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Grid-Connected Photovoltaic System: System Overview and Sizing Principles

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***Abstract*—**The optimal size of a photovoltaic (PV) array is considered a critical factor in designing an efficient PV system due to the dependence of the PV cell performance on temperature. A high temperature can lead to voltage losses of solar panels, whereas a low temperature can cause voltage overproduction. There are two possible scenarios of the inverter's operation in which they are associated with the erroneous calculations of the number of PV panels: 1) If the number of the panels is scant and the temperature is high, the minimum voltage required to operate the inverter will not be reached. As a result, the inverter will shut down. 2) Comparably, if the number of panels is excessive and the temperature is low, the produced voltage will be more than the maximum limit of the inverter which can cause the inverter to get disconnected or even damaged. This article aims to assess theoretical and practical methodologies to calculate size and determine the topology of a PV array. The results are validated by applying an experimental evaluation for a 100 kW Grid-connected PV system for a location in Halifax, Nova Scotia and achieving a satisfactory system performance compared to the previous work done.

***Keywords*—**Sizing PV panels, grid-connected PV, topology of PV array, theoretical and practical methodologies.

I. Introduction

PV solar energy is constantly growing where its developments are globally attracting large investments, which lead to a huge leap forward for solar industry. PV grid-connected systems of different sizes and power ratings have been proposed and developed in the literature. They are categorized in three groups: small scale (watts to tens of kW), medium-scale (tens of kW to a few hundreds kW), large-scale (hundreds of kW to several hundreds of MW) [1]-[8]. These systems include PV arrays, DC-DC converter, maximum power point tracking (MPPT) controller, inverter, Voltage Source Converter (VSC) and grid connection equipment. In grid connecting system, the voltage produced by the PV-array system is increased by using a DC-DC boost converter and then supplied to a 3-phase inverter that will be controlled by a VSC. A block diagram depicts this system in Fig. 1.

A. PV System

A PV cell is the fundamental element in a solar PV system. Solar cells consist of semiconducting materials that have their unique physical and chemical properties of allowing sunlight to directly convert to electricity. The process by which solar energy is converted to electricity is known as the PV effect. To create a PV module which is mutually understood as a PV panel, a number of solar cells are connected in series or parallel. To compose a PV string, PV panels are connected in series which are then connected in parallel to create a PV array. Thus, an array is a number of PV strings wired in parallel while a string is a number of PV panels wired in series. The total DC output power produced from solar arrays is continuously varying with varying environmental conditions. The output power can be used for several applications, to store electricity in batteries, supply DC loads, supply an inverter to provide AC voltage for residential, institutional, commercial buildings, or inject it to an electric utility grid. Mathematical modeling is used to assess the behavior of solar cells under standard test conditions (STC). Under this standard, a cell temperature of 25 ◦C and solar insolation of 1 kW/m^2 has been specified. The practical PV cell modeling including the series and parallel (shunt) resistances has been proposed in the literature where different parameters such as solar irradiation, temperature, series resistance and shunt resistance can affect the characteristics of V-1 and V-P curves of the solar panels [9]-[11].

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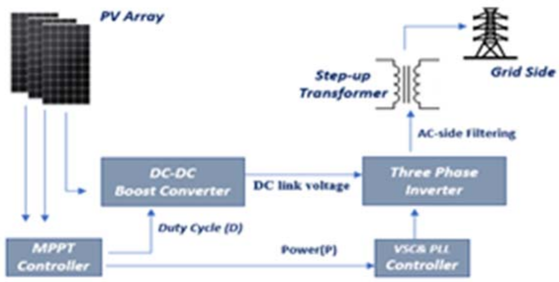

Fig. 1 Grid connected PV system

B. DC-DC Boost Converter and MPPT Controller

The output from a PV array is used as input to a DC-DC boost converter whose intent is to boost and regulate the DC link voltage which will be fed to the inverter. This could also remedy the output of the inverter. In order to provide maximum power available to a load or grid, it is imperative to run at Maximum Power Point (MPP). A maximum power point tracking (MPPT) algorithm can be applied to achieve two goals i.e. 1) maintain a constant DC voltage being supplied to inverter and 2) ensure that the PV operates at MPP using a DC/DC boost converter controlled by MMPT algorithms. In literature, many such algorithms have been established and compared [3], [5], [12], [13]. By taking in consideration the sensitivity of boost converter to changes in its duty cycle (D) with the input voltage (V_{in}) and output voltage (V_{out}) in question (1), a boost converter whose duty cycle (D) can be modified by employing a MPPT algorithm. In order to extract maximum power from a PV array, and maintain a constant DC link voltage, D is modified by the MPPT controller.

$$V_{out} = (\frac{1}{1-D})V_{in} \quad (1)$$

C. VSC Inverter

The output of the PV panels is DC current and voltage. Yet, DC output cannot be supplied to the grid. Instead a three phase AC current and voltage are required. In this respect a VSC is applied to maintain unity power factor as well as fix the DC link voltage. The underlying principle behind a VSC controller system is same as dq current controller. It consists of two loops which are an external control loop used to fix the DC link voltage, and an internal control loop applied to control the grid's active and reactive current. The dq transformation which is in fact known as the park's transformation changes the time-domain components of a three-phase system to direct, quadrature and zero components [14].

D. Voltage Controller

In order to minimize and control the error between measured DC link voltage and reference DC link voltage, a Proportional Integral (PI) controller can be applied. The resulting error is then delivered to PI to generate the proportional direct axis current (I_d) that will be considered as reference current for the current controller. To guarantee operating at unity power factor, the proportional quadrature axis current (I_q) is set to zero. The output of PI controller is then utilized to maintain and control the output of the active current from the inverter by controlling the d-axis components [3], [6].

E. Phase Lock Loop and Current Controller

Phase Lock Loop (PLL) is utilized to evaluate the main grid phase and accordingly manage the Pulse-width modulation (PWM) input for inverter. In PLL, the dq transformation is used to the points of measurements for the three-phase current and voltage of the grid side. In current controller, the reference I_{dq} and measured I_{dq} currents are compared, the error is supplied to the PI regulator. The error current will be converted to two components of voltage (V_d, V_q) by PI regulator. The output of the LPP (I_{dq}, V_{dq}) and voltage output of the current controller are transformed by Clarke transformation to a three-phase modulating signals. Further details of the entire VSC control structure are reported in literature [3], [5], [6], [14], [15]. A low pass filter is used to filter high frequency harmonics produced by the inverter.

II. PV Array Sizing

Sizing PV array is the basis for designing an efficient PV system. The sizing of PV system depends on many factors including the efficiency of PV module, the amount of money, area available, and the type of application and functional requirements. The output power generation of the designed PV system could be then estimated based on local solar radiation and weather data. In a grid connected system, the sizing exercise is a crucial step to determine the type, size, and the power rating of the inverter through which the inverter could be operated safely and efficiently. The inverter converts the DC electricity produced by the PV arrays to AC which is then delivered to the utility grid. The inverter must approach the capability to handle all power generated by the PV arrays. In this section, we will dissect the effect of the solar irradiation, ambient temperature on the performance of three critical parameters of PV panels, namely short circuit current (I_{sc}), open circuit voltage (V_{oc}), and Maximum Power (P_m) and consequently on the invert functionality. The cell acts more like a current source than a voltage source as shown in Fig. 2.

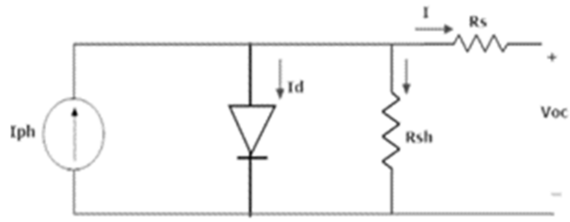

Fig. 1 The equivalent circuit *of PV* cell

A. Solar Irradiation effect on I_{sc} and V_{oc}

From Fig. 2, we can obtain:

$$I = I_{ph} - I_d - I_{Rh}$$
$$I = I_{ph} - I_s\left[exp\frac{q(V+R_sI)}{nKT} - 1\right] - \frac{V+R_sI}{R_{sh}} \quad (2)$$

where I_{ph}: photogenerated current, I_s: the reverse saturation current, n: the ideality factor, K: the Boltzmann constant, q: electron's charge, R_s: the series resistance, R_{sh}: the shunt resistance, T: the temperature of the cell in kelvin.

- In the short circuit condition $V = 0, I = I_{sc}$ and we consider ideally PV cell ($R_s \ll R_{sh}$), so $R_s = 0$ is negligible. From (2), we can obtain $I_{sc} = I_{ph}$ which is *linear* equation of a *proportional relationship* between I_{sc} and solar irradiation.
- In open circuit condition $V = V_{oc}, I = 0, R_{sh} \gg V_{oc}$, so from (2) we obtain: $V_{oc} = \frac{nKT}{q}\ln(\frac{I_{ph}+I_s}{I_s})$

TABLE I
ELECTRICAL SPECIFICATIONS FOR LG 320W PV MODULE

Number of cells	60
Maximum Power (Pmax)	320
Maximum Power Voltage (Vmp)	33.3
Maximum Power Current (Imp)	9.62
Open circuit Voltage (Voc)	40.8
Short-circuit Current (Isc)	10.19
Temperature Characteristics	
Temperature coefficient of Pmax	-0.37%/C°
Temperature coefficient of Isc	0.03%/C°
Temperature coefficient of Voc	-0.27%/C°

So V_{oc} increases in logarithmic manner with the increase of the solar irradiation. Thus, with variation of solar irradiation, the I_{sc} of the PV cell linearly increases while the V_{oc} logarithmically increases [16], [17].

B. Ambient Temperature Effect on I_{sc} and V_{oc}

Information on temperature coefficients can be found in PV module datasheets. Those coefficients are required when deciding the size of PV system and they indicate the behavior of three important parameters with changing temperature. According to literature [18], the V_{oc} decreases when temperature is increases since I_s depends on temperature. Equation (3) indicates that a rise in temperature decreases the band gap energy of semiconductors:

$$I_s = A * \exp(\frac{-q*E_g}{KT}) \quad (3)$$

where (E_g) indicates the band gap of a semiconductor in electron volts units. A is constant with a value of $1.5 * 10^8$. Decreased band gap energy means that there are more photons with enough energy and hence increase in photocurrent I_{ph} while I_{sc} minutely increase with increasing temperature. This information is useful to determine the size of PV array and design grid-connected PV system taking in consideration the inverter's maximum and minimum operating voltages. The aim is to model a system in which the DC voltage generated sustains within the voltage range. The crucial factor is temperature. A high ambient temperature warms the solar cells which will adversely affect the voltage production, while low ambient temperature can lead to overproduction of voltage. Inverter can shut down if not supplied with minimum voltage due to high ambient temperature. In the same manner, going beyond the maximum voltage input because of lower temperature, the inverter can go offline and possibly suffering damage [19]. It should also be ensured that inverter's MPPT window span covers the maximum and minimum output voltage of solar array. In order for the inverter to function properly, the minimum output voltage generated by the solar array should not be less than the minimum input voltage of the inverter. Likewise, to avoid damage to inverter, the maximum output voltage of a solar array must not exceed the maximum input voltage of the inverter.

III. System Description

A step-by-step overview will be performed for the process used to determine the size of grid-connected PV system. For simulation purposes, a 100 kW grid-connected PV system will be considered to examine the suggested approaches, ensure supply a voltage that falls within the invert's operating range and ultimately deliver active power of 100 kW to the grid side. Note that, we will not consider the restriction imposed by budget and area to design the system. LG 320W solar PV module is used; electrical specifications for the (LG320N1K-A5) module are listed in Table I.

IV. Approaches for Calculating Array Size

A. Theoretical Method

Electrical utilities are purposed to serve the customers at a specific voltage level. For example, in North America, this voltage is set to 114-126 V and frequency is set to 60 Hz. However, the magnitude of voltage supplied to customers will differ with the length of the distribution feeder. Voltage regulation in transmission line is needed because of the impedance of the line between its sending and receiving ends. Legal and local practices can dictate such acceptances. Actual service voltage falling within tolerance of ± 5% or ± 10% could be accepted. The single-phase Root Mean Square (RMS) voltage is required which is V_{rms} =110 V. By applying the regulation of 10%; V_{rms} will be calculated as:

$$V_{rms} = 120 + (120 * 0.1) \approx 132\text{V}$$

The peak value (V_p) could be calculated as:

$$V_p = V_{rms} * 1.414 \approx 186.67\text{V}$$

For considering a three-phase system (grid side). Line to line voltage (V_{L-L}) = Single phase voltage *1.732

$$V_{L-L} = 132 * 1.732 \approx 220 \text{ V}$$

The peak value (V_p) could be calculated as:

$$V_p = 220 * 1.414 \approx 300\text{V}$$

This is considered the maximum peak.

Every panel has a specific output voltage which is sent to the inverter. Therefore, we will further concentrate on the inverter side, due to having a fixed DC-link input voltage; the inverter output voltage depends on its DC input voltage. The phase output voltage will have different amplitude levels including $\pm\frac{2}{3}, 0, \pm\frac{1}{3}$ of the DC input voltage, hence the peak value of output voltage could be obtained using the following equation:

$$V_p = \frac{2}{3} * V_{dc}$$

$$V_{dc} = 3 * \frac{300}{2} = 450 \text{ V}$$

Thus, the DC link voltage is $V_{dc} = 450\ V$. At the DC side the 450 V has to be fixed to attain the 300 V at grid side. The $V_{dc} = 450\ V$ is fixed at the output DC voltage of the boost converter. By considering a 75% duty cycle, the signal is on 75% for every switching action and off 25% of the time. Substituted in (1), we will get;

$$V_{in} = V_{pv\_required} \approx 115V$$

This value is considered the minimum required voltage should be produced by the PV panel. From the PV module datasheet, we have (P_{mp}) = 320W, $(V_{mp}) = 33.3\ V$, (I_{mp}) =

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9.62A. String sizing calculations depend on the minimum required voltage produced by the PV panel, according to the boost converter calculation the minimum required voltage is represented by: $V_{pv\_required} = 115\,V$. To accomplish 115 V from the available panel specifications, the panels must be connected in series. The number of panels connected in series (N_s) could be calculated as:

$$N_s = \frac{V_{pv\ required}}{V_{mp}} = \frac{115}{33.3} = 3.45$$

This is corresponding to the minimum voltage required. Therefore, rounding up N_s, at least 4 panels must be connected in series. As we will obtain and analyze the simulation results of the model of 100 kW grid-connected PV SYSTEM, the total power required from the PV is 100 kW. Each array should produce power given as:

$$(P_{array}) = \frac{\text{total power}}{\text{Ns}} = \frac{100KW}{4} = 25\,kW$$

From here, the number of panels connected in parallel (N_p) could be calculated as:

$$V_{total} * I_{total} = P_{array}$$

$$V_{total} = N_s * V_{mp} = 4\,panels * 33.3 = 133.2V$$

$$133.2 * I_{total} = 25kW$$

$$I_{total} = \frac{25kW}{133.2} = 187.68A$$

$$N_p = \frac{187.68}{I_{mp}} = \frac{187.68}{9.62} \approx 20 \text{ panels}$$

B. Practical Approach

The aim of sizing the strings is to provide a voltage supply that would fall within operating range of the inverter. This will ensure safe and efficient operation of the inverter. In this strategy, calculations to determine the string size are contingent upon the specific voltages of the panels and the inverter, geographic location and temperature of installation site. According to [20], (4) is used to calculate the minimum number of PV panels connected in series; a string, which are needed to keep the inverter operating during high temperature. Likewise, (5) will be used to calculate the maximum number of panels in the string to maintain the inverter operating during low temperature.

1) The minimum voltage of panels is calculated using the high temperature of the respective installation site which would in fact correspond to the lowest expected voltage [20].

$$V_{min} = V_{mp} * [1 + \left((T_{Max} + T_{add} - T_{STC}) * \left(\frac{TC_{Vmp}}{100}\right)\right)] \quad (4)$$

where V_{mp}:Maximum power voltage, can be found in Table I; T_{Max}: the highest temperature of installation site [°C], 2% ASHARE is more industrial uses. T_{STC}: STC temperature is 25 °C; T_{add}: Temperature related to the installation method [°C]. TC_{Vmp}: The power temperature coefficient can be found in Table I; T_{add}: The changes of the temperature related to the method used to mount the PV panels. In case of roof-mounted system with (> 6 in. standoff), $T_{add} = 30$.

TC_{Vmp} information is available from solar ABCs which include a site weather data which are provided by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHARE). These data can be accessed by entering zip-code of the location to retrieve weather data close to your location. In Halifax, our closest weather data of installation site is shown in Fig. 3. Thus, we will have:$V_{mp} = 33.3V$, $T_{Max} = 18, T_{add} = 30, T_{STC} = 25$. TC_{Vmp} =-0.37%/°C. From (4) and substitute the given values, we obtain $V_{min} = 30.46\,V$.

By assuming the operating range of the inverter within (V_{start} = 100 V to V_{end} =300 V), the minimum string size N_{min} is given by: $N_{min} = \frac{V_{start}}{V_{min}} = \frac{100}{30.46} =$ 3.2 panels. As we calculated the minimum number of panels, we need to consider rounding up $N_{min} \approx 4$ panels.

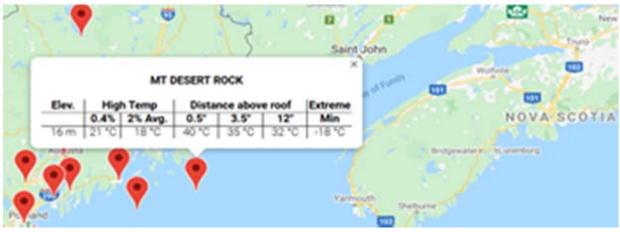

Fig. 2 ASHARE weather data of the respective location

2) Maximum number of panels that can be connected in series and ensure a maximum PV voltage does not surpass the maximum voltage of inverter. The maximum voltage of panel can be calculated using lower temperature of the respective installation location which would produce maximum expected voltage [20].

$$V_{max} = V_{oc} * [1 + \left((T_{min} - T_{STC}) * \left(\frac{TC_{oc}}{100}\right)\right)] \quad (5)$$

where V_{oc}: *open-circuit voltage* which is found on datasheet, T_{min}:lowest expected ambient temperature for the respective site as shown in Fig. 3. TC_{oc}:V_{oc} temperature-coefficient, could be found on datasheet. Thus, we will have: $V_{oc} = 40.8V$, $T_{min} = -18$, TC_{Voc} =-0.27%/°C. From (5) and substitute the given values, we obtain $V_{max} = 45.53\,V$. The maximum string size N_{max} is given by: $N_{max} = \frac{V_{end}}{V_{max}} = \frac{300}{45.53}$ = 6.58. As we calculated the maximum number of panels, we need to consider rounding down $N_{max} \approx$ 6 panels.

V. PV System Configuration and Simulation Results

An overview of array configuration is shown in Fig. 4, which includes 20 strings of 4 panels wired in series. The 20 strings are connected together in parallel to create one array that will connect to the boost converter. We will investigate the effect of corresponding wiring on the performance of a 100 kW grid connected PV system. Simulated performance of the system is carried out using the MATLAB simulation tool. To perform the calculation, we use $V_{mp} = 33.3$ V and $I_{mp} = 9.62$ A. Total voltage produced from 20 strings of 4 panels each will be $33.3 * 4 = 133.2$ V. The parallel connection will keep the voltage same i.e. 133.2 however the output current from each panel will add up and become 9.62A *20 =192.4 A. The output voltage and current from each array is shown in Fig. 5. Hence the total power from each array will be 133.3V*192.4 A ≈ 25 kW. This means for 100 kW we will need four such arrays that will be connected in parallel. Connecting the four circuits in parallel allows us to maintain the 450 DC link voltage as shown in Fig. 6.

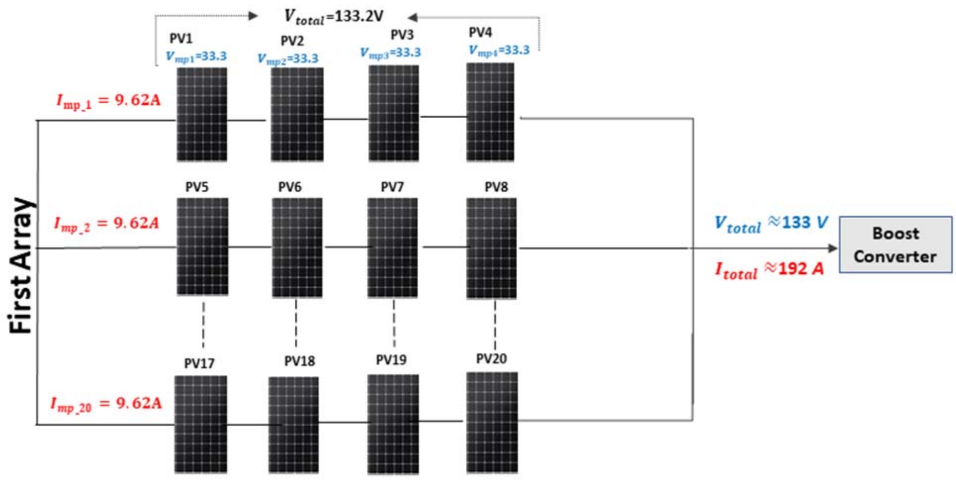

Fig. 3 Array configuration

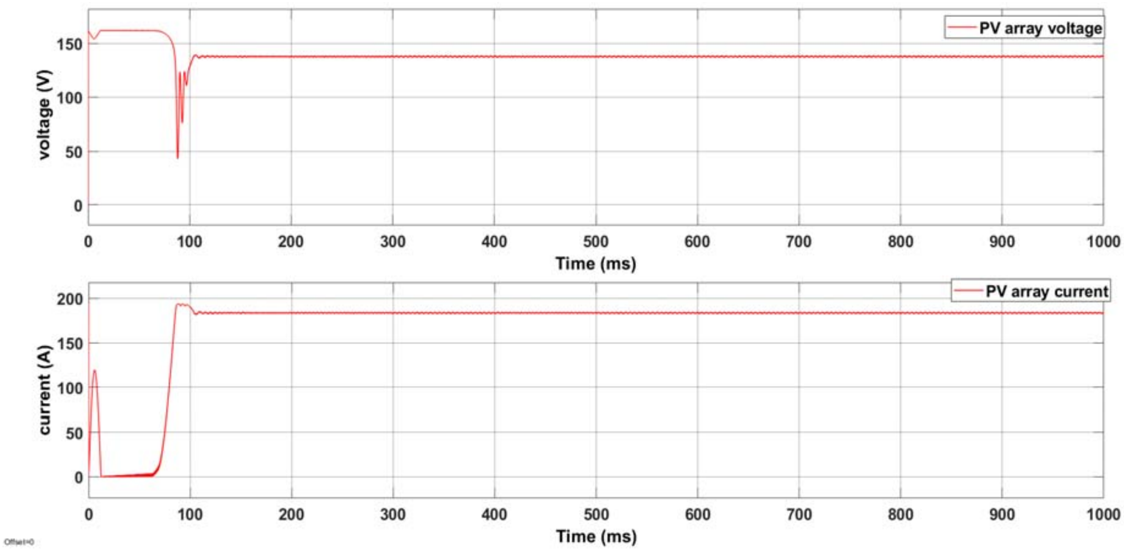

Fig. 4 Array output voltage and current

The PV array is configured to produce only active power and not reactive power. As shown in Fig. 7, each array produces a power output of 25 kW. 4 such arrays would produce 100 kW at the grid side. Fig. 8 indicates that reference active power is fixed at 100 kW and the produced active power also was close to 100 kW. After the initial disturbance of 0.15 seconds, the power stabilizes around 93.5 kW. Likewise, Fig. 9, the reactive power is set to zero, and produced reactive is also zero which can be achieved after 0.8 seconds. Fig. 10 shows that DC link voltage is settled on 450 V, within 0.15 seconds of disturbance during tracking procedure. As shown in Fig. 10, the efficiency of the system reaches to 93.5% which is in fact comparison between the ideal active power and supplied active power to the grid said.

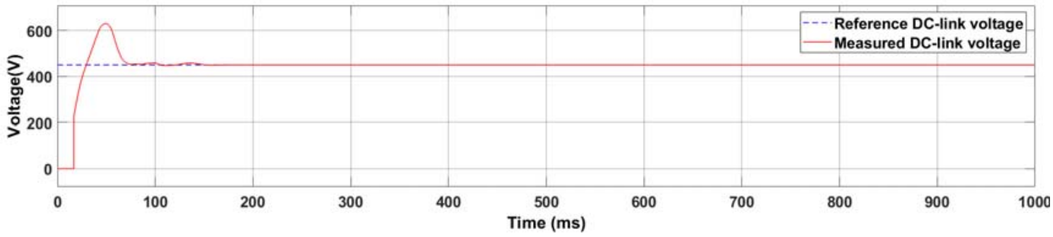

Fig. 5 DC link voltage

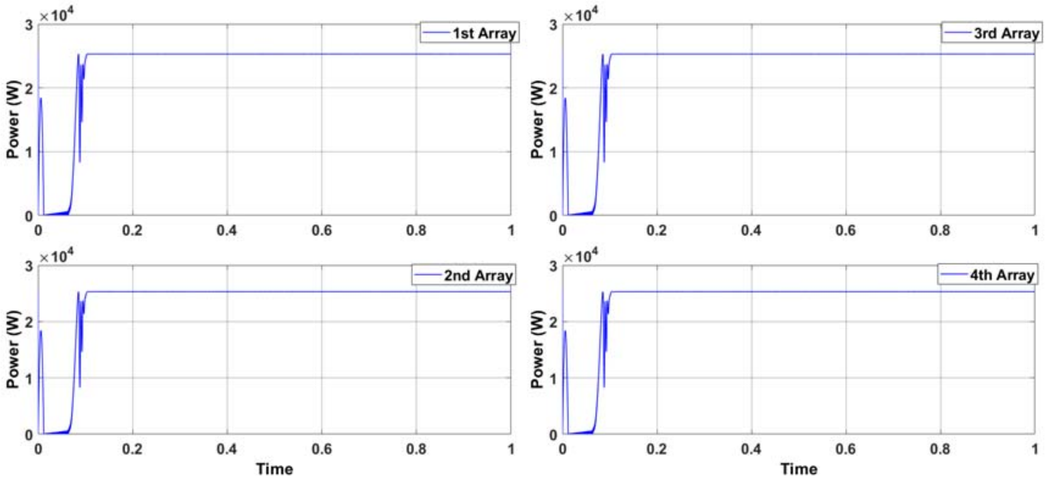

Fig. 6 Power output of 25 kW from each array

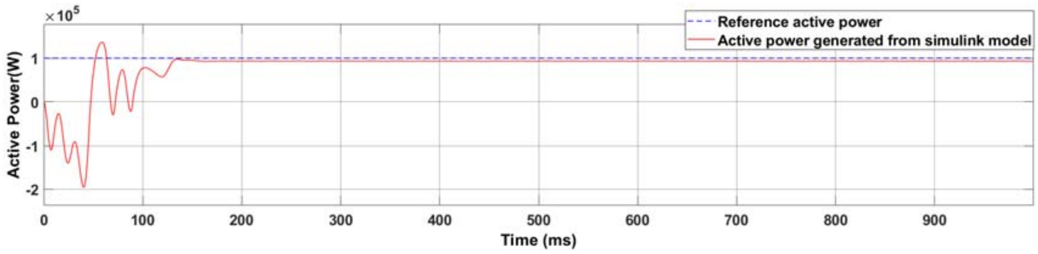

Fig. 7 Reference active power vs. produced active power

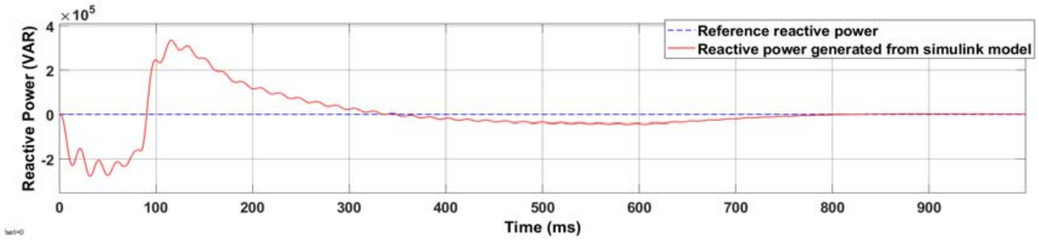

Fig. 8 Reference reactive power vs. produced reactive power

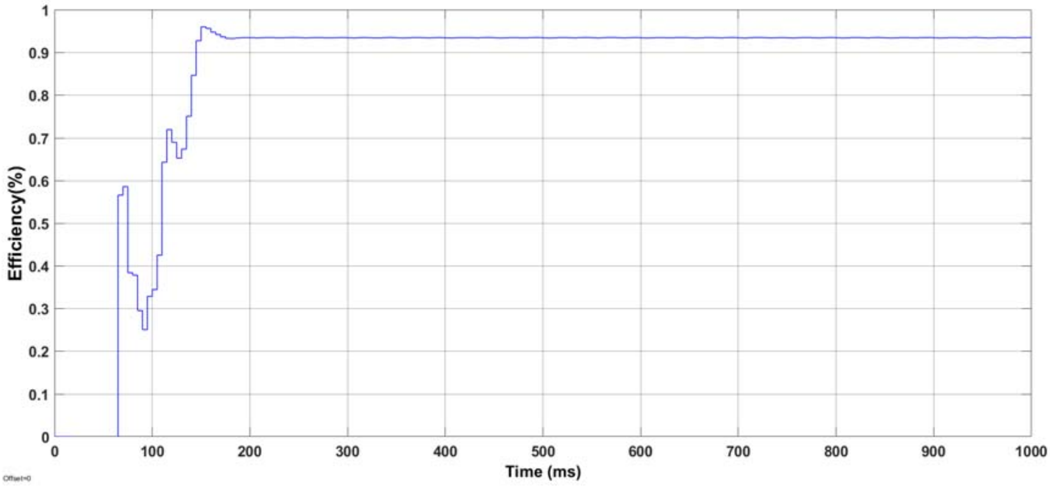

Fig. 10 Efficiency of the system

VI. Conclusion

Over or under-sizing of the PV panels for a grid-connected PV system could lead to defect problems in PV system design. The issues in determining the size of array is the limits of maximum and minimum operating voltages of the inverter. We investigated the crucial factors of sizing principle to ensure that we do not encounter any system issues, and operate the inverter efficiently. As a way of validation, we explored two different methods to determine the PV size. In this regard, a Simulink model of the 100 kW Grid-Connected PV is utilized for a location in Halifax, NS to evaluate the two methodologies for calculating array size. These methods indicate that enough energy was generated by the PV system and supplied to the grid with an overall efficiency of 93%.

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