficiency 3. High self-discharge
Lithium ion (Li-ion)	1. Long life time 2. High energy	1. High cost 2. High damage during overcharging
Lithium Polymer	1. Long life time 2. High energy	1. High cost 2. Low safety

VI.1 Model Description

Stand-alone system uses PV array of SUNTECH STP295-24-Ve with 4 series modules per string and 1 parallel strings to provide 1KW, DC-DC boost converter with a dc link capacitor of 1.11e-6 F, a filter inductance of 15e-2 H, and a filter capacitance of 6e-4 F. MPPT technique is used to control the duty cycle of converter. The output of converter is connected to Dc-Ac inverter which is connected to non-linear load with 200 W, 100 VAR, and 220 V. The overall system runs at a typical frequency of 10KHZ, and 1% percentage ripple in output voltage.

VI.2 Simulation Results

This section shows the simulation results for the system. Both of **Figure 11**, and **Figure 12** show PV Array Characteristic under changing temperature at different values.

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Figure 13, shows that the dc link capacitor (C_{PV}) keep the output voltage of PV array at a constant value. **Error! Reference source not found.** 14, shows the output voltage of boost converter. Finally **Figure 15** and **Figure 16**, show the output voltage and current of the connected load.

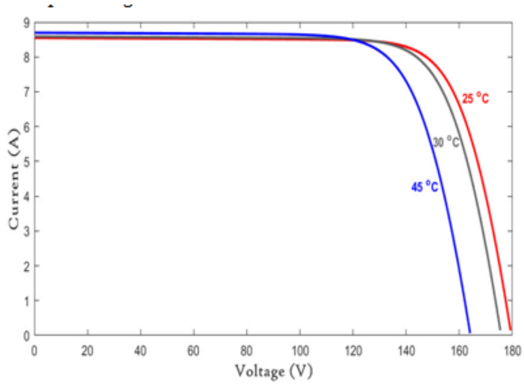

Figure 11. Voltage- Current PV Array Characteristic

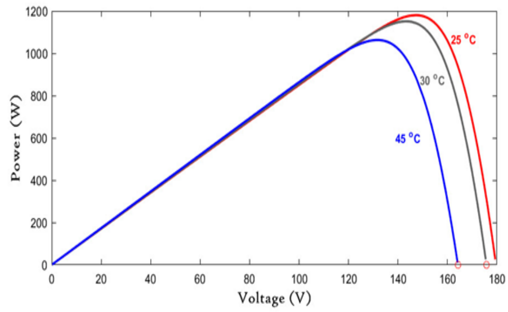

Figure 12. Voltage- Power PV Array Characteristic

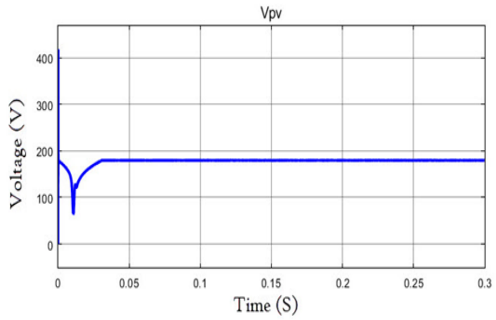

Figure 13. The output Voltage of Dc-Link Capacitor

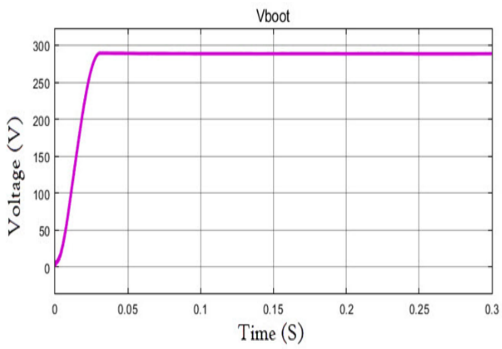

Figure 14. The output Voltage of Dc-Dc Boost Converter

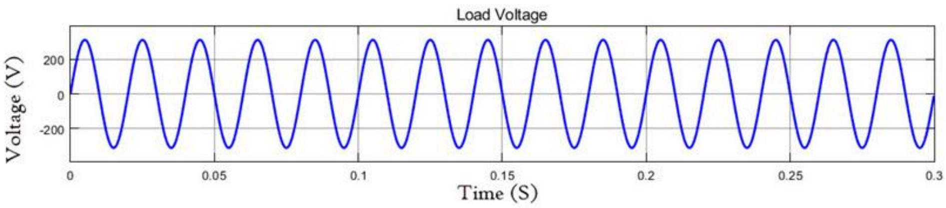

Figure 15. The Output Voltage of Non-Linear Load

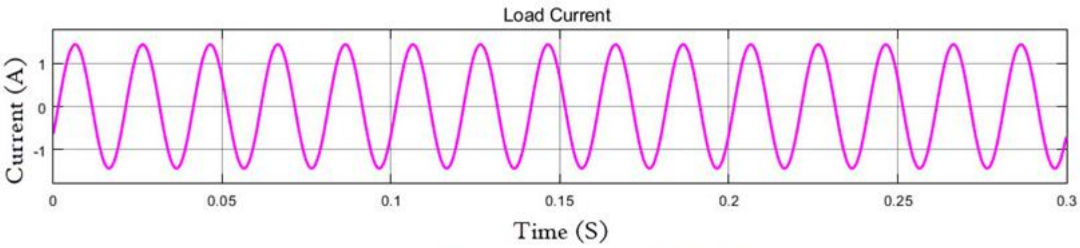

Figure 16. The Output Current of Non-Linear Load

Appendix [1]

SUNTECH STP295-24/Ve PV module electrical characteristics at STC: irradiance 1000 W/m2, module temperature 25 °C, AM=1.5	
Maximum power (Pmax)	295 W
Optimum operating voltage (Vmp)	35.6 V
Optimum operating current (Imp)	8.29 A
Open circuit voltage (Voc)	44.3 V
Short circuit current (Isc)	8.74 A

VIII. CONCLUSION

This work represents the modeling of standalone PV system. This system is designed and modeled using MATLAB/SIMULINK to meet some of household for a house located in Zagazig city. This model is very important to be used for remote and rural areas; also it's a good design for running different loads when power is outage or at night. It consist of PV SUNTECH STP295-24/Ve model with a P&O MPPT algorithm to control a boost dc-dc converter PWM. The system also includes dc-ac single phase full bridge inverter connected to PLL control system to ensure pure wave.

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