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Maximum Power Point Box (MPPB) Design to Advance BIPV Installations on Residential Properties

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Article Info	ABSTRACT
	Photovoltaic installations on residential properties gained high momentums during the past decade. Building integrated photovoltaic materials are well developed and has the potential to advance the photovoltaic systems installations on residential and commercial buildings. One of the main limitations on residential system is the utility allowable AC power generation. The installation of BIPV on houses offer numerous orientation and tilts of the PV system which ensure sun energy is harvested for wider timeframe. The different orientations and tilts reflect changes in the generate output power. The available residential inverters have one of two MPPTs which limit the orientation and tilts of the system to a maximum of two options per inverter. Adding more inverters will add cost burden on the system, exceed the utility maximum allowable AC power generation, and additional inverters will not work at rated power throughout the day. The works in this paper include the detail design of a maximum power point box (MPPB) that harvest the sun energy for different orientations and tilts, manage and regulate the DC Bus Bar voltage level as well as generated DC power prior the inverter input terminal. The process is governed by an input from the inverter using an industrial communication protocol such as MODBUS. The aim of the box is to reduce the number of inverters required for maximum power generation while maintaining the maximum AC limits set the by utilities. The paper includes the details design with the proposed circuit along its optimum logics. Case study is also included

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1.   INTRODUCTION

The United Nation (UN) along numerous governments acknowledged the risk of climate change and set regulations and policies to address these issues [1-3]. Photovoltaic (PV) systems are one of the main renewable energy systems that UN and Government promote to mitigate the climate change impact on the planet. PV technology converts solar energy into electric power without any gas emissions [4-6]. Numerous governments introduce an incentive benefits for owners (residential and commercial) to install PV systems on their properties [7-8]. These incentives and other factors increased the installation of small microgrid system especially on residential properties [9]. This dramatical increase of PV system installation has the potential to impact on the current network. These impacts could be in the form of voltage variation, unbalance harmonics and stress on distribution transformer [9-12]. To reduce the impact on the utility grid, policies are set in place to limit the installed renewable energy system size for single and three phase projects. The limitation of the maximum AC power generation by the micro-grid control or reduces the impact that the installed PV system could indorse on the electrical network. However, this limitation along with the sun path throughout the day

and year, reduce the house generation capacity. The sun path changes throughout the day which reflect on the PV output [13, 14]. To maximize the sun energy at the PV system, the designer should follow the sun path using a mechanical tracking devise [15]. For residential properties, the PV system is installed on the roof which makes it very costly to install a mechanical tracking devise. Without the tracking devise, the peak output of the installed system occurs during short period of the day. The designer is forced to size the inverter to comply with the peak generation period which only exist during short time of the day. Furthermore, the inverter is equipped with maximum power point tracker (MPPT) to extract the maximum possible power from the PV panels [16-18]. The PV panels that is installed to one MPPT should have the same orientation and tilts. Therefore, for an inverter to capture more orientations, additional number of MPPT should be part of the proposed inverter. Unfortunately, the currently available inverters for residential properties for single phase systems has one or two MPPTs. The limited number of MPPTs limit the number of orientations and tilts to a maximum of two for small scale residential properties.

The work in this paper focuses on the detailed design of a maximum power point box (MPPB) to allow for numerous orientations and tilts connection of PV arrays at residential properties systems. The paper shows how the MPPB allows house owner to track the sun using additional panels to maximize the system outputs. The proposed system can make use of the building integrated PV materials to reduce the cost of the installed system. Case study is also included

2.   THEORETICAL STUDY

The PV system converts the sun light into electrical direct current. The circuit in Figure 1 represents the PV system as a current source [19-27]. The solar cell is presented using current source, diode and resistors. The generated current magnitude depends on the sun radiations and temperature. Figure 2 represents the shape of the output of a solar cell.
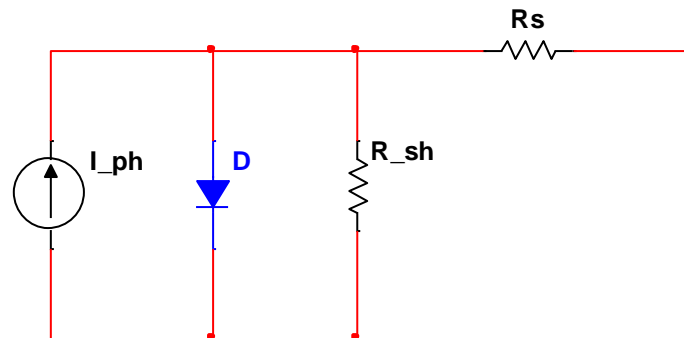

Figure 1. Circuit representation for solar cell

It is clearly shown in Figure 2 the changes in PV output with the change in solar radiations. The solar radiation at the PV panels depends on the seasons, day time, tilt and orientation of the panels. It is possible for the sun radiation to be at one Sun however the sun at the panels is below 0.5 Sun. it is worth nothing that one Sun is equate to 1000W/m^2 of radiation. Based on this information, the orientation and tilt play an important role in maximizing the energy output of the installed PV system.

From Figure 2, the output current of the PV panel under fixed radiation stays constant until the voltage reaches a certain value then dive toward zero. Also checking the power output behavior, the power increases until reaches maximum value at a nominal voltage before it dives toward the zero. This phenomenon urged researchers to introduce maximum power point tracker (MPPT) to regulate the voltage that reflect maximum output power [27-29].

The output power of PV panel is a function of the following variables:
- Characteristics of the PV panels
- Sun radiations in Wm2
- Tilt angle of the panels
- Sun radiation incident angel to the surface

As the sun moves throughout the day, the sun radiation on the fixed panel orientation changes which reflect a change in power outputs.

$$P_{pv} = function \; of \begin{Bmatrix} Sun\_Radiation \\ Panel\_Tilt\_Angle \\ Radiation - Incident\_Angle \end{Bmatrix}$$
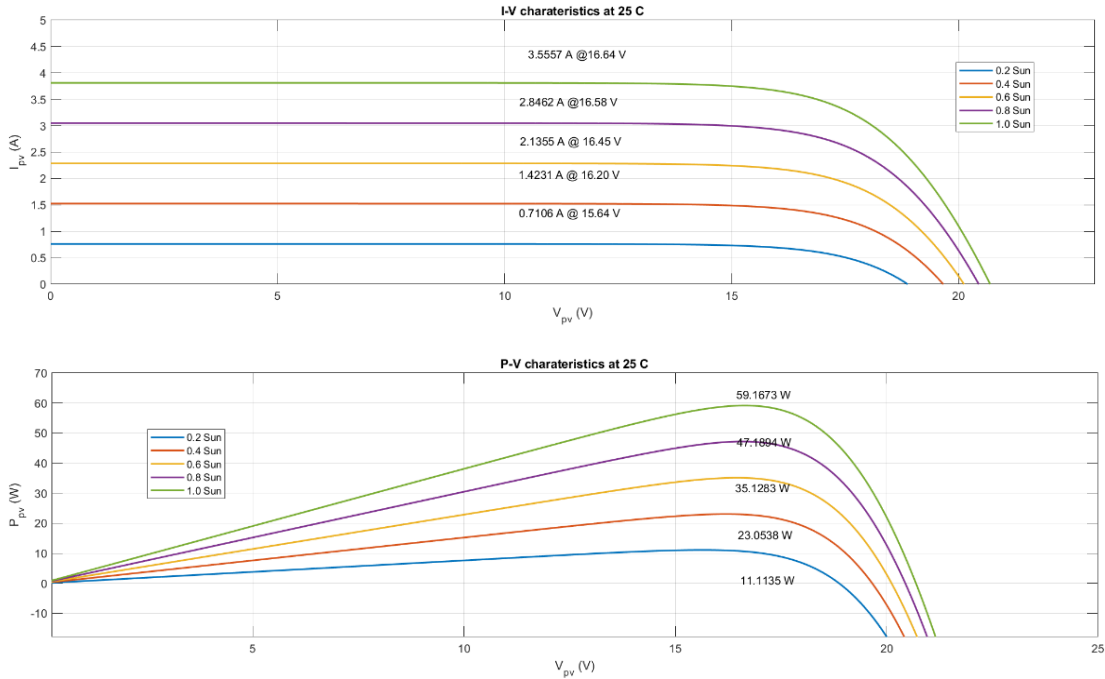
Figure 2. PV output in relation to sun radiation

Figure 3 shows the sun radiation angle to the panels under different tilt angle. It is clearly shown the change in G_i at the panel (G_i is the amount of radiation that reaches the panels at 90 degrees). In Figure 3, G is the global radiation that reaches the panels and G_i is calculated using the G value, incident angle of sun G and the tilt angle. The change in current generated from the PV panels is computed using equation 1 [16-18]. Equation 1 shows that the PV current is a function of the sun radiation at 90 degrees on the panel.

$$I_{ph} = function\ of\ \frac{G_i}{G_n} \tag{1}$$

Where

G_i is the sun radiation at 90 degrees to the panel

G is the standard sun radiation under test condition of the panels. It is usually $1000w/m^2$
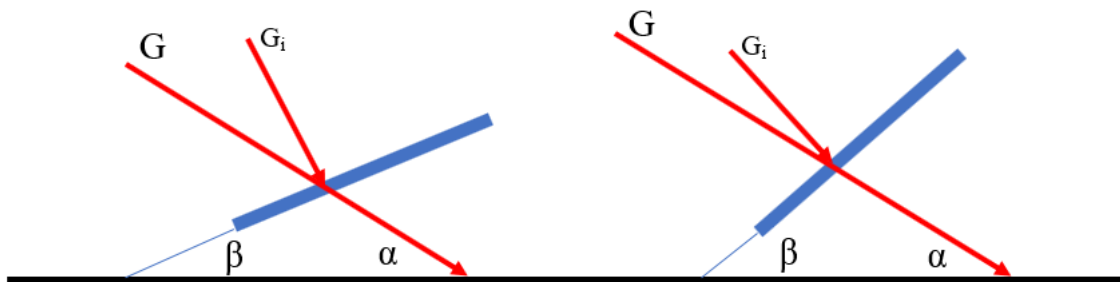

Figure 3. direct radiation on the panels for different tilt angle and sun angle to ground

2.1 Building Integrated PV (BIPV) System

The advancement in PV cells technology allows the integration of PV with building materials. These integrationsallow for installation of PV cells under numerous orientations and tilts. Figure 4 shows a possible installation of PV system under the BIPV concept. The system in the figure is formed by vertical BIPV walls facing east and west, one system facing east with tilt of β, one system facing west with β tilt and one system horizontal. The figure shows that at one moment, the sun radiation G intercept the system under different angle which reflect different G_i on each system. It is also worth noting that the West orientated PV system has no direct sun interface which mean no direct G_i directed to the installed West BIPV system. Based on this information, during east radiation, the power of the west oriented system is very low in comparison to the east system. The total output power of the house is computed using equation 2:

$$P_h = \sum_{i=1}^{n} P_i \tag{2}$$

Where

P_h is the house total output power of the installed BIPV systems

n is the total number of system with different orientation or tilt. For example, in Fig 4, n is 5

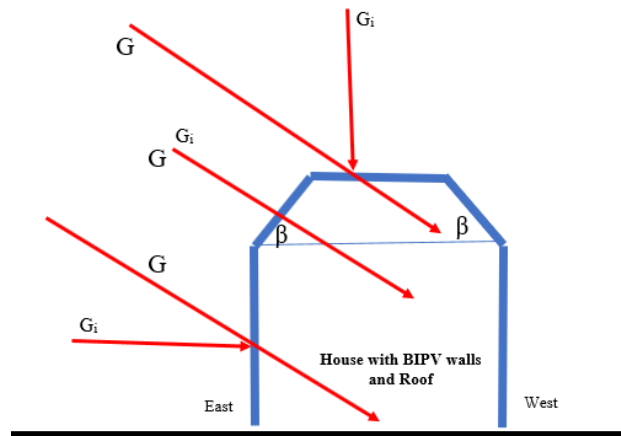P_i is the individual BIPV system power outputs

Figure 4. BIPV solar house with different orientations and tilts

2.2 Solar Irradiance and angles

The different orientation and tilt of the PV system on the house changes the sun position in relation to the panels. This section contains the information regarding the sun positions in respect of the panel orientation and tilt. The sun position with respect to an observer on earth can be fully described by means of two astronomical angles, the solar altitude (α) and the solar azimuth (z). [30] The solar declination and hour angle need to be defined. These are required in all other solar angle formulations:

1. Declination angle, δ: The angle between the Sun's direction and the equatorial plane. δ varies smoothly from +23.45 ° at midsummer in the northern hemisphere, to -23.45 ° at northern midwinter. Declination angle can be determined by [30] $\delta = 23.45° \sin 360365 n+284$ (1) where n is the day in the year ($n = 1$ on 1 January).

2. Hour angle, h: is the angle through which the Earth has rotated since solar noon. Since the Earth rotates at 360°/24 hour = 15°/ h. The hour angle is positive in the evening and negative in the morning, the hour angle is given by equation 3 [30]:

$$h = localtime - 12\ 15° \tag{3}$$

3. Solar altitude angle, α: The angle between the solar beam and the horizontal.

4. Solar zenith angle, ϕ: The angle between the solar beam and the normal on the horizon as shown in Figure 5

5. Solar altitude and solar zenith angles are complementing each other ($\alpha + \phi = 90°$) and calculated by equation 4 [3].

6. Solar azimuth angle, z: the angle between the solar beam and the longitude meridian. In northern hemisphere, z equals 0° for a surface facing due south, 180° due north, 0° to 180° for a surface facing westwards and, 0° to −180° eastward. Equation 5 for is used to compute the solar azimuth angle

$$\sin\alpha = \cos\phi = \sin L \sin\delta + \cos L \cos\delta \cos h \tag{4}$$

$$\sin z = \cos\delta \sin h\ /\ \cos\alpha \tag{5}$$

where

L is the local latitude, values north of the equator are positive and those souths are negative, -90< L <90.

Determining the sun location and its angle to the ground or to the panels, allow the designer to determine the radiation directed to the panels at 90 degrees. Analyzing Figure 5, the angles can be found to be as follows:

1. Tilt angle, β: is the angle between the plane surface and the horizontal (with 0< β <90 for a surface facing towards the equator; 90 < β < -90 for a surface facing away from the equator).
2. Surface azimuth angle, Zs: is the angle between the normal to the surface and the local longitude meridian. Sign convention is as for z. For a horizontal surface, Zs is 0° always. Zenith angle, angle of incidence, Tilt angle, solar azimuth angle and Surface azimuth angle for a tilted surface [31].
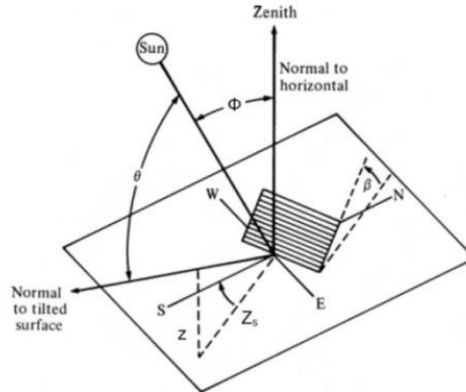3. Angle of incidence, θ: the angle between solar beam and surface normal.

Figure 5. Sun location and its incident on ground and solar panel [30]

3.   MPPB DESIGN

Many countries set the limit of the grid connected PV system that can be installed at residential properties. The PV output varies between daily hours and seasons. To ensure maximum power is always achieved, additional panel can be installed. The installation of additional panels without a rigid control system will push the system to exceed the allowable generation limits at certain time of the day. The aim of this paper is to design the MPPB system to harvest the required DC energy, when additional panels are installed, without exceeding the inverter requirements or the utility maximum allowed AC power. Also, this approach advances the BIPV implementations worldwide. The role of the MPPB is to collect the maximum power from each set of PV panels using multi MPPT system, acting as intermittent current sources, connected in parallel. Figure 6 shows the setup of the DC control methodology. The system compares the maximum current to a reference current, if the value exceeds the reference value, the system will initiate the PI controller to limit the power, otherwise the system will initiate the MPPT concept to harvest the maximum power of the system.
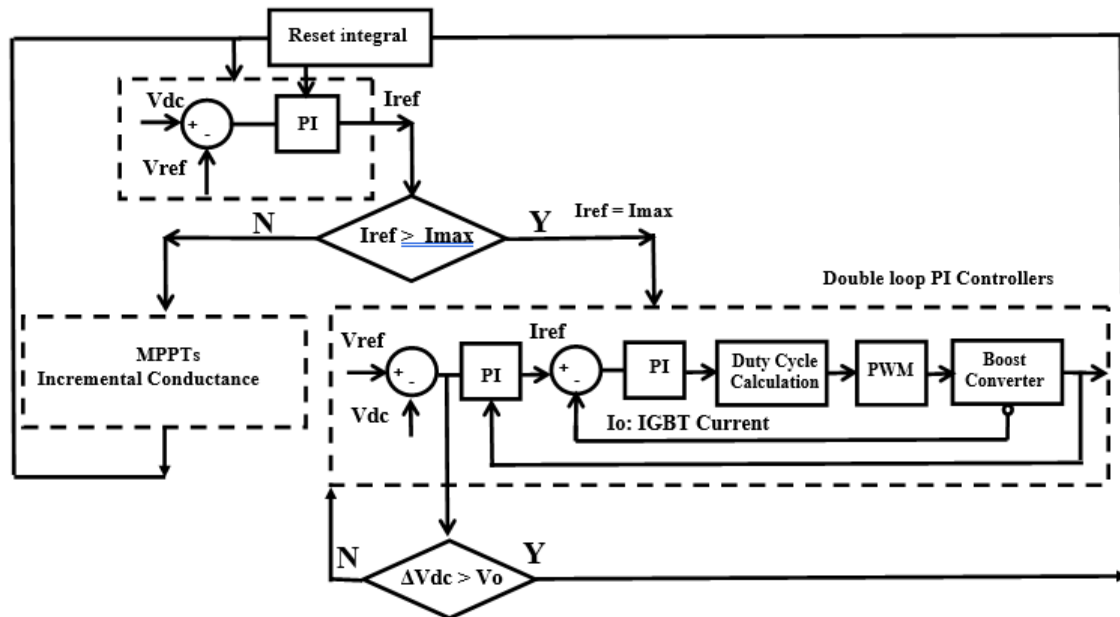

Figure 6. DC power control inside the proposed MPPB

Figure 7 shows the simulation output of the power controlled using the proposed algorithm, it is clearly shown the power control capability of the MPPB. This ensure the power at the inverter doesn't exceed the desirable limits. This process allows the inverter with the MPPB circuit to install additional PV panels at different orientations. Also Figure 7 shows that adding BIPV has the potential to stabilize the power output for longer day period which advance the system reliability. Figure 8 shows the DC voltage at the common bus bar as well as the Vdc ref 500V, the drop in the voltage can be noticed at time 3:00 pm where the irradiance becomes insufficient to generate 15KW so the MPPt are back on and Iref becomes variable according to the available irradiance.
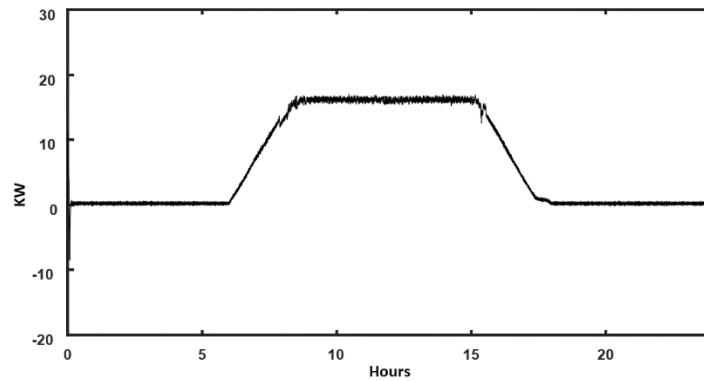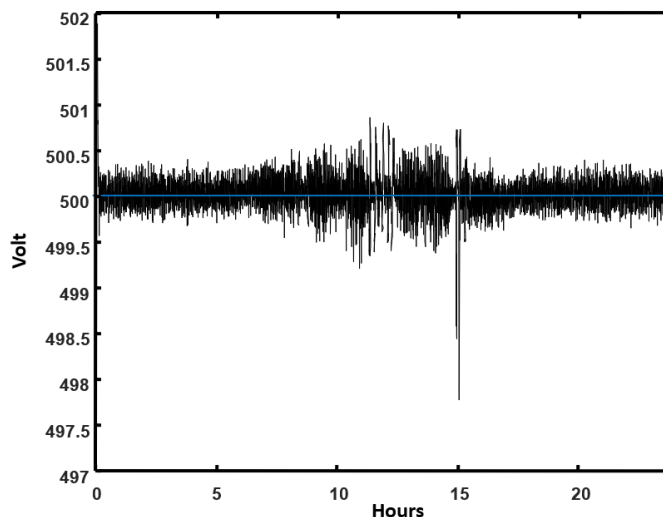

Figure 7. simulation output of the proposed inverter

Figure 8. Vdc versus Vdc-ref based on the proposed MPPB

4.   CASE STUDY
The case study is based on an existing 15kW inverter installed with the following data:
- 15kW inverter with maximum DC power of 15.25kW
- Inverter desirable voltage is 500Vdc
- South oriented with tilt angle 23° at Dubai

The building owner decided to install two additional glass facial walls facing east, west. The size of each wall is 150 m². The owner decided to use solar panels for the glass walls. Without the MPPB system as proposed in this paper, an additional inverter is required to be installed. The new inverter not only cost money and additional installation on the AC side, it could lead to the change of the existing one (the new inverter must be able to communicate with the existing inverter for synchronization requirements, Also, both inverters maximum AC capacity could exceed the utility allowable limits, so this won't be an acceptable option for the project.

The solution is to control the power generation at the DC level, which is acceptable by utilities and governments. That is why the presence of the MPPB offers a great advantage over system without MPPB. Deploying the paper novel MPPB concept allows for the installation of both walls to be made of BIPV materials

and for the owner to generate extra power without the need to upgrade or change the AC system. The design ensures each wall has 75 panels of 305W connected to the MPPB along with the existing panels. Figure 9 shows the irradiance of each orientation, as well as the total irradiance, during the first of January 2018 at Dubai.
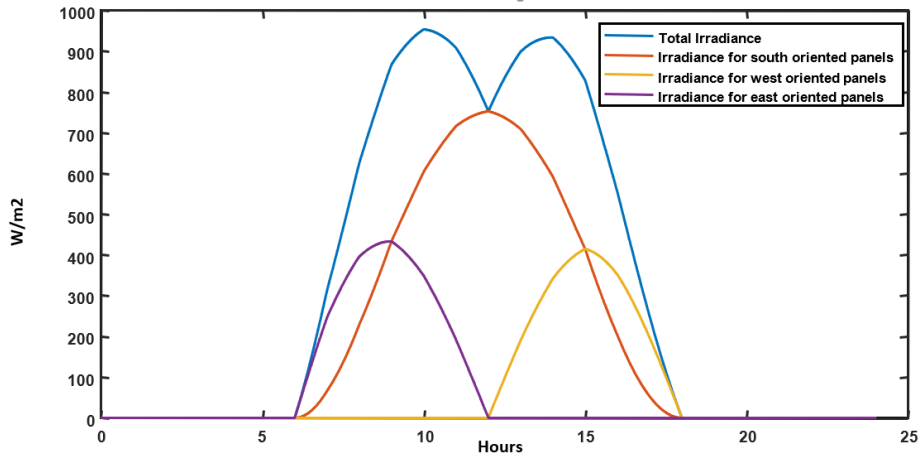
Figure 9. Sun radiation for the first of Jan 2018

Figure 10 shows the connection diagram between the MPPB, Inverter, and Grid. It is worth noting that a data cable required to link between the MPPB and the inverter. The role of the data link is to provide the actual AC power at the output of the inverter which set the reference current at the DC side of the inverter.

The case study simulation outputs are captured in Figure 11. The collected data shows the complete system without capping, which is represented by the extended modeling. It also highlights the capping capability of the system which is presented by the extended system with limitation. The simulation shows the system capability to control the power to the nominal value which allow for the additional panels to be installed at the existing inverter terminal. Table 1 reflects the power generation for the existing systems, the system with additional panels with and without limitations. It is worth noting that this work was verified using system advisory module engineering software.

Table 1. Power generation for one day for different system conditions

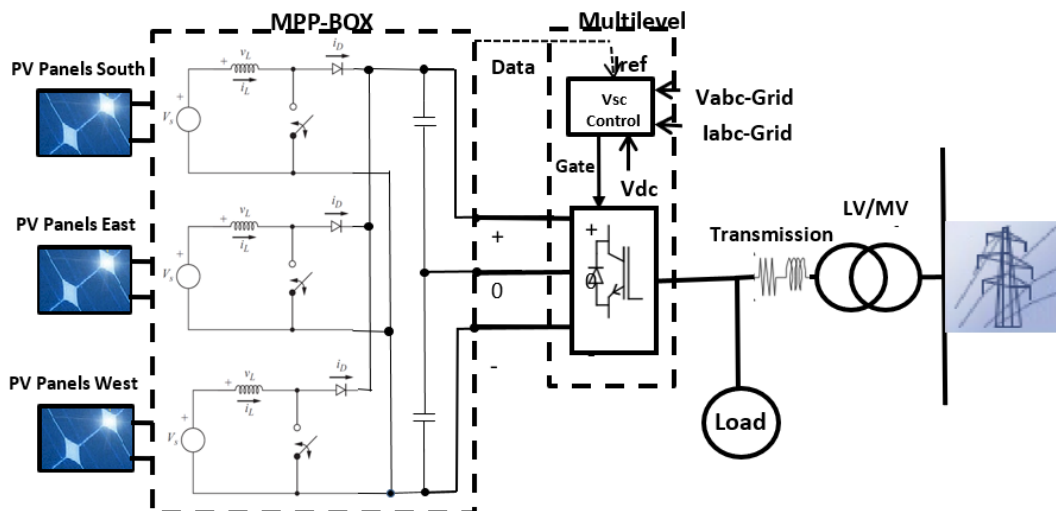| System Details	1st of January Power Generation (kWh)	Comment
Existing System	93	
Complete system without limitation	154	This system exceeds the maximum AC power limitation which is unacceptable by the utilities
Complete system with limitation	140	The system caped at 15kW peak

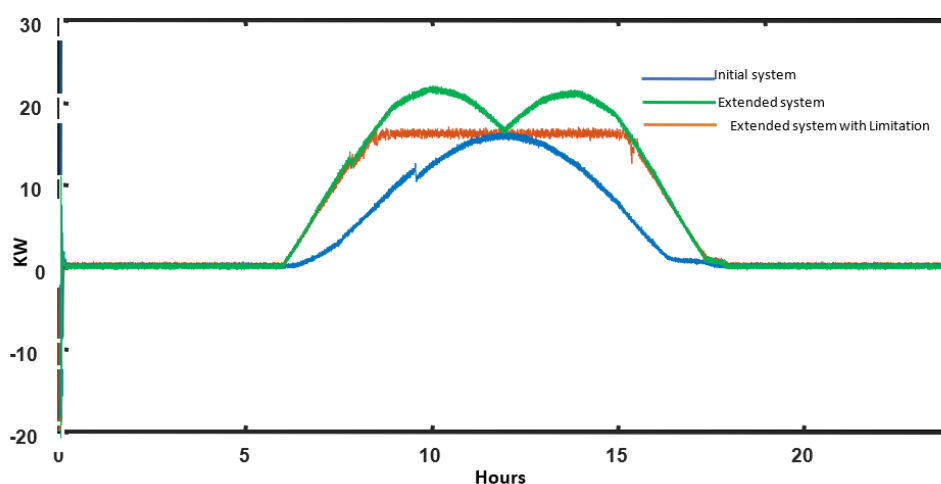Figure 10. Connection diagram between the panels, MPPB, Inverter and Grid

Figure 11. System output data collection under different conditions

5. CONCLUSION

The paper addresses an important and growing topic in power generation and renewable energy. The work highlights the importance of controlling the power at the inverter terminal using the proposed MPPB to advance the BIPV implementations. The MPPB box allow house owner to generate additional electrical energy without exceeding the inverter or the utility AC power limits. Without the proposed MPPB, the owner cannot increase the house generation without additional investments in inverter systems if permitted by the utility. Therefore, the proposed MPPB offer an easy solution to owners to increase their generation capacity and to advance BIPV implementations without the requirements of additional alteration to the AC networks. The case study shows the additional benefits that owner can gain from the MPPB. Table 1 shows the advancements in power generation when using BIPV with the proposed MPPB.

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