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Control Strategy for DC Bus Voltage Regulation in Photovoltaic System with Battery Energy

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Abstract: **Currently, several studies and researches are focusing on improving the efficiency and performance of PV inverters connected to the network, all these studies based on the minimization of losses by reducing equipment, the development of new components, new designs and topologies, with reduced costs. In this work, we develop a new principle called the optimal distribution of power; this concept based on the creation of a bidirectional DC converter block with battery (BCB) to ensure high and stable DC voltage at the entrance of the PV inverter. Based on the simulation results obtained from Matlab/Simulink, it has found that it is necessary to control the DC voltage bus of PV inverter.**

Keywords: PV, inverter, performance, efficiency, bidirectional converter, battery.

I. INTRODUCTION

The use of electricity generated from solar energy has recently become more common, perhaps because of the environmental threats arising from the production of electricity from fossil fuels and nuclear power. Although the efficiency of PV panels still poor, the PV energy is a great opportunity for several applications including residential and commercial buildings, electrical vehicles, water pumping systems, and rural applications. There are two types of PV system; the off-grid, also known as stand-alone system, which consists of PV array, storage system, and power conditioning unit. The other type is the grid connected system. This system provides energy to a load and/or to the utility according to the load conditions.

In order to increase PV proportion in these applications, the efficiency of the PV system should reach an acceptable range. This objective has led researchers to move toward different area of focus to achieve this goal at the cell, module, and array and system level; where a module consists of connected PV cells in one frame and array is a complete PV unit consisting of connected modules with structural support. The performance of the system do not depend only on the operation conditions such as partial shadowing, high temperature, or degradation of electrical characteristics of several damaged panels, but they are also strongly dependent on the PV system configuration.

Although, a lot of researches focus on how to improve the efficiency of PV system by improving the system performance through looking for the best operation conditions for the PV system, optimum configuration topologies and implementing power electronics devices to improve the overall efficiency. In [7] the author discusses a comparative study of efficiency for topologies in photovoltaic energy conversion systems. He demonstrates that the decentralized topology is chosen as the best topology since it has higher efficiency and it is fault tolerant.

In [2-3], the concept of multi string is presented and compared with the either concept, this topology combines the advantages of string and centralized topologies as it increases the energy output due to its ability to follow the MPP of each string independently while using a central inverter for reduced cost

In the work of [15], the author makes experimental study of the concept of team concept. The objective of this concept is to modify the curve of output of the inverters to improve the efficiency of conversion of the energy in the region of the characteristic in which the PV generator is supplying energy to the inverter and where usually the efficiency of one inverter is very low.

In this paper, we propose a new system configuration approach using a bidirectional DC converter block with battery (BCB), for controlling the chagrining and discharging of battery, a controller is developed. This paper will cover, in section II, existing PV system configurations, in section III, the proposed topology, in section IV simulation model of PV systems, and the conclusion in section V.

II. EXISTING PV SYSTEM CONFIGURATIONS

Reconfigurable architectures are of great interest to system designers. This interest is gaining more momentum as technological advances and improvements to system components become modular and allow for greater design flexibility and innovation. The utility interactive system, the simplest system in terms of design, is configured with added components to improve its efficiency. Currently the following configurations are found in the literature:
Central-inverter; multi-DC/DC-central inverter; string inverter; team inverter and module inverter configuration.

We present in this section only the dynamical configuration PV systems. The two main conceptions are the followings:

A. *Master-slave Topology*

In order to improve the reliability of the centralized topology, master-slave configuration was developed using a number of parallel inverters that are connected to the array as shown in Figure 17 (b). The required number of active inverters is chosen such that if one
inverter fails, the other inverters transform the whole generated power. Moreover, the inverters can be designed to operate according to the irradiance level, where for low irradiance level some of the inverters are shut down (14). This technique extends the lifetime of inverters and the overall efficiency. However, the cost of this topology is higher than that of the centralized topology and electrical mismatching loss due to
shading is still a problem PV [14] [7].

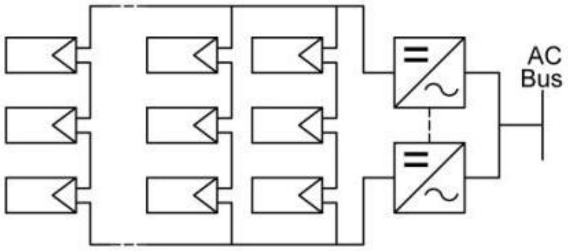


Fig1: Master slave configuration

B. *Team Concept Topology*

The Team-Inverter configuration, shown in Figure 17 (e), uses controllable switches to connect the parallel string inverters according to the solar insolation (16). The system connects the proper number of strings in parallel to a specific number of parallel inverters, thus maximizing the efficiency of the connected inverters. This topology is used for large PV systems; it combines the string technology with the master-slave concept. During low irradiance conditions, the generated energy from each string in the PV system does not match the optimal working efficiency of the inverters. Therefore,adding more than one string in parallel and connecting them to the optimal number of inverters, the amount of energy will match the optimal working point of the chosen inverter(s). As the irradiance level increases, the PV array is divided into smaller strings to inverters to operate at their rated power.

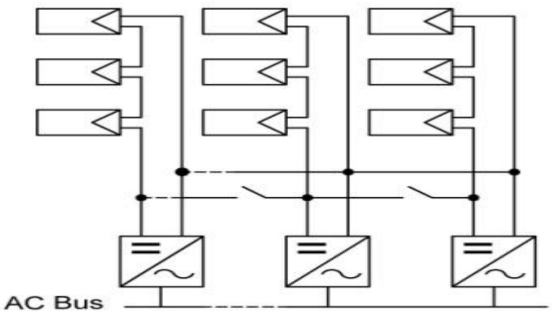


Fig 2: Team inverter configuration

III. INVERTER EFFICIENCY

The following description of the simulation–oriented models refers to the variables of the PV power conversion chain depicted in Fig.3:

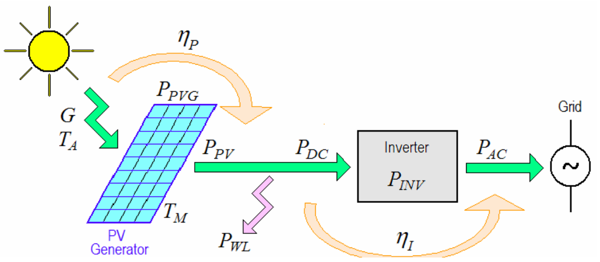


Fig 3: Elements of the PV power conversion chain

The output of a grid-connected PV system depends on the PV/inverter sizing ratio (Rs) 1, defined as the ratio of PV array capacity at standard test conditions to the inverter's rated input capacity. Properly matching PV and inverter rated capacities improves grid-connected system performance. Optimal sizing depends on local climate, surface orientation and inclination, inverter performance, and the PV/inverter cost ratio (T) [11].

Under low insolation (incident solar power), a PV array generates power below its rated capacity, leading to inverter operation at partial load. Inverter efficiency drops with part-load operation: it also becomes sub-optimal when a significantly undersized inverter is made to operate mainly in conditions of overload, which result in energy loss. Figure 1 illustrates inverter efficiency under both overload and partial-load operation (inverter sizing) [12].

The efficiency of the inverter is the most important parameter in a photovoltaic system connected to the grid.

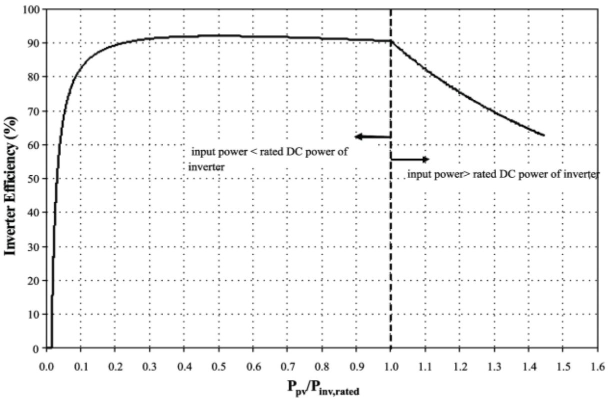


Fig 4. Inverter efficiency as a function of fractional load, defined as the ratio of input power (PPV) to the inverter's rated capacity (Pinv,rated).

According to this curve, we can note the following remarks:

- The inverters provide their maximum power at half load.
- When the illumination exceeds 1000 W/m^2, the performance starts to deteriorate.
- The maximum efficiency of the inverter reaches approximately between 0.5 and 0.6 of the load.

From these observations, it is clear that to achieve high performance; we must run the inverters in a defined load range.

According to this principle, we will develop a new configuration to ensure better efficiency of the inverter. That is to say, the entire installation.

A. *Inverter model*

If the inverter input power does not exceed the maximum inverter rated power, noted as *Pinvmax*, the available power at the inverter output P_{AC} is given by:

$$P_{AC} = \eta_1 \times P_{DC} \qquad (1)$$

Where η1 stands for the inverter efficiency, which can be modeled as [11,12] :

$$\eta_1 = \frac{p}{k_0 + (1+k_1)p + k_2 . p^2} \; ; \; p = \frac{P_{AC}}{P_{INVMAX}} \qquad (2)$$

where k_0 stands for the losses coefficient at no load, being k_1- k_2 : linear and quadratic current losses coefficients.

Replacing (1) into (2) and solving for PAC, leads to:

$$P_{AC} = \frac{-(1+k_1) + \sqrt{(1+k_1)^2 - 4k_2\left(k_0 - \frac{P_{DC}}{P_{INVMAX}}\right)}}{2\frac{k_2}{P_{INVMAX}}} \qquad (3)$$

For input power ranges higher than the inverter maximum rated power, this work assumes the operating mode suggested in [12] to avoid power delivery interruptions, i.e. the inverter's control limits the input power to its maximum value until the overload conditions are no longer present.

Therefore, in this case :

$$P_{AC} = P_{INVMAX} \qquad (4)$$

In summary, given the input power PDC and the inverter maximum power PINVMAX, the AC output power can be computed from Eqs. (3-4). The losses coefficients values adopted in this work are listed in Table I from an exhaustive laboratory test of a large number of PV grid-connected nverters reported in [11,12] which classifies the inverter's efficiency into two categories: low and high efficiency.

Table I: Values of losses coefficients for low and high efficiency inverters

Inverter efficiency	K0	K1	K2
Low	0.0100	0.015	0.06
high	0.0050	0.005	

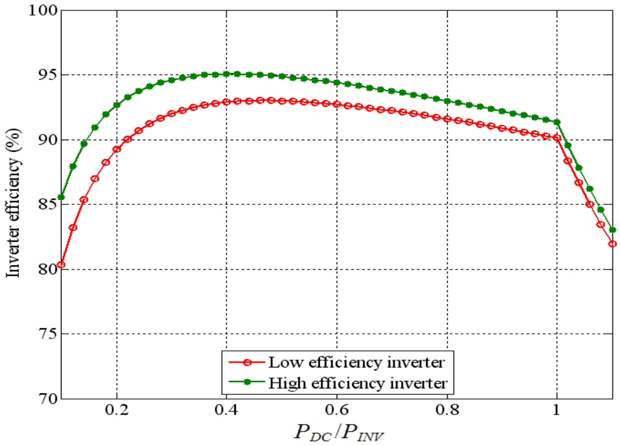


Fig 5: Efficiencies of low and high efficiency inverters

The corresponding efficiencies are plotted in Fig. 5 in of P_{DC}/P_{INVMAX}. As it can be seen, the maximum efficiency value is nearly 95% for the high efficiency inverter and 93% for the low efficiency one. Furthermore, the figure also shows the better performance of the high efficiency inverter under partial load operation [11][12].

IV. THE PROPOSED CONCEPT

A. *Presentation of the System*

A scheme of the studied system is presented in Fig.6 the different power directions are represented. The sign convention in Fig. 6 is used as a reference throughout the whole paper. The main components of the hybrid system are the PV generator, the MPPT, the bidirectional converter with battery and the inverter.

According to the sign convention, the laws of physics require the power balance in the system described by:

$$P_{load} = P_{pv}(t) + P_{bat}(t) \qquad (4)$$

In general, the performance of a PV inverter depends on the power of the grid report issued on the power received by the photovoltaic field (16)

$$\eta_1 = \frac{P_{AC}}{P_{DC}} \quad (5)$$

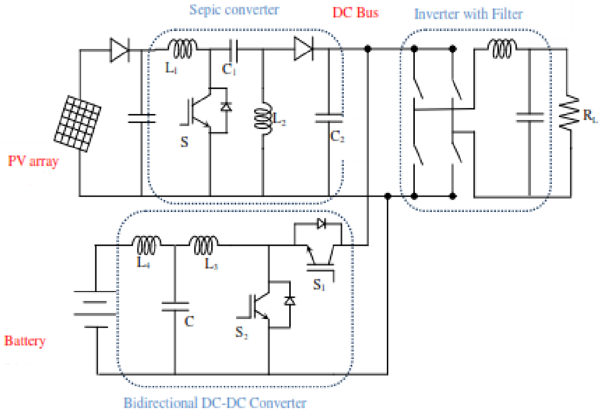


Fig 6：Block diagram of Proposed system Configuration

For best performance, it is necessary an optimal input power; the output power is fixed by the grid.

$$\eta_{optimal} = \frac{P_{AC}}{P_{DCoptimal}}, P_{DCoptimal} \approx \frac{1}{2} P_{DC} \quad (6)$$

Where : $P_{DC\ optimal}$: the power corresponds to the optimal performance

To adapt the power input to the optimal power, we must change the value of P_{DC}, we have two possibility for varying the input power whether the current or voltage of Pdc, in this case we chose the change the voltage DC by installing the battery controlled by a bi-directional converter.

The function of the battery is not to storage the power but for ensure the exchange of power to increase or decrease the input power of inverter. There are three mode.

B. *B. Bidirectional DC- DC converter operation*

The bidirectional boost buck DC- DC converter is used for the battery charging topology [14]. One of the advantages of the converter is that it is a transformer less type with less size, weight and cost. The power circuit includes two sets of anti parallel connected IGBT and Diode as well as a boost inductor with two filtering capacitors. Charging or discharging the battery can be realized by controlling the two IGBT switches [14].

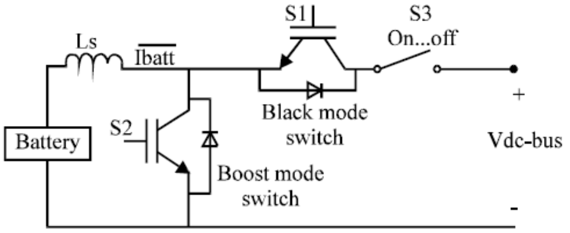


Fig 7: Diagram of bidirectional DC converter

When the battery is being charged, switch S2 and diode D1 conduct current alternately. With S2 turned on, current flows from the DC bus, passes through the inductor and flows through IGBT S2. Energy is stored in the inductor during this state. Once S2 is turned off the current continue to flow through D1. Inductor's energy will boost the voltage and charge the EV batteries. When the batteries are being discharged by the DC- DC converter the current flows from the batteries, passes through IGBT switch S1 and the inductor [14].

After S1 is turned off the current keeps flowing through diode D2 to decay. In this case, the converter acts in buck mode. By controlling the duty cycle of the switches, required voltage output can be obtained. Figure 7 shows the four operation state.

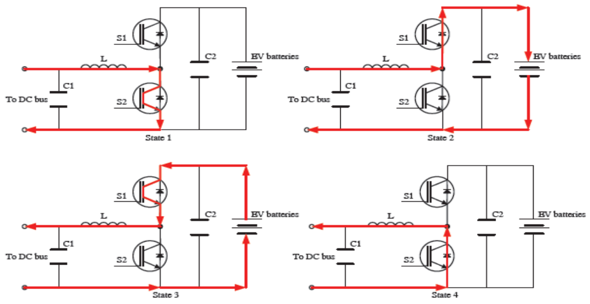


Fig 8 : operation of bidirectional DC-DC converter; state 1 and state 2 are charging mode, state 3 and state 4 are discharging mode

C. *Modeling of Battery*

A standard battery model presented in [13] is implemented in this paper. To avoid the battery algebraic loop problem, this model uses only the state of charge (SOC) of the battery as a state variable. Moreover, model in [31] can precisely characterize four types of battery chemistries including lead-acid battery.

The battery is modeled using a simple series connected controlled voltage source with a constant resistive value, as shown in Figure 9, where the controlled voltage source is described by

$$E = E_0 - K\frac{Q}{Q - \int idt} + A\exp\left(-B\int idt\right) \quad (7)$$

$$V_{Battery} = E - R_{in} I_{Battery} \quad (8)$$

where E_0 is the no load battery voltage (V), K is the polarization voltage (V), Q is the battery capacity (Ah), A is the exponential zone amplitude (V), B is the exponential zone time constant inverse (Ah)−1, $V_{Battery}$ is the battery voltage (V), R_{in} is the battery internal resistance (Ω), $I_{Battery}$ is the battery current (A), and ∫ idt is the charge supplied and drawn by the battery (Ah).
The battery model based on [14] is developed in Matlab Simulink environment and connected to a DC-DC buck-boost bidirectional converter using controlled voltage source as shown in Figure 10.

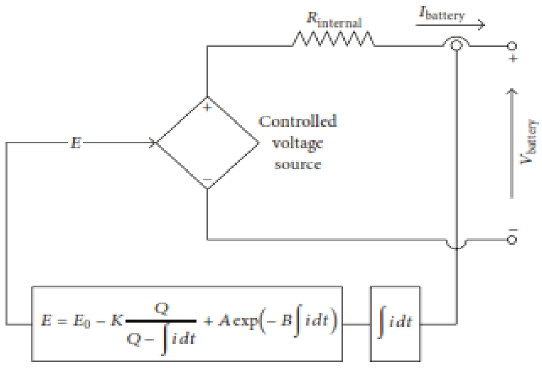


Fig 9 : Nonlinear standard battery model

V. ONTROLLER FOR DC-DC CONVERTER

Control of the charging/discharging of BES is achieved by using a buck-boost converter circuit with two PI controllers, as shown in Figure 5, where PI7 processes the DC bus voltage discrepancies during disturbances to make the bus voltage follow the voltage set point set as Vdc,ref = 500 V. The internal current control loop is also adopted for the battery current controller compensated by PI8.The output signal from PI8 is passed to the PWM generation circuit where the logic circuit is used for the decisions, including the charge, discharge, or halt modes of operation. The switch S1 is triggered and S2 is zero during the boost (discharge)mode and vice versa during the buck (charge) mode to absorb power from the DC bus.
Both S1 and S2 become zero (halt mode) when no regulation signal is transferred [16].

As mentioned before, for buck operation switch S5 and S8 needs to be turned on. And for boost operation switch S6 and S7 needs to be turned on.

For buck converter, the duty ratio,

$$D = \frac{V_0}{V_i} \qquad (9)$$

Where, Vo denotes output voltage and Vi denotes input voltage.

For boost converter, the duty ratio,

$$D = 1 - \frac{V_i}{V_0} \qquad (10)$$

For buck-boost converter, the equation will be:

$$\frac{V_0}{V_i} = D(\frac{1}{1-D)}) \qquad (11)$$

Control schemes of the DC/DC bidirectional converter

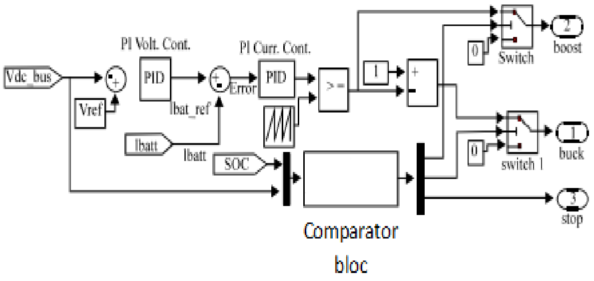


Fig 10 : Flowchart for SOC and BCB power charge/discharge controls

The voltage gain of the bidirectional converter in the buck state can be expressed as :

C

$$G_{V1} = \frac{V_L}{V_H} = \frac{d_3(1-d_3)}{N(1-d_3)+1} \qquad (12)$$

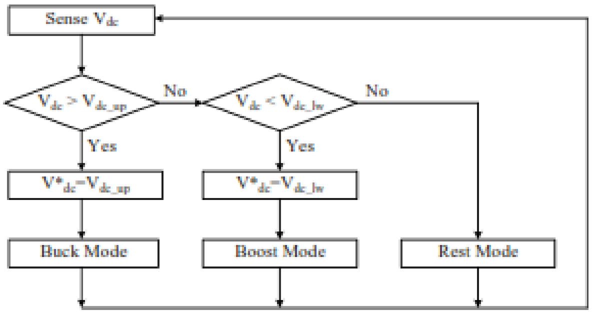
and the voltage gain of the bidirectional converter in the boost state can be represented as,

$$G_{V2} = \frac{V_H}{V_L} = \frac{2+N}{(1-d_1)} \qquad (13)$$

The control circuit should guarantee that both switches do not operate at the same time.
The following constraints are used for charging/discharging as follows:

1) If Vdc≥Vdc-up then charging and Vdc-ref=Vdc-up
2) If Vdc≤Vdc-lw then discharging and Vdc-ref=Vdc-lw
3) Vdc-lw≤Vdc≤ Vdc-up then no control =reset

c. the flow chart of the program



VI. SIMULATION RESULTS

The results found by this architecture are very interesting, so we can consider that our model is consistent and accurate enough for a first optimization approach.

The simulation model of the proposed standalone PV-wave hybrid system with battery energy is built in Matlab Simulink environment under different operating conditions.

The DC-DC converter is simulated with a constant input voltage of 600 V, a constant output voltage of 300 V, a switching frequency of 20 kHz and the parameters given in Table I.
The simulation was carried out at a relative phase-shift of d = 0:15.

A. *Simulation parameters*

Table I : Parameter of PV array

Maximum rated power Pmax	12000KW
Maximum voltage Vmax	33.7V
Maximum current I max	3.87A
Open circuit voltage Voc	42.1V
Schort circuit voltage Isc	3.56A
Output voltage rating	337V
Output current rating	35.6A
Number of modules in a string series Nss	10
Number of modules in a string parallel Npp	10

Table II : Parameter of PV system

Vin (nom)	337 V
Vout (nom)	540 V
Cin	78.6 µF
Lboost	444 µH
Cout	154.69 µF
Switching frequency	10 kHz

Table III : Parameter of PV inverter

Carrier frequency	5000hz
Modulation index	0.85
Frequency of output voltage	50hz
Ll_{oad}	5 mH
R_{load}	10 Ω

Table V: Parameter of bidirectional DC and battery

Rated power Pdc	2KW
Inductor L	373 µH
C_{bat}	282.2 µF
C_{bus}	1130 µF

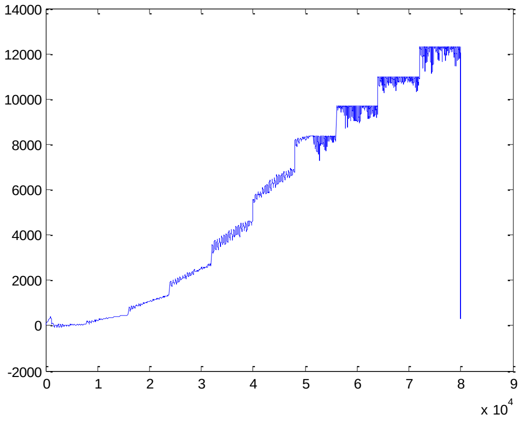


Fig11: Changing Illumination Conditions of PV System

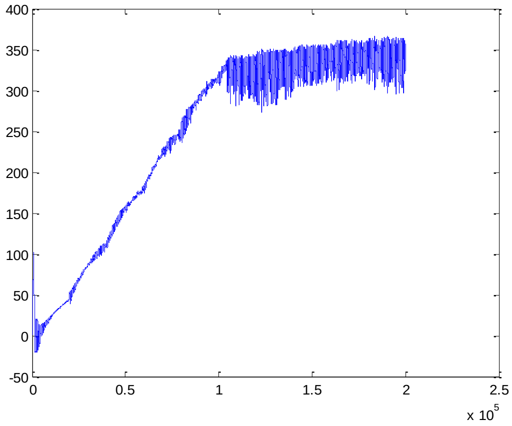


Fig 12: The curve of PV voltage

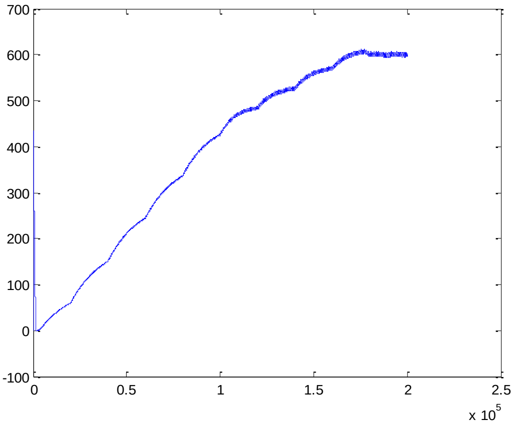


Fig 13: Variable DC-Link Voltage of PV inverter

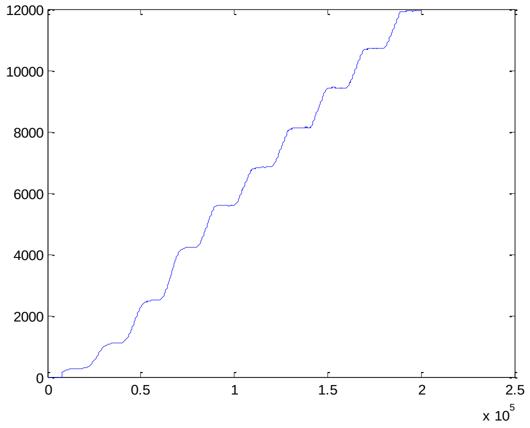


Fig 14: Variation of input power of PV inverter

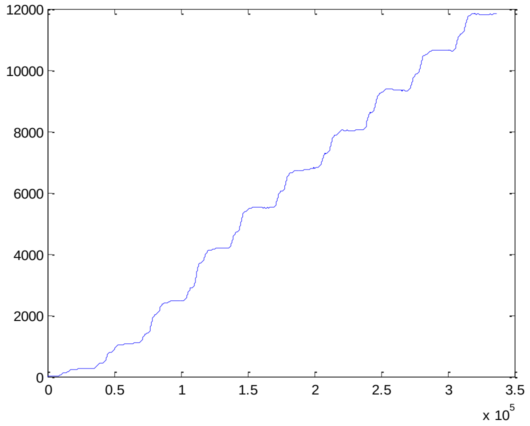


Fig 15: Variation of output power of PV inverter

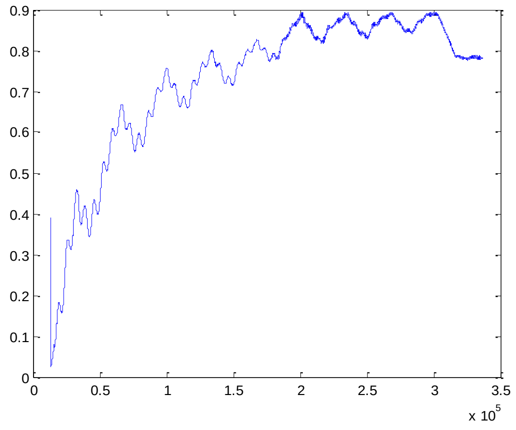


Fig 16: The efficiency of PV inverter under changing illumination condition

B. Analysis and diagnostic results

In all of the simulation, we used a variable curve for solar illumination to verify our system in different load.

According to the got results, we note that in fig 12, the PV voltage stabilizes at about 1 µs in the value of 350V. That is to say, at half load. In fig 13; The DC voltage stabilizes in the range 500 to 600 V to about 1.2 microseconds, this mean that when the BCB begin to adjust the bus voltage with the reference.

In the efficiency curve (fig 16), we can see that the output of inverter stabilized between 0.8 and 0.9 when the illumination 500w/m2, in another point in this monument the BCB ensures the exchange of the power.

In order to reduce the cost of the BCB system, we used this system with many strings. This solution is cost-effective because the power exchange is very little and the BCB does not work continuously.

CONCLUSION

Our goal through this architecture is to create a new hybrid concept basing on the combination of PV system with bidirectional DC.

This System has just confirmed that the best way for optimization of a system is of going directly on the factors, which influenced it. The BCB system based on the optimal distribution of powers in order to reach better efficiency. According to the results of simulation, we can confirm the feasibility of this architecture and the possibility of carrying out this topology in a system PV connected to the grid, but we must optimize it to reach good mode of operation.

In this study, we tried to use a bidirectional DC converter with battery not for store energy but for adjusting the power input of a PV inverter. This last is important for equipment that ensures more functionality in PV systems overcoats with the evolution of PV and increased this new energy into the grid.

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