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A New Power Management Control Strategy for PV-Battery Hybrid System

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Abstract:: photovoltaic are limited in terms of available power due to their intermittent nature. Therefore, in order to balance the power difference between PV and load in an islanded DC microgrid, a battery energy storage system should be used. An energy management control technique for a PV-battery hybrid system is examined in this paper in order to meet the load power needs at all moments. In order to minimize the losses, a unidirectional boost converter is utilized to track the maximum power point or curtail power from the PV array to the common DC load. A buck converter is proposed to connect in parallel with boost converter to charging the battery energy storage system; another boost converter is used to control battery storage's discharge operation. The proposed approach for the power flow load and converters is used to preserve balance of power in the hybrid system, as well as charge/discharge of the battery storage to support the PV panel occurs depending on the PV power generated, state of charging, and the load power requirement. A double-loop control strategy is proposed for each converter taking into consideration the battery's state of charge, battery charge rate limits, and adjusting operating point for PV array in order to avoid overcharge. Additionally, the control system is implemented without needing for programmatic elements or a state diagram. The proposed control strategy design, analysis, and validation results under several operating scenarios are presented and discussed. This work represents a simple method to make the hybrid system more efficient and reliable.

Keywords: Energy Management, Hybrid Stand-alone System, Solar Photovoltaic System, Autonomous Control, DC Microgrid.

1. INTRODUCTION AND OVERVIEW

Solar photovoltaic (PV) has many benefits such as low maintenance, low emission, and decreasing costs as a result of both improvements in technology and higher volume production of solar arrays. The generated power from solar panels dependents on two factors: surrounding temperature and solar radiation, therefore, the solar arrays suffer from the intermittent nature.

In the stand-alone system, the intermittency issue should be solved by interconnections PV array with additional energy sources like fuel cell, microturbine or wind [1]. Also, some approaches adding storage to the system such as supercapacitor, superconducting magnetic, compressed air, or battery energy storage system (BESS) instead of complementary energy sources. So that, making a hybrid PV-BESS in order to balance the load and PV energy production via supply/ store the required /surplus loads power is required. Battery storage unit is considered to be mature technology and more cost-effective on a small scale. There are many types of batteries including lithium-ion, nickel-cadmium, and lead-acid batteries [2]. The more cost-effective solution remains the lead-acid batteries.

A BESS can be connected directly across the load [3], however, such an arrangement has many drawbacks. For example, when the load variations suddenly, may damage the battery because large surge currents appear at this moment. There is also a requirement that the DC load voltage is equal to the BESS nominal voltage. Another method interfacing to dc bus using bidirectional dc/dc converter to achieve discharging/charging power required load demand [4], [5]. The disadvantage of this is that power efficiency is reduced when the battery is charged because the power must be handled by two dc/dc converters which cause more power losses.

A state machine is commonly used in current energy management for hybrid systems [6], or the use of a programmed algorithm [7]. In several papers, various power management control techniques for a hybrid system have been published. Passivity-based control approach is proposed as a power management control approach in [8]. However, the power flow through components is achieved

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using a programmed algorithm. The proposed algorithm does not discuss the current limitation of charging the battery.

In reference [9], the authors suggested optimal energy management for the hybrid system. The system operated with five modes and energy management is achieved with the programmed algorithm. On the other hands, the PV array is forced to run in all modes with maximum power point tracking (MPPT), while, the battery charging/discharge currents constraint is not discussed.

In [10] suggests a three-state state machine with four case situations in order to guarantee that the hybrid standalone system's power balance is maintained. The obtained simulation results did not appear the control on the state of charging (SOC) when the PV power equals the power load.

Reference [11] proposes a four-state state machine with four case states to achieve a power management strategy. Moreover, the PV array is managed to operate in MPPT in all modes, therefore, when the BESS is in charged up and the produced PV power is higher than the load power, the hybrid system becomes unstable. Fuzzy Logic Controller to handle the power flow between both the PV modules and the BESS is suggested in [12]. Also, a single loop control technique is used and the power balance dependent on loads segmentation is considered.

A hybrid stand-alone system's design and performance analysis to reduce the Amper-Hour the capacity of a BESS is proposed in [13]. The proposed approach depends on a state machine, while the PV array is managed to operate in MPPT in all modes. A hybrid system controller design and construction are proposed in [14]. A state machine with five modes is used in this paper. The simulation results showed that the ripple in Vdc when PV power transitions from MPPT to current control is existing.

The proposed strategy in [15] depends on a state machine in PV/ BESS/ fuel cell hybrid stand-alone system to control the power management. The BESS is, however, connected straightly across the load. A power conditioner system between load and BESS has been used for the proposed arrangement in [16]. The proposed system is a single-stage optimized solution for the BESS charge and discharging mode. Moreover, a complementary switching structure is used in the bidirectional converter. In this work, the complementary switching may cause the overlap in discharging and charging mode. Also, the system operating in MPPT in all modes. In reference [17], combination between full-bridge and buck converter for BESS discharge/ charge mode is proposed. Moreover, the system is designed to operate in four modes and the control strategy for the discharge/ charge operation is not fully covered.

From the above literature review, some drawbacks are noticed such as the batteries are connected directly across the loads, the limitations of charge/ discharge of BESS current are neglected, the hybrid system is managed to operate in MPPT in all modes (not discussed if the PV power produced exceeds the power demand and when the charging of BESS reaches to its maximum value), unnecessary power losses through battery charging, single-loop control is used and a state machine or a programmed algorithm is proposed. A new energy management control technique for PV-BESS hybrid system under variable generation and load conditions is suggested in this paper. The main advantages of the suggested structure and control approach are listed below:

1) The control strategy can be implemented without the required programmed algorithm or discrete state.
2) The limitation constraints of battery charging current are included.
3) A dual-loop control technique is utilized to achieve the working of charging/ discharge battery converters and PV converter.
4) The efficiency of the hybrid stand-alone system is increased by charging the BESS through one dc to dc converter instead of using two dc to dc converter.
5) PV panels can be operated at MPPT by using P and O algorithm or curtail PV power without using another control loop. Also, the complexity of the controller scheme is avoided.

The remaining part of the paper is set out as follows: a description of the structure of the system is presented and the power management strategies in section 2 are explained. This is followed in section 3 by a discussion of PV panel modeling, boost converter, buck converter as well as control design. Section 4 displays the simulation output under different variations in generation and load. Finally, conclusion remarks are presented in section 5.

2. SYSTEM TOPOLOGY AND ENERGY MANAGEMENT STRATEGY

In general, there are two configurations when joining a PV panel with a BESS in a hybrid system. The first configuration which can be used in a stand-alone system. The BESS is attached directly to the load in this configuration and the load voltage is defined according to the actual BESS voltage [18].

Additionally, the PV generation power in this case, is regulated to preserve the battery SOC within predetermined limits [19]. Whereas, in the second configuration, the bidirectional dc/dc configuration is utilized to join between the BESS and the load. This type of arrangement gives additional flexibility in selecting the BESS nominal voltage, stores surplus PV power in the BESS to achieve the balance in the hybrid system, permits controllable discharging, and provides peak load of power. As a consequence, BESS charging requires two converters which causing unnecessary power losses. In this paper, the power efficiency is increased by using the configuration is shown in Figure1. In this structure, two independent converters for BESS discharging and charging scenario are used. The unidirectional boost

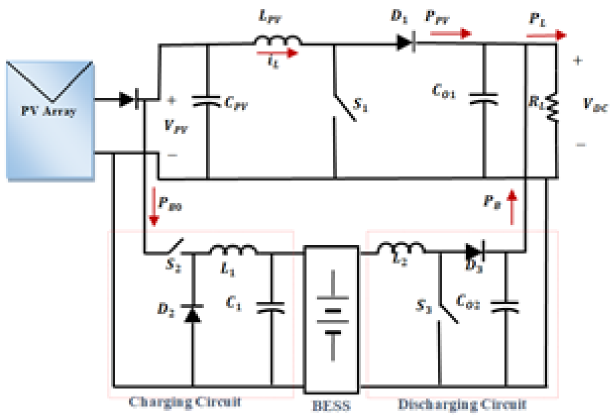

Figure 1. Hybrid System Structure

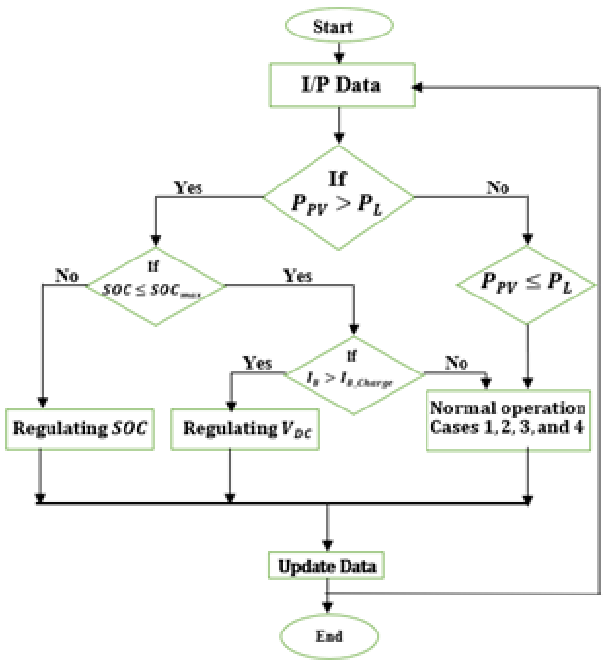

Figure 2. Flowchart of the energy management strategy algorithm

converter for the PV panel is operated to enable MPPT (the perturb and observe algorithm is used) by controlling the input voltage of the PV panel terminal to the MPPT through normal operation. The voltage at the DC load and discharge / charge BESS current is controlled by the discharge and charge BESS converters using a double loop control scheme instead of using two control parameters as proposed in [11] to avoid overlap.

Instead of using one large capacitor for the DC load, a small capacitor is connected across each converter output. The discharge/charge method of the BESS is controlled based on PV power (P_{PV}) generated and the required load power (P_{load}). The buck charging converter reroutes the excess P_{PV} to charges the BESS, while the unidirectional boost discharging converter delivers the required power from the BESS.

Several features are included in the configuration and energy management such as: 1) P_{PV} is used first to meet load requirements, followed by battery charging. 2) the battery source providing the deficit amount of power when the P_{PV} less than P_{load}. 3) P_{PV} processed either for the load requirement or battery charging via a single conversion stage. 4) Battery power is also used a single power conversion stage to satisfy the load requirement. According the energy management strategy shown in Figure2 the hybrid system has been managed. Figure3 illustrated the control strategy that is used in this work. Average current mode control is used for the BESS and PV because of greater noise immunity and supplies additional robust voltage control if compared with peak current mode control [20]. To decrease measurement noise, switching noise, and current ripple a first order low pass filter is used for battery current, DC load voltage, and PV inductor current.

The optimal voltage reference (V^*_{PV}) of the PV panel is produced by the control system in Figure3 dependent on the system constraints like the PV maximum power, load power, and battery SOC. The power coordinate in the hybrid system can be divided into two working conditions according to these variables: normal, and SOC/DC load voltage regulations as listed in the following parts:

A. Normal Case of Operation

When the system operating with normal operation, V^*_{PV} is produced only from the V_{MPPT} algorithm and the additional loop in the PV voltage controller stays inactive. In this case, the maximum power obtainable at the out panel is injected into the connected load by the PV boost converter. By controlling the load voltage to a reference value, the BESS charge/discharge converters deliver the system's power balance. The BESS either absorbs any surplus power or provides every deficit of power needed to meet the load, according to the SOC limits of the BESS.

The hybrid system operates in normal operation has two main conditions: a first condition is available when the SOC of the BESS is less than the maximum SOC_{max} threshold, therefore, the switching selector enables the MPPT. Another condition is available when the BESS charging current attempts to adjust the DC load to be equal to or lower than the maximum charging limit. In the PV voltage controller, the error signal for $PI-VDC$ is positive if the V_{DC} is lower than the nominal voltage. By enabled anti-windup for the $PI-VDC$, the output of the controller is forced to be zero because of the positive saturation limit.

So, in the normal operating hybrid system, this control loop will be inactive. The hybrid system operates in four cases as shown in TableI, depended on the P_{PV} generated and the load power requirements

According to the case-1, if the produced P_{PV} exceeds

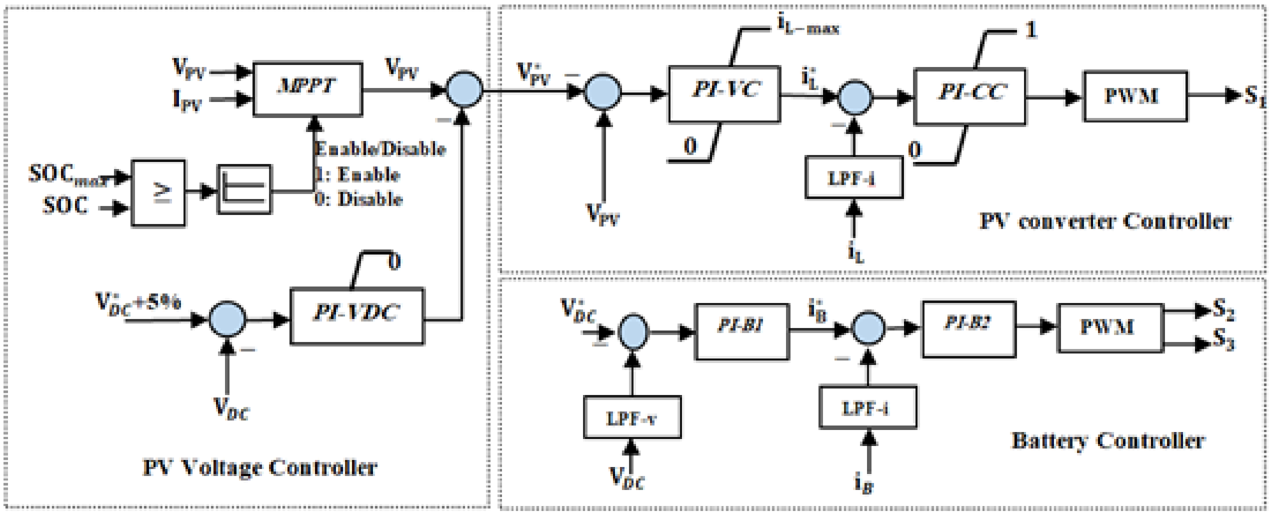

Figure 3. Control System Structure

TABLE I. CASES OF HYBRID SYSTEM WITH NORMAL OPERATION

Case	Condition	Operation Case
Case-1	P_{PV} ¿ P_{Load}	MPPT + BESS charging
Case-2	$P_{PV} = P_{Load}$	MPPT + BESS shut down
Case-3	P_{PV} ¡ P_{Load}	MPPT + BESS discharging
Case-4	$P_{PV} = 0$	BESS discharging

the power demand, the excess power is stored with in BESS. According to the connected load, the BESS charging begins using the buck converter as per the load demand. The controller of the buck converter should be designed to transfer the excess P_{PV} to the BESS after preserving the load voltage while the PV panel operating at MPPT.

The case-2 of the normal operation occurs if the P_{PV} is precisely sufficient to satisfy the power demand only. The PV panel operates at MPPT and provides the full P_{PV} to the load while the charging/discharging BESS converters are shut down. The wanted power is supplied by the BESS if the P_{PV} is not sufficient, according to case-3, to satisfy the power demands. the BESS discharging takes place through the boost converter which follow the power demand. The PV panel converter is enabled to MPPT while the BESS discharge converter's controller is set to preserve the load voltage. During the night as in case-4, the power demand is satisfied by the BESS only because the irradiation is inadequate to produce P_{PV} .

B. SOC/VDC Regulation

The BESS will charge until it reaches the SOC_{max} value when the power provided by the PV panel is larger than the load demand. When the BESS reaches the SOC_{max}, the output of the comparator which is used to deactivate the algorithm of MPPT and the PV panel curtails power. Thus, the power extracted from the PV panel is reduced until the SOC settles at SOC_{max} and the BESS current drops to zero. In this case, the hybrid system keeps working in order to the power provided by the PV panels ability to match the load demand. During normal operation of the hybrid system, many operating disturbances can happen. For example, the generated PV power is increased because of temperature decrease or irradiance increase and/or the load decreases. At this point, the BESS charging will absorb the surplus P_{PV} available to preserve the DC load voltage constant at the nominal value. Consequently, when the SOC reaches the SOC_{max} value disables the MPPT algorithm and the PV panel curtails power. Another disturbance may be occurred when the PV power is decreased and/or the load is increased, moving the operating point towards the MPPT and the PV panel operating with the MPPT algorithm again. If the P_{PV} continues to decrease and/or the load continues to increase, the BESS discharge supplies the power of the deficit to control the load voltage.

Through the above disturbance, the PI-VDC loop in the P_{PV} regulator is supposed to be inactive. if the P_{PV} is larger than the P_{Load} the BESS will absorb the surplus power available to control the load voltage. Consequently, the BESS charging current is restricted and depends on the BESS chemistry. When the load is light and the P_{PV} is high, the BESS charging current may grow outside this limit.

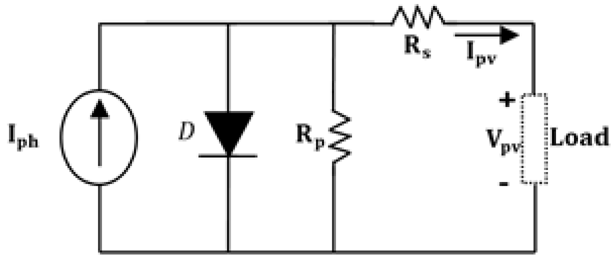

Figure 4. A solar cell's equivalent circuit

Therefore, the regulator will control the BESS charging current with a maximum charging limit. At this period, the converter controlled the BESS charging current rather than the load voltage. At this stage, the load voltage is increased because of the excess energy which cannot be absorbed by the BESS. Therefore, in order to preserve the balance of power in the hybrid system, the P_{PV} should be decreased. To control the load voltage when the charging converter control the BESS charging current, using the PI-VDC loop to regulate the load voltage with the maximum limit allowed (less than 5% of the nominal voltage). If V_{DC} goes to increase outside the maximum limited load voltage, the PI-VDC control loop begins to move the PV panel reference voltage to the operating region of the voltage source of the V-I characteristic. Furthermore, when the PV power decrease and/or the load power increases is occurred, the output of the PI-VDC loop will continuously shift the V^*_{PV} to control V_{DC}. Moreover, the decreasing as in P_{PV} as well as increasing in the load will allow V_{DC} to decrease and the current controller of the BESS charge will be decrease too.

3. MATHEMATICAL MODELING AND CONTROL DESIGN

This section demonstrates the mathematical modeling and proposed PV panel control designs, PV boost converter, as well as the charge/discharge BESS converters are shown in this section. Table 2 represented the parameters of the hybrid system.

A. PV Model

Figure4 represented the equivalent circuit for a solar cell. In this paper, to describe the features of the solar panel, the model is based on a single diode. The relationship between V-I characteristic for the PV panel is given by [21].

$$I = n_p \left[I_{ph} - I_s \left\{ \exp\left(\left(\frac{q}{AkT} \right) \left(\frac{v}{n_s} + \frac{I}{n_p} R_s \right) \right) - 1 \right\} - \frac{\frac{v}{n_s} + \frac{I}{n_p} R_s}{R_p} \right] \quad (1)$$

Where I and V are the current and voltage of the PV panel, respectively; A represented the diode quality factor (1.5); T is the PV panel's surface temperature measured in Kelvin; I_{ph} is the photo-generated current; q represented the charge of electrons (1.602 ∗

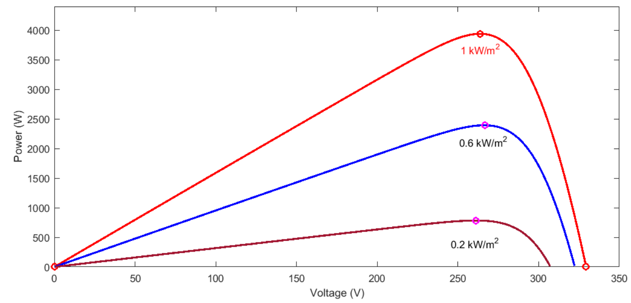

Figure 5. Output of V-P Characteristic under different radiation

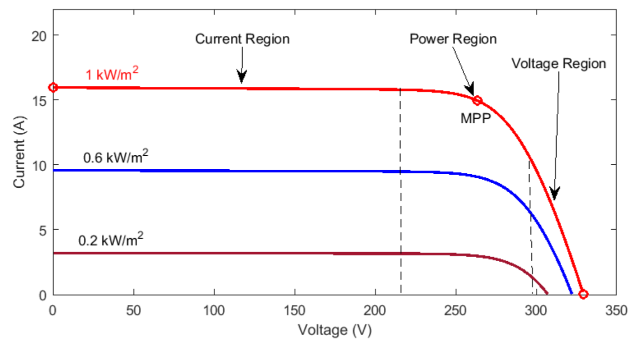

Figure 6. Output of V-I Characteristic

[U+3016]10[U+3017]^{-19}C); the Boltzmann constant represented by k (1.38∗ [U+3016]10[U+3017]$^{-23}J/K$); I_s represented the diode saturation current; R_p and R_s are the cell parallel and series the PV panel resistances, respectively; n_p and n_s are the number of parallel and series cell strings, respectively.

In this work, each PV panel involved 60 cells. The PV array contains two parallel strings, and each string contains nine panels linked together in a series. So, the total power equals 3.94 kW. Figure5, figure6 shows the relations between V-P and V-I characteristics at MPP with temperature 25 C under three operating condition.

B. PV Unidirectional Boost Converter Control Design

A DC/DC boost converter is used to link the PV array to the load. The DC/DC boost converter used a double loop PI controller scheme to regulated the PV array's output current and voltage. Two loops are used in the proposed controller; the voltage control loop represented the outer loop which manages PV voltage as the reference value while the current control loop represented the inner loop as illustrated in Figure7

The outer loop's output works as a reference current of the boost converter input current by limiting the PI control between zero as a lower value and maximum PV array current as an upper value. The converter's switching frequency is 20 kHz and the LPF's time constant is [U+3016]5 ∗ 10[U+3017]$^{-5}$seconds. The averaged model

TABLE II. SYSTEM PARAMETERS

Design Parameters	value
PV Input Capacitor, C_{PV}	470 μF
PV Inductor, L_{PV}	880 μH
PV Output Capacitor, C_{O1}	1200 μF
Buck Capacitor, C_1	1200 μF
Buck Inductor, L_1	550 μH
Boost Capacitor, C_{O2}	1200 μF
Boost Inductor, L_2	880 μH
Nominal Load Voltage, V_{DC}	400 V
Nominal Battery Voltage, V_B	192 V
Voltage in the PV Open Circuit, V_{OC}	329.4 V
Current in the PV Short Circuit, I_{SC}	15.95 A
Load Resistance (low, med, high)	$30, 41, 70\ \Omega$

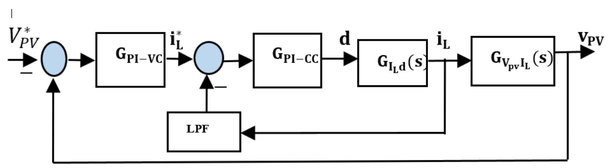

Figure 7. Closed Loop Control Model of Boost Converter

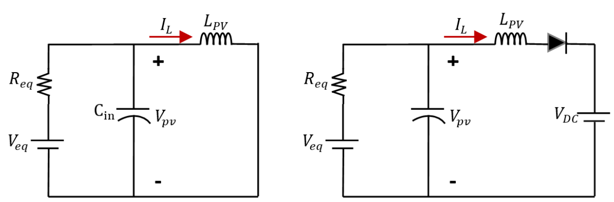

Figure 8. PV Boost Converter Circuit Model

equations obtained in switching on and off states are used to derive the voltage and current loop transfer functions for a boost converter, as illustrated in Figure8.

Equations 2 and 3 show the averaged state equations when the switch is on and off state and using dynamic resistance of PV panel in the voltage and current source regions.

$$L_P V \frac{di_L}{dt} = V_{PV} + V_{DC} * d \tag{2}$$

$$C_{PV} \frac{dV_{PV}}{dt} = \frac{V_{PV}}{r_{PV}} - i_L \tag{3}$$

Where d represented the averaged control input, r_{PV} represented the dynamic resistance of a PV panel about the operating conditions and designated with a negative number, i_L is inductor current, and V_{DC} is the nominal load voltage. After tacking Laplace transform for equations 2 and 3, the transfer functions for the inner loop with d as input and i_L as output while inductor current as input and V_{PV} as output for the outer loop can be written as,

$$G_{i_L d}(s) = \frac{i_L(s)}{d(s)} = \frac{(SC_{PV}r_{PV} - 1)V_{DC}}{s^2 L_{PV}C_{PV}r_{PV} - sL_{PV} + r_{PV}} \tag{4}$$

$$G_{V_{PV} i_L}(s) = \frac{V_{PV}(s)}{i_L(s)} = \frac{-r_{PV}}{sC_{PV}r_{PV} - 1} \tag{5}$$

By multiplication of the two transfer functions of Eq.4 and Eq.5, yield the integrated feed-forward gain as illustrated in (6).

$$\frac{V_{PV}(s)}{d(s)} = \frac{V_{PV}(s)}{i_L(s)} * \frac{i_L(s)}{d(s)} \tag{6}$$

The frequency response method is used to design the PI controllers and selected as follows:

$$G_{PI-VC} = \frac{s+20}{s}$$

$$G_{PI-CC} = \frac{s+50}{s}$$

By using the above controllers in the current and voltage loops, the boost converter operates as an underdamped system with the least settling time and minimum overshoot. Additionally, as shown in Figure9, the open loop frequency response with two dynamic resistance and without using a PI controller, while in figure10 the controllers are tested for stability with dynamic resistances using two resistances; $r_{PV} - cs$ in the current source area and $r_{PV} - vs$ in the voltage source area, the gain and phase margin vary slightly. Also, this demonstrates the controller's robustness in the face of large variations in r_{PV}.

C. Control Design of Buck Converter

The average buck converter state space equations described in [11]. The time constants for the low-pass filters

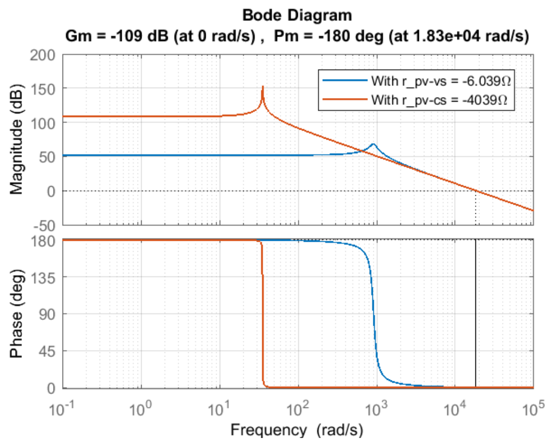

Figure 9. Bode plot of PV Boost Converter Open-loop

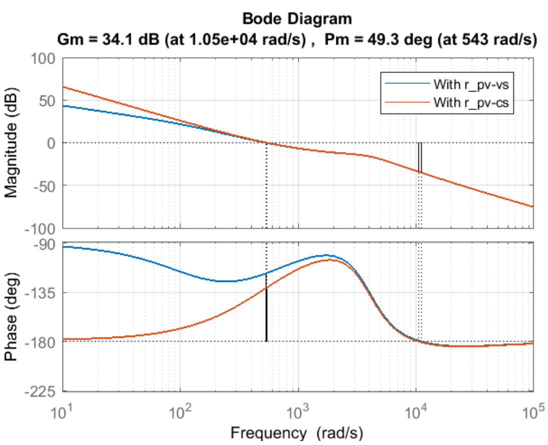

Figure 10. Bode plot of Closed-loop

LPF-v and LPF-i are selected to be $1 * 10^{-4}$ seconds and $5 * 10^{-5}$ seconds, respectively. Depends on TableII with the converter's switching frequency is 20 kHz, the frequency response method is used to design PI controllers of the voltage and current loops. The designed controller of PI_{VC} and PI_{CC} are given as

$$PI - VC = \frac{0.25s+50}{s}$$

$$G_{PI-CC} = \frac{0.01s+20}{s}$$

4. SIMULATION RESULTS

Matlab simulations is used to verify the proposed control strategy. it is tested the normal operation with all cases using three scenarios; changing the irradiance of solar panel, changing the irradiance with charging/ discharging repeatedly, and changing the connected load. Moreover, the SOC and V_{DC} regulations are tested.

A. Normal Operation

When the irradiance changed, accordingly the power extract from the PV array is changed too. Figure16(a) represented the simulation result when the PV irradiance is decreased with three steps; from 1000 to 600 w/m2, 600 to 300 w/m2, and from 300 to 0 w/m2 within 20 sec. In all plots, voltage is represented in volt, current is represented in ampere, and active power is represented watt. the SOC setting with 60%.

According to Figure20 (a), it can be noted that, the P_{PV} is larger than the power load through the first 5 sec. Therefore, the BESS is charged in order to control the load voltage. During the second step, the power generated from the PV panel is only sufficient to satisfy the power demand. Thus, in this case, both the reduction of discharging and charging current to zero, i.e. the BESS converters are shut down for charging/discharging. At this step notes that, the small difference between the P_{PV} and P_{Load} which means the losses in the system during unidirectional boost converter is very low. The solar radiation reduces further during the third step and the P_{PV} is insufficient to satisfy the requirement for power load. So, the BESS will supply the deficit of the power via discharging converter. At the night, the solar irradiance is decreased to zero. in this case, the BESS will supply the power to the load via discharging converter and it can be noted the small difference between P_B and P_{Load} which means the losses in the system is very low during buck converter

From Figure16 (b) and (c), notes that the PV current reduced with PV irradiance, therefore, the battery current increased to achieve the load current requirement. According to Figures16 (e) the load voltage small decreased at each three steps within the prelimited minimum and maximum values and return to specified reference with less than 0.2 sec.

Additionally, to test the controller, the solar irradiance is changing suddenly to examine the change from discharge to charge case then return to discharge case is very smooth as shown in Figure23.

Furthermore, the controller examined with load variable as shown in Figure27. It can be noted that, the four cases of hybrid system with normal operation are explained the active power and SOC. Load voltage decrease in a moment of increasing the load and return to nominal value with less than 0.15 sec.

B. SOC and Load Voltage Regulation

If the SOC reaches its maximum value, the operation of controller focuses on regulating the PV voltage away from the MPPT as illustrated in Figure31. From Figure31, it is noted that the V_{PV}^{*} rises from 263 V to 306 V. Corresponding to the new reference voltage the P_{PV} decreases to 2400 W to achieve the balance of power in the hybrid system as well as discontinuing the BESS from charging.

The BESS reacts quickly when the power load increases, to accommodate the new load. Therefore, the SOC is reduced to less than its maximum value and the PV panel is

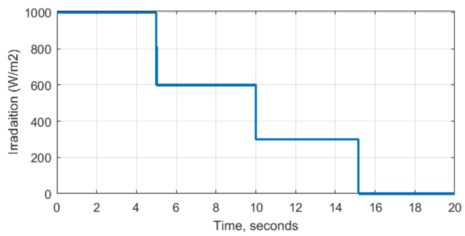

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Figure 11

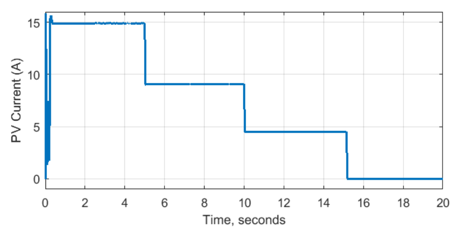

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Figure 12

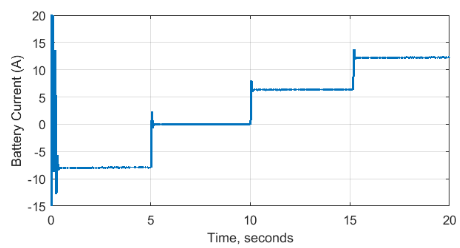

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Figure 13

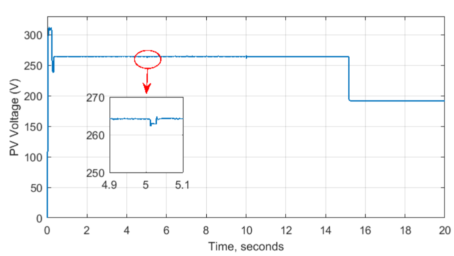

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Figure 14

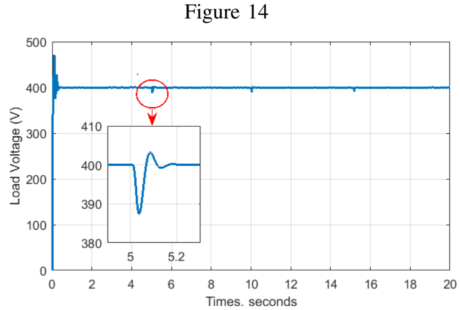

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Figure 15

Figure 16. Simulation results of (a) Solar radiation (b) Current of PV (c) Current of Battery (d) Voltage of PV (e) Voltage of Load.

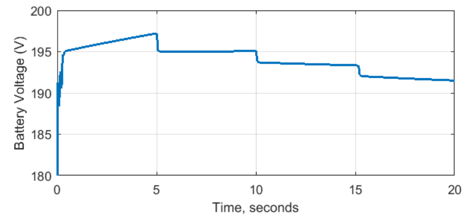

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Figure 17

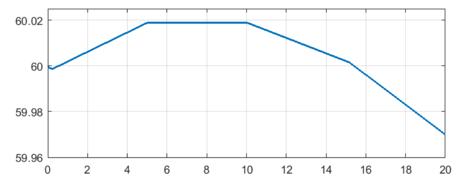

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Figure 18

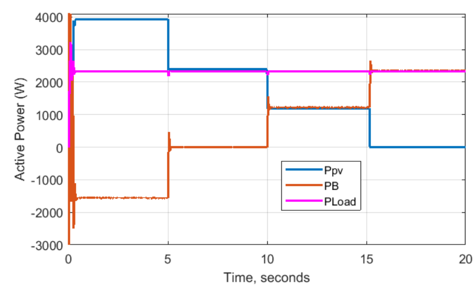

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Figure 19

Figure 20. Simulation results of (a) Voltage of Battery (b) SOC (c) Active Power.

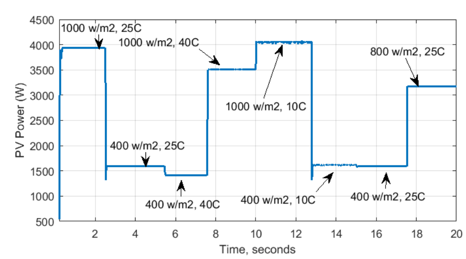

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Figure 21

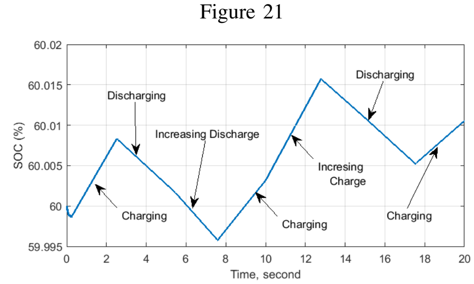

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Figure 22

Figure 23. Simulation results of (a) PV Power (b) State of Charging.

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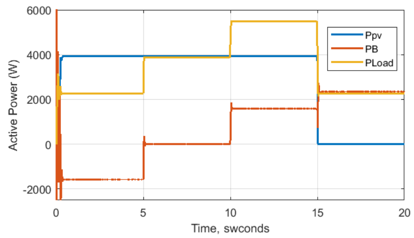

Figure 24

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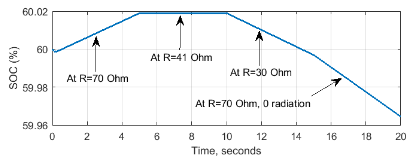

Figure 25

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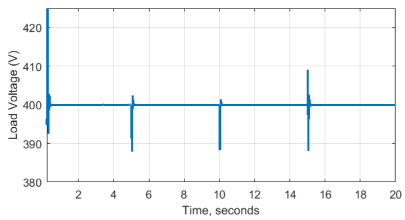

Figure 26

Figure 27. Plots of (a) PV Power (b) State of Charging (c) Load Voltage..

forced to operate back with MPPT. It can be noted that, the hybrid system regulating the SOC when reach to maximum value within less than 0.3 sec and the PV panel is operate with MPPT with less than 0.1 sec.

The battery's charging current is limited (12 A in this paper) based on the lead acid battery. When a light loaded is connected, the P_{PV} may exceed the limit for the BESS. Therefore, the load voltage starts rising because the BESS charging converter cannot adjust it by absorbing the surplus energy. The PI-VDC in the external loop operates to shift the V^{*}_{PV} away from MPPT with less than 0.2 sec. to adjust the load voltage with the maximum limit value. Thus, the P_{PV} reduces according to the new V^{*}_{PV} as illustrated in Figure35. It should be noticed that, the controller operates efficiently and smoothly in all cases of working without losing the operating stability. The control of the hybrid system that is used does not have any limitations and it is characterized by tacking all considerations without neglecting any parameter. Also, the autonomous control represents the modern trend in the construction of DC and AC Microgrid.

5. CONCLUSION

An efficient power management control strategy with a double-loop for adjusting a hybrid stand-alone system has been designed and tested. The proposed strategy regulates the P_{PV} converter as well as the charge/discharge BESS

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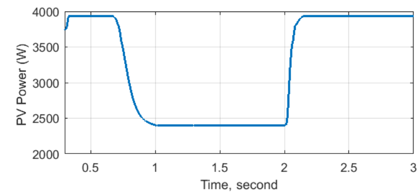

Figure 28

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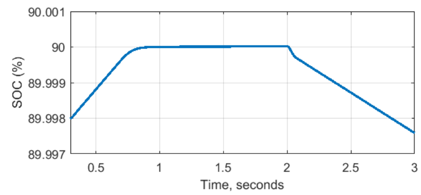

Figure 29

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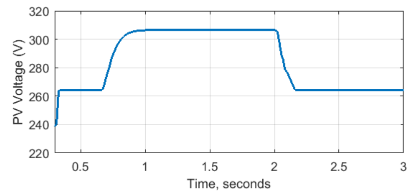

Figure 30

Figure 31. Plots of (a) PV Power (b) State of Charging (c) PV Voltage.

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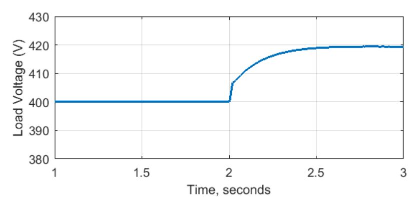

Figure 32

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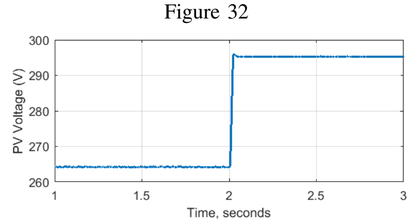

Figure 33

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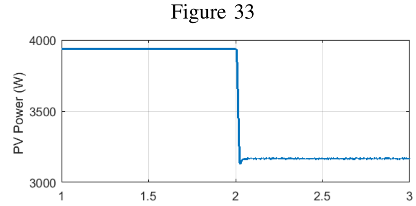

Figure 34

Figure 35. Plots of (a) Load Voltage (b) PV Voltage (c) PV Power.

converter in the presence of a predetermined limit. Dependent on the PV maximum power, the battery state-of-charge, and the load power the hybrid system operation has been divided into two categories: normal operation, SOC and load voltage regulation strategies to easily control the power transfer inside the hybrid system. During normal operation, the PV panel work at MPPT in all cases while curtailing the P_{PV} when SOC and/or load voltage regulation scenario. The proposed hybrid system has the following advantages: (1) fewer switches are required for battery charging, resulting in lower power losses; (2) seamless power transfer between BESS and load; (3) autonomous control is used to produce a smooth transition between MPP and SOC or DC voltage regulation instead of using a state machine, that requires another control the regulate the DC bus. The suggested strategy and control scheme under various radiation and load conditions has been identified and validated in the hybrid system.

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