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Control of Hybrid Units in Low-Voltage Islanded DC Microgrid Based on Decentralized Energy Management Strategies

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Abstract

This paper attempted to control a hybrid DC microgrid in islanded operation mode using decentralized power management strategies. Unlike traditional approaches where a Photovoltaic (PV) module is controlled as current source, the current proposed strategy controls PV module as a voltage source that follows the current/voltage adaptive characteristic curve. Proposed I/V characteristic for hybrid PV/battery and wind turbine generator (WTG) adapts the DG behavior independently in accordance with the load demand. Hence, the PV module can spend its maximum power on load demand and spend the extra energy on charging the battery, which will maintain the power balance within the DC microgrid. When load demand is beyond the maximum PV generation power, WTG will supply the energy shortage. The proposed control system was applied on the DC microgrid in order to achieve control objectives through a decentralized procedure, without telecommunication links or any central energy management system. In order to validate the proposed strategies, the control system was implemented on a DC microgrid within MATLAB/SIMULINK, where the simulation results were analyzed.

Keywords: *DC microgrid, energy management, decentralized control, droop method, hybrid unit*

1. INTRODUCTION

In recent years, electric energy consumption has been rising steadily. Hence, it has become crucial to offer an optimum structure for transmission and distribution systems to reduce losses and increase efficiency. In this regard, the concept of microgrid and smart grid has been developed most recently. Smart grids refer to electricity networks of the future revolutionizing the clean electric energy supply in the 21st century based on modern communication technology and renewable energy sources with greater reliability and more flexibility than conventional power systems. Smart grids are based on the principle of decentralization of power networks, where the power systems are divided into smaller networks called microgrids connected to the DGs. Microgrid refers to an accumulation of loads and distributed generation resources in low and medium voltage levels functioning as a power system for power generation and if possible, as Combined Heat and Power (CHP) [1]-[4]. A microgrid is utilized through two modes of connected to the network or independently of the network. Electrical energy generation sources used in microgrids can be micro-turbines, fuel cells, Photovoltaic solar cells, wind turbines or other forms of distributed generation along with any storage devices such as super-capacitors and batteries [5]. Due to population growth and increased demand for electrical energy,

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there have been great challenges in increasing environmental pollution, depleting fossil fuels, limited construction of new transmission lines, greater reliability as well as changes and economic developments in the electricity market, all of which requiring higher level of distributed generation. With the progress made in distributed generation technology, there have been many advantages together with numerous problems in terms of network operation and protection. For example, one of the problems arising due to the growth and development of power systems is the aggravated level of fault current and short circuit because to the presence of DGs within a microgrid. Therefore, the causes and important advantages for the use of DGs in microgrids and electrical power distribution systems can be generally categorized as follows [6]-[7]:

1. Not requiring too much investment, employment of public participation and average assets
2. Short construction period
3. Elimination of transmission losses and power distribution loss reduction compared to large centralized power plants
4. Ease of use as CHP (combined heat and power generation)
5. Portability and easy handling
6. Access to sources of energy supply with high protection factor (passive defense)
7. The possibility of localization and local production
8. Easy locating and not requiring special gas supply network

The DC microgrids have been widely discussed by researchers most recently. All DGs and loads in a DC microgrid are connected to a common DC bus voltage. The main purpose of analyzing this microgrid is to maintain a power balance between sources of energy generation and battery storage system, common DC bus voltage stability and maintaining the range of voltage within the allowable limit from 0.95 to 1.05 pu. and energy management [8]-[11]. Generally, loads are DC type and in the presence of AC loads, they will be connected to PCC[1] via power electronic converters.

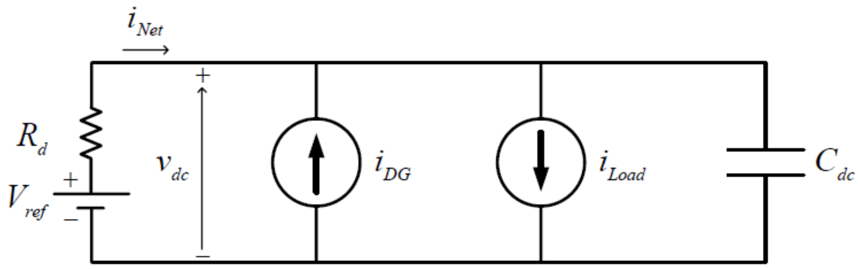


Fig. 1. Schematic diagram of a DC microgrid

Figure 1 shows the diagram of a DC microgrid. In the above figure, V_{ref} represents the reference voltage of microgrid, R_d is source resistance, i_{DG} is current injected into the microgrid by distributed generation unit(s), i_{Load} is load current or power consumption and C_{dc} is the microgrid capacitor. This type of microgrid usually applies distributed generation resources with DC nature, such as PV and fuel cell so as to supply its power. In case there are sources such as wind turbines and synchronous generators, the supply output will be injected into the microgrid through a rectifier. The upstream distribution system is connected to the DC microgrid common bus through a step-down transformer, static circuit breaker and power electronic converter. Generally, the control objectives of DC microgrids in the field of energy management can be divided into two categories [12]-[13]:

- Optimal power distribution among DGs in order to support the common bus voltage (voltage regulation) and reduce circulating currents.
- Controlling the state of charge (SOC) of battery and keeping it in optimum level.

[1] Point of Common Coupling (PCC)

Conventional droop controllers to achieve both mentioned targets simultaneously are not effective. Although the above objectives can be achieved by centralized controllers, the implementation of the above method requires high-speed communication and telecommunication links, which can reduce the reliability of the entire system. These limitations can be overcome by proposing a decentralized controller for DC microgrid, which brings about several advantages such as higher reliability, optimum voltage regulation and uniform load distribution [14]-[15]. In independent and local decentralized microgrid control, the virtual resistance value is determined by trial and error, or artificial intelligence techniques, where the former is extremely time-consuming and rarely yields an optimal solution. In case there are several DGs in a microgrid connected to different capacities by a common bus, it will be essential to maintain power balance and decrease the circulating currents in the microgrid.

A DC microgrid has been practically implemented in Energy and Water Research Lab Nanyang, University of Singapore [16]. Coordinated control of multiple sources, DC distributed generations and energy storage systems were realized based on hierarchical control. Bus voltage functions particularly as an indicator in the analysis of the balance of power demand, while a Wireless Control was applied to achieve reliable performance. There was a logical interaction between maximum power and effective battery management using coordinated control according to a central energy management system. Microgrid hierarchical control is characterized by controlling system behavior ranging from voltage stability to energy management at three distinct levels. At the first level, the microgrid voltage stability is fulfilled through controlling the droop levels of DGs and batteries, while the controller errors are zeroed at the second control level. In the third layer, hierarchical control deals with a macro approach to energy management in the microgrid including: Maintaining power balance, monitoring and control of power flow between the microgrid and upstream distribution network using droop control [17]-[18]. A control strategy can be a proposed to achieve stable microgrid performance in different functional states, leading to both DC bus voltage stability and good quality load supply [19].

The newly proposed method optimally adapts the battery energy storage system so as to operate under the proposed control strategy in two modes of connected to the main grid and isolated regardless of the functional status of the microgrid. Generally, when the microgrid is connected to the main grid aligned with its normal operation, the AC grid power electronic converter injects the active power into the microgrid in order to stabilize the DC voltage, where energy storage systems can preserve their power for necessary situations and prevention of load shedding. By such control method, seamless transfer of battery converter shall be facilitated between charge and discharge modes as well as the rectification and the main network inverter entailing reliable performance for various microgrid operating conditions [20]. Furthermore in [21], a DC microgrid involved DGs and battery energy storage system (BESS) along with an independent three-level control strategy for DC microgrid with slack terminal selected for every system performance situation. It is noteworthy that functional status of the microgrid is identified and analyzed by common DC voltage and transition between different microgrid operating points. A four-terminal DC microgrid with a voltage source converter connected to the main network involve a wind turbine, a battery energy storage system and a modeled DC load, where the newly proposed control scheme was applied under different functional conditions such as load changes, output power variations, load shedding, connected and isolated performances and energy generation cease on the system.

When microgrid operates in isolated mode, DG converter (wind turbine) operates as voltage source playing the role of slack bus. The converter output is monitored to achieve the targets only through receiving feedback from current output disregarding the voltage range. In order to achieve more accurate and practical results, it is suggested to measure the output voltage and current of converters [22]-[23]. Given the optimal allocation of power between distributed generation units, the controlling effect on the circulating currents among resources has been ignored. Droop control is a classic conventional method to divide the load current within DC microgrids [24]. Conventional droop control has been developed through linear reduction of output voltage for increasing the output current. The fundamental limitation in conventional droop is that application of line resistance in DC microgrid controlled by droop method will curtail the accuracy of output current allocations, since the converter output voltages cannot be precisely identical. In this reference, the performance of DC microgrid was improved while proposing a low-bandwidth communication system based on optimal droop control. Contrary to the conventional approach, control system does not require a secondary centralized controller. In fact, the local controllers and low bandwidth communication systems are used to exchange information between the converters. In fact, droop controller is used to ensure stable voltage while current controllers are used in each converter to improve in real-time the accuracy of current allocation and DC bus voltage regulation. In this scheme, all controllers are local and the low-bandwidth communication systems are used only to swap DC voltage values and currents between converters; hence, a hybrid control scheme composed of centralized and decentralized controls are applied. The main disadvantages of the proposed method are lack of energy storage systems to support the voltage regulation and power balance in the microgrid, thus decreasing system reliability due to the utilization of telecommunication links [25]-[26].

Coordinated control of distributed generation energy sources in a microgrid not only establishes the SOC balance between energy storage systems, but also curtails the circulating currents on the basis of droop control [27]. Using the proposed method of this reference, the battery with higher SOC delivers more power and vice versa. Therefore, the energy stored in a battery with higher SOC is discharged more quickly than batteries with lower SOC. The SOC difference between the energy storage units gradually diminishes and eventually the load power is divided equally among the energy storage sources. Moreover, load allocation rate can be adjusted by changing the SOC level in adaptive droop control. This approach requires no communication links, leading to specify the optimal level of battery SOC as well as effective performance and increased battery life. It can also be generalized to several energy storage systems. The disadvantage of the proposed method is that time delay of batteries for power injection into the common DC bus has been disregarded. Moreover, it does not distribute the power effectively between the DG units and batteries, which might lead to circulating currents within the microgrid.

In [28], a control method was proposed according to droop control and virtual resistance for load current sharing and reducing the circulating current in a low voltage DC microgrid through parallel DC-DC converter. Conventional droop methods lead to weak current sharing and voltage drop in DC microgrid. The circulating current in the microgrid is created due to the mismatch of output voltage of power electronic converters. Therefore, this reference introduced an indicator named DI (Droop Index), which both improves microgrid performance and reduces losses and current allocation difference in the converter output. The newly proposed adaptive droop method can curtail the circulating current and current allocation difference of converters by real-time virtual resistance. Virtual resistance added to the converter output can achieve voltage regulation within the allowable range while desirably distributing the power. The disadvantage of the proposed technique is that the scope of virtual resistance is determined without the use of artificial intelligence methods, thus increasing the duration of converter control and probably leading to unstable converter output. Moreover, this method does not allow determining the optimal virtual resistance. Another disadvantage of this method is that SOC of batteries is disregarded and the DC microgrid energy management plan is not general and applicable.

This paper proposed a decentralized management strategy for hybrid PV/battery unit and wind turbine module. According to the proposed strategy, PV is as controlled the voltage source following I/V multi-segment characteristic curve. The I/V multi-segment characteristic curve of the hybrid module and droop characteristic of wind turbine can independently and locally adapt the generation power of units with load demand and delivering maximum power generated by PV module to microgrid. In the case of load demand is more than MPPT power of the PV module; the wind turbine will supply the energy shortage. If the total generation of DGs is lower than load demand, the battery begins to discharge so as to supply the load demand. These strategies establish the balance of power and maintain the level of battery SOC within the allowable range. In general, the battery system in hybrid unit establishes the power balance in the microgrid and also adjusts the common bus voltage. All the above targets will be fulfilled only through local and independent control, without any need for centralized control or communication links.

2. PROBLEM STATEMENT AND OBJECTIVES

Generally, the aim of the proposed control strategy was to coordinate the performance of hybrid PV/battery unit and wind turbine generator through droop control method, so that maximum power of PV module is delivered to the microgrid. This objective can provide the balance of power, preserving battery SOC at an optimum level and voltage regulation in DC microgrid. This control strategy provides the following benefits without dependence on telecommunication links in the microgrid:

1. The hybrid unit can deliver total power of the PV to the DC microgrid after charging the battery at the desired SOC level.
2. The hybrid unit absorbs the power from the wind turbine so as to charge the battery without interfering the power balance in the microgrid. In other words, the required power will alter to charge the battery independently on the basis of load variations and available DG power, so as to supply the load demand fully in real-time.
3. If PV generation power is more than the load demand, the hybrid unit will supply load demand completely and store the excess power in the battery, in the case of battery SOC is less than the minimum SOC.
4. If the battery is fully charged or the battery SOC is within the allowable range, or the excess power of PV is over the nominal capacity of the battery, PV MPPT controller take away PV operating point from the MPP region to adapt generation power with the load demand.
5. In the microgrid normal operation mode, the battery unit will not provide any portion of the load demand so long as the load demand has not surpassed the generation power of DGs. Hence, the battery energy storage system in the hybrid unit establishes power balance in an isolated microgrid similar to each separate or independent battery unit.

The contribution of this investigation lies on the achieving all of these results by an independent control strategy without the need for communication links or any centralized energy management system. This feature increases system reliability compared with centralized control method. It is worth noting that the proposed control strategy for the hybrid unit of PV/battery entails interoperability in multi-unit combinations, which is beyond the scope of this paper.

3. DC MICROGRID HYBRID STRUCTURE

In this paper, the hybrid unit included a PV module and battery, and a wind turbine generator is supposed in a adaptive droop control microgrid as shown in Figure 2. The control strategy was designed and implemented so as to be generalized to a larger number of hybrid units and droop control units. Notably, microgrid droop control refers to the third layer of hierarchical control within microgrid energy management system.

Figure 2 illustrates hybrid PV/battery, wind turbine generator (WTG) and constant power load in proposed DC microgrid. The wind turbine represents an energy source controlled by droop method with internal control loops in order to meet the load demand and regulate the DC link voltage. The PV array was regulated by a unidirectional boost converter so as to connect to microgrid common bus at the desired voltage level. I_{pvo} is the current injected by PV module into the DC link while I_B represents the current in the battery terminals. The battery unit is connected to the DC link by a bidirectional power electronic converter so as to fully control the process of charging and discharging the battery. Moreover, the use of a DC/DC converter increased the flexibility of DC link and battery voltage selection [30]. The hybrid unit is connected to the DC microgrid common bus by a voltage source converter (VSC) which is a DC/DC converter and a feeder resistance (R), where control strategy shared between PV module and battery will control the battery SOC and adjust microgrid voltage by the VSC strategy. In fact, the power management strategy in a hybrid DC microgrid can be divided into two subsets, the first is the VSC strategy that managing the power flow between DC microgrid and hybrid unit while directly coordinating the PV and battery performance in order to support the power balance in the hybrid system. The second subset involves the DC/DC converter control system that managing the power flow between the PV and WTG units, battery and DC microgrid in order to maintain the power balance. Moreover, the DC/DC converter of battery unit can regulate the DC link voltage through controlling the reference voltage, whereas the PV converter is controlled so as to inject the available power into the DC link.

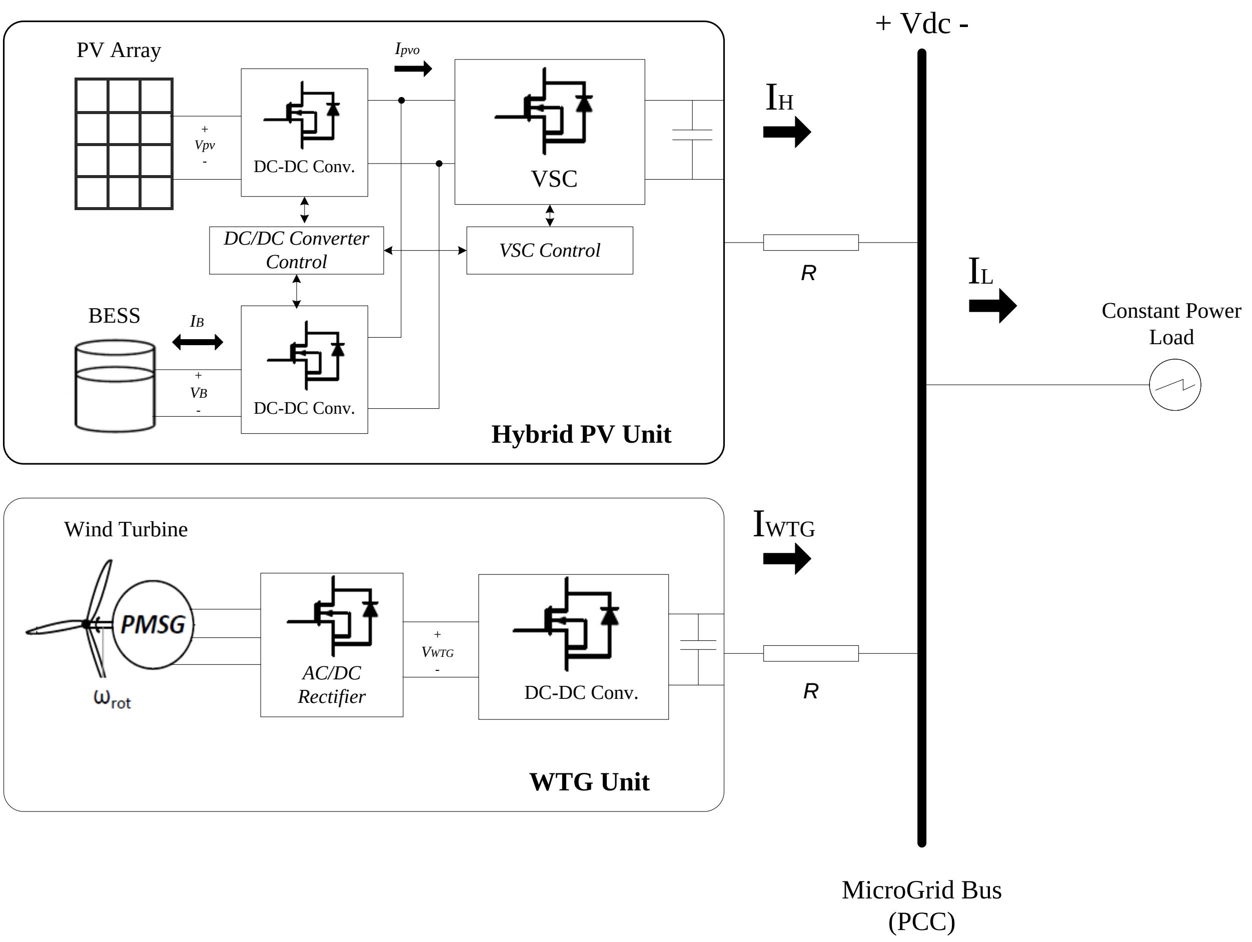


Fig. 2. Block diagram of proposed DC microgrid

4. VSC CONTROL STRATEGY

The purpose of VSC control strategy is the synchronization of hybrid unit performance with the wind turbine within the DC microgrid. I/V Characteristic curve of wind turbine has been shown in Figure 3. $I_{WTG\text{-}max}$ refers to the maximum current that can be produced by WTG unit and delivered to the microgrid.

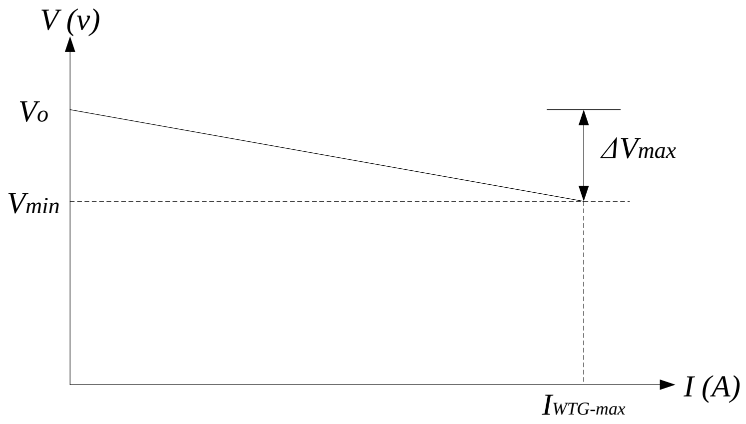


Fig. 3. Current/voltage characteristics of the Wind Turbine Generator (WTG)

In fact, VSC or DC/DC converter in the hybrid unit is controlled similar to voltage source aimed at adjusting the power or output current of the unit. This target is achieved by controlling the output voltage of the unit as shown in Figure 4. Output current (I_H) is regulated indirectly by controlling the battery current (I_B) by P_I controller. It is also worth noting that DC/DC converter of battery supports the power balance in the hybrid unit by adjusting the common DC link voltage. Control error (e_P) in PI controller input is calculated as follows:

$$e_{\mathrm{P}} = I_{B-ref} - I_B = I_{B-ref} - (I_H - I_{pvo}) \quad (1)$$

In order to simplify calculations, the power dissipation is disregarded [31]-[35]. Reference current (I_{ref}) is defined as follows:

$$I_{\mathrm{ref}} = I_{B-ref} + I_{pvo} \quad (2)$$

Hence, the control error (e_P) can be reformulated as follows:

$$e_{\mathrm{p}} = I_{ref} - I_H \quad (3)$$

From the above equation, it can be concluded that regulation of current I_B in the reference value $I_{B\text{-}ref}$ is equivalent to regulation of output current of the hybrid unit (I_H) in the reference current I_{ref}. Moreover, the controller can be applied directly in order to adjust I_H in the reference value I_{ref} using the measured of I_{pvo} and the reference current value $I_{B\text{-}ref}$. Notably, when the reference value is calculated using the measured I_{pvo}, the VSC output current is regulated in I_{ref} and converter losses are supplied by the battery.

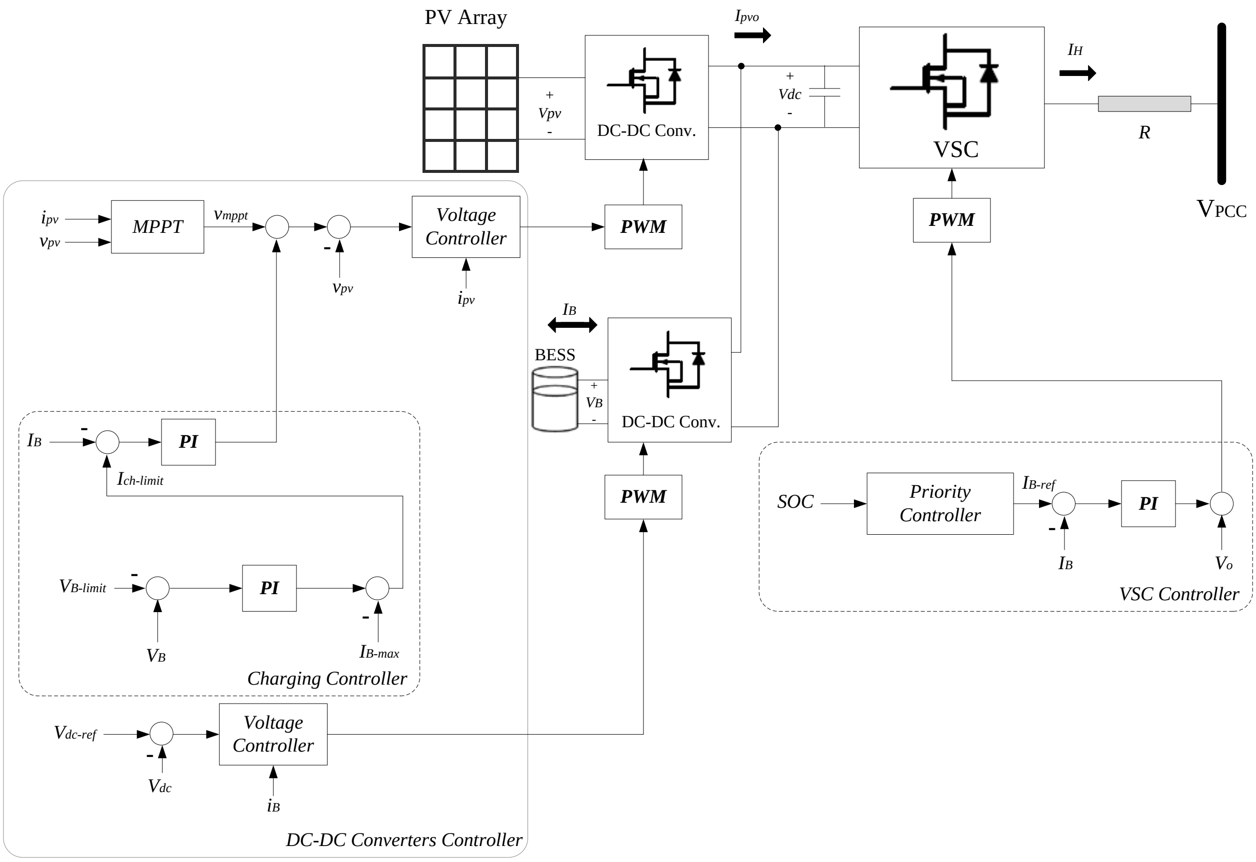


Fig. 4. Proposed control strategy

Generally, the output current is controlled by voltage that the operating range of which is limited within V_o and V_{min} in order to create the I/V characteristic curve of the hybrid unit. The V/I adaptive characteristic of hybrid unit has been shown in Figure 5. As can be seen, I_L is load demand and I_{B-max} is maximum current supplied or absorbed by the battery. According to this figure, if the load demand is less than the MPPT of PV units, the hybrid unit will behave as a voltage source in the microgrid, adapting its output power to the load demand. In this scenario, if the battery SOC is less than SOC_{min}, then battery will be charged, and if the SOC is within the allowable range, the battery will be in floating status. Notably, the battery SOC allowable range in this study was assumed in the range of 40 to 80 percent as shown in Table 1. The middle part of the mentioned curve displays a condition where the load demand is between the maximum power generation of PV and wind turbine. In this scenario, the hybrid unit acts as a controlled power source delivering the MPP power of PV module where the battery status will be floating. In the third part of the curve, the load demand is higher than the total power generation of DGs. In this situation, the DGs generate their maximum power and battery supplied the rest of the load demand by discharging. In this mode, the hybrid unit will act as a voltage source in the microgrid while the battery stays in discharging status until SOC_{min} has met.

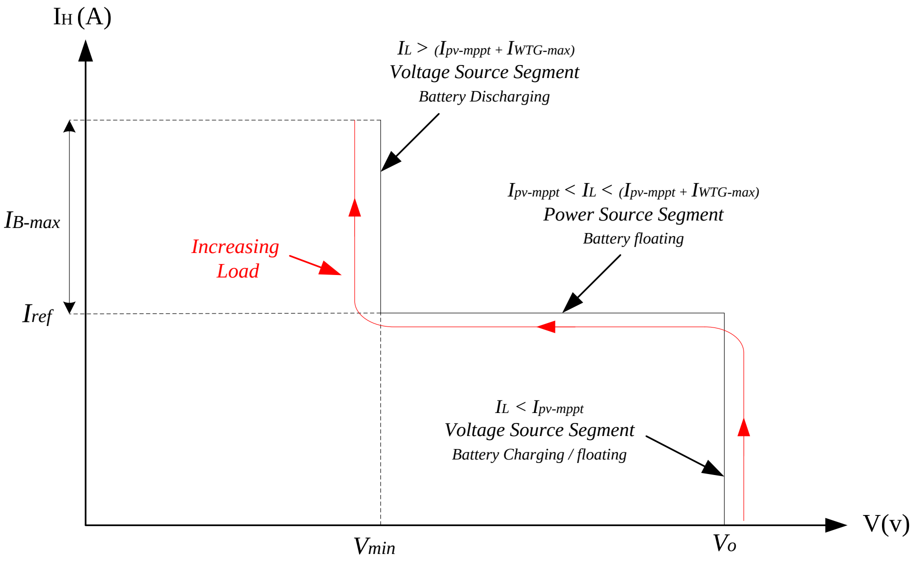


Fig. 5. Equivalent voltage/current characteristics of the hybrid unit

Since the operational voltage of DC microgrid is regulated by wind turbine (WTG) according to droop characteristic of this unit and delivered current (I_{WTG}), voltage was considered an independent variable in Figure 5. Unlike the operating point voltage varying based on I_{WTG}, the hybrid unit adjusts I_H in I_{ref} using the PI controller. In other words, PI controller is used to compensate the voltage changes due to the droop characteristic of wind turbine. In order to coordinate the microgrid performance, I/V characteristics of hybrid unit and WTG are combined as shown in Figure 6. The structure of I/V characteristic curve is determined based on the load changes, output power of PV arrays and battery SOC level.

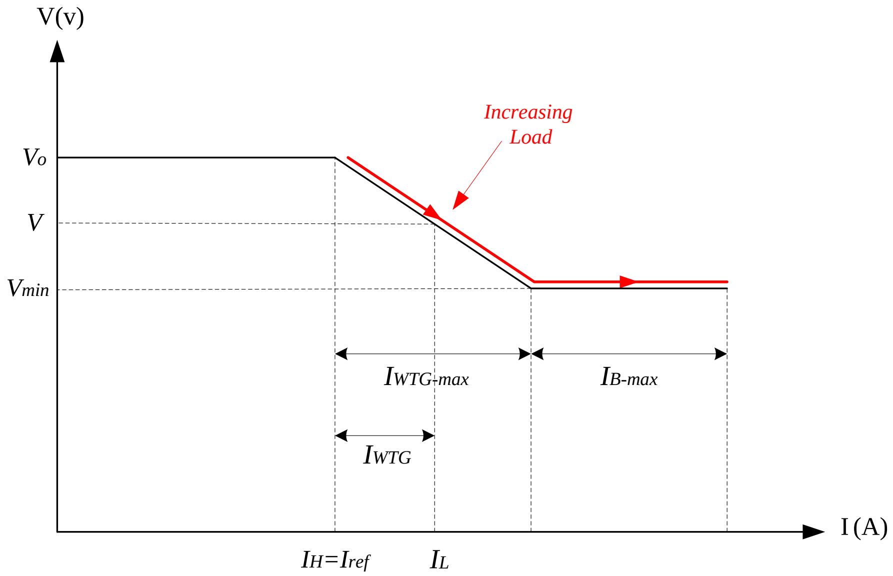


Fig. 6. Equivalent current/voltage characteristics of the DC microgrid with the increasing load trajectory

The purpose of VSC controller or DC/DC converter in the hybrid unit at any moment is to charge the battery or inject the total power available in the PV module to the DC microgrid. Furthermore, Priority Controller in Figure 4 specified the reference current $I_{B\text{-}ref}$ on the basis of battery SOC level and reference value SOC_{nom} in accordance with the battery charge curve in terms of SOC. Reference level

SOC_{nom} is the nominal value of battery charge level while the controller try to reach the SOC to this reference value, so the battery can supply the required power during peak load or reduced generation power of PV. Control loops designed in Figure 4 implement the control strategies on two independent levels:

- Level 1: At this level, priority of control strategy has been set based on the battery charge or delivery of total power available in PV to the microgrid. In fact, Priority Controller will determine the target based on the battery SOC level.
- Level 2: Control objectives in this level have been set based on supporting balance of power in DC microgrid and preventing the battery SOC from exceeding the allowable range.

For a comprehensive description of the proposed control strategy, the performance of microgrid was divided into two different scenarios based on the battery SOC and control strategy objectives. In both scenarios, the MPPT algorithm was used to extract the maximum power of PV module ($I_{pvo}=I_{pv\text{-}mppt}$). These scenarios will be explored in the next section.

4.1. Nominal operation scenario

This control strategy becomes operational when $SOC \geq SOC_{nom}$. In this case, Priority Controller zeros the $I_{B\text{-}ref}$ reference current; Therefore, I_{ref} current is determined on the basis of $I_{pvo}=I_{pv\text{-}mppt}$. It is noteworthy that Priority Controller has no direct or closed-loop control on the battery, but the battery current is controlled rather indirectly by injecting current into the microgrid in reference value I_{ref}. This design helps support the power balance in the microgrid and put the supply of load demand on the highest priority in operational scenarios. The system's operating point can be placed on any part of the I/V characteristic of microgrid based on the load demand (I_L) and $I_{pv\text{-}mppt}$ which are divided into three subcategories:

1. $I_{\mathrm{pv-mppt}} \leq \mathrm{I_L} \leq (I_{pv-mppt} + I_{WTG-max})$: This mode is equivalent to the middle part of characteristics in Figures 5 and 6, where the hybrid unit injects the total power available in PV unit into the microgrid. The rest of the load demand is supplied by the wind turbine, maintaining and regulating the microgrid voltage within the allowable range based on the droop characteristic of WTG. Notably, $I_{Pv\text{-}mppt}$ varied depending on the level of solar radiation and temperature. Hence, any decrease or increase in power generation of PV unit will move the I/V characteristic to the left or right in figure 6, respectively. This effect is shown in Figure 7 where the power output of PV module has decreased from point I to II, which caused power losses of hybrid module from $I_{H\text{-}I}$ to $I_{H\text{-}II}$, transferring the entire I/V curve to the left. Moreover, the power output of wind turbine increases from point I to II in order to compensate the shortage power generation of PV module.

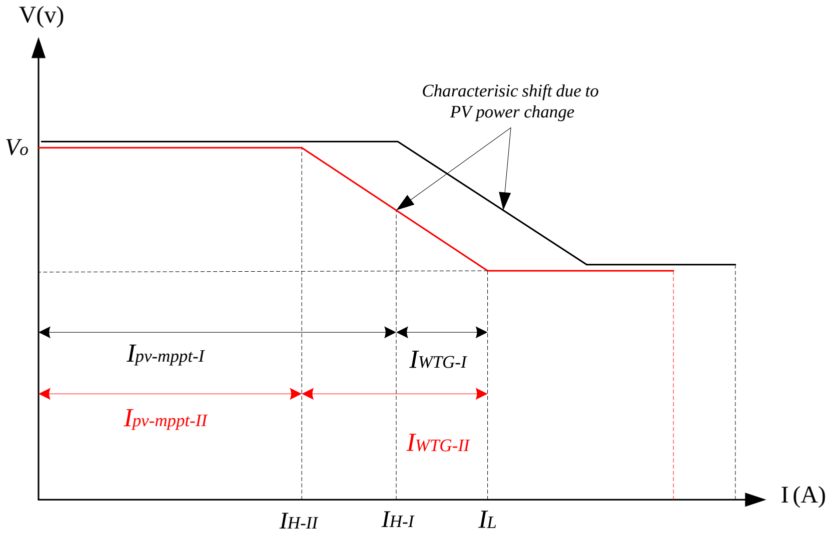


Fig. 7. I/V characteristics of the microgrid in the nominal operating scenario when PV power decreases

2. $\mathrm{I_L} > (I_{pv-mppt} + I_{WTG-max})$: The wind turbine generator decreases the voltage in response to the increased load demand based on the droop characteristic, achieving its nominal current at point $V=V_{min}$. If the load increases once again or the PV module generation power decreases, since the load demand (I_L) is greater than the total generation of DGs, wind turbines will attempt to bring the voltage to less than V_{min}. Therefore, the hybrid unit begins to adjust the DC bus voltage in V_{min} value based on I/V curve suggested in Figure 6. This target is achieved by regulating the output of wind turbine within its nominal range and supplying the power shortage by the hybrid unit so as to establish a power balance in the microgrid. In fact, the DC-DC converter of battery injects the excess current in order to adjust the microgrid voltage within the allowable range. Notably, in this scenario, if the load current exceeds the nominal current of the battery and the battery is fully discharged, the load shedding scenario should be implemented, but it is beyond the scope of this paper [25].

3. $\mathrm{I_L} < I_{pv-mppt}$: In this mode, since the hybrid unit inclines at any moment to inject current $I_{pv-mppt}$ into the microgrid and this current is more than the load demand, the current generated by wind turbine becomes zero, supplying the total load demand by the hybrid unit in $V=V_o$. Moreover, since the range of $I_{pv-mppt}$ produced by the hybrid unit is more than the load demand, the microgrid voltage tends to rise to more than nominal value V_o. In this situation, the DC/DC converter absorbs the excess current ($I_{Pv-mppt}$- I_L) and charge the battery (if necessary) to regulate the DC link voltage within the allowable range or the MPPT controller of PV unit transfers the operating point out to the MPP region, thus adapting the generation power to the load demand. This mechanism can maintain the power balance in the hybrid unit and microgrid. This scenario is shown in Figure 8 where the load demand drops from I_{L-I} to I_{L-II}. Notably, although the target in this mode is to inject the total power of PV module into the microgrid, the top priority is to establish the power balance in the microgrid. This can be fulfilled by supplying the load demand and storing the excess energy if necessary.

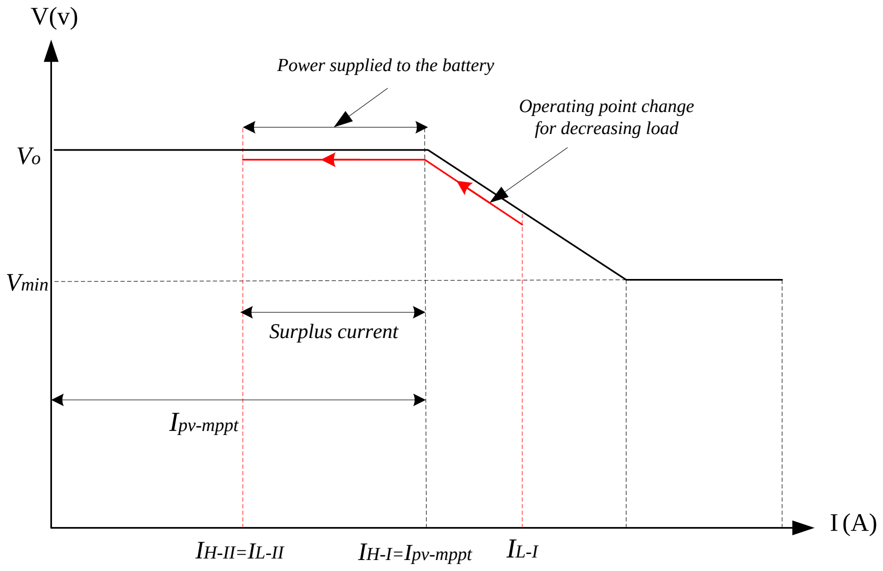


Fig. 8. I/V operating point trajectory when the load changes from $I_{L\text{-}I}$ to $I_{L\text{-}II}$, where $I_{L\text{-}II} < I_{pv\text{-}mppt}$

4.2. Battery charging scenario

This control strategy is operated when SOC <SOC_{min}; also this strategy can be applied when the SOC is less than SOC_{max} and there is excess energy in the system. Therefore the reference current $I_{B\text{-}ref}$ is regulated in the value of -$I_{B\text{-}max}$ (maximum charging current) and reference I_{ref} in the value of (I_{pvo}- $I_{B\text{-}max}$). Using a constant charge curve SOC/$I_{B\text{-}ref}$ similar to Figure 9 as Priority Controller, the battery can be analyzed and modeled within the hybrid unit [36]:

$$I_{B-ref} = -I_{B-max} + I_{B-max}\left(1 - e^{-\frac{SOC - SOC_{nom} + \delta SOC}{\delta SOC / k_{\delta}}}\right) \quad (4)$$

In the above equation, SOC_{nom} represents the reference battery charge level which the controller of the BESS tends to reach this SOC level. When the battery charge level reaches SOC_{ref}, the constant K_{δ} will determine how fast the reference charge current $I_{ch\text{-}ref}$ decreases to zero (i.e. battery discharge rate). Both K_{δ} and δSOC are selected according to battery specification and design preference.

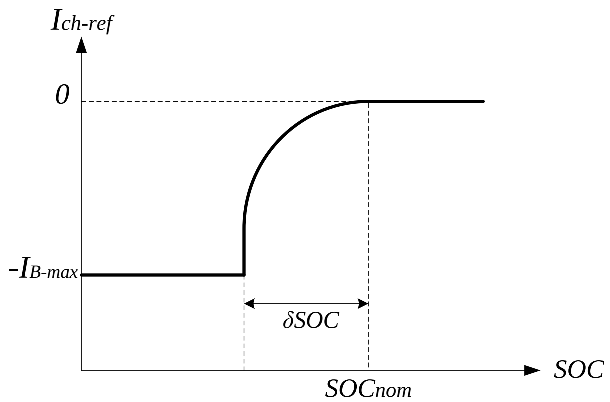


Fig. 9. SOC/$I_{B\text{-}ref}$ characteristic curve of the battery

The proposed control strategy in this scenario is divided into two parts:

1- $I_{B-max} \leq I_{pv-mppt}$: In this case, the current produced by PV unit is sufficient for battery charge and excessive current is injected into the microgrid. Current injection into the microgrid (I_H) is derived from the difference ($I_{Pv-mppt}$ – I_{B-max}). In fact, when the VSC injects the current into the microgrid, the DC/DC converter of battery injects the PV unit's remaining power into the battery in order to adjust the DC link voltage. Hence, the battery charging process can be fulfilled by indirectly controlling the power injected into the DC microgrid. It is noteworthy, however, the major target of control strategy in this scenario involves battery charge, the top priority is to support the establishment of power balance within the microgrid for decentralized controlling of the DC microgrid. Figure 10 illustrates the displacement of operating point and I/V characteristic in order to support the power balance during battery charging.

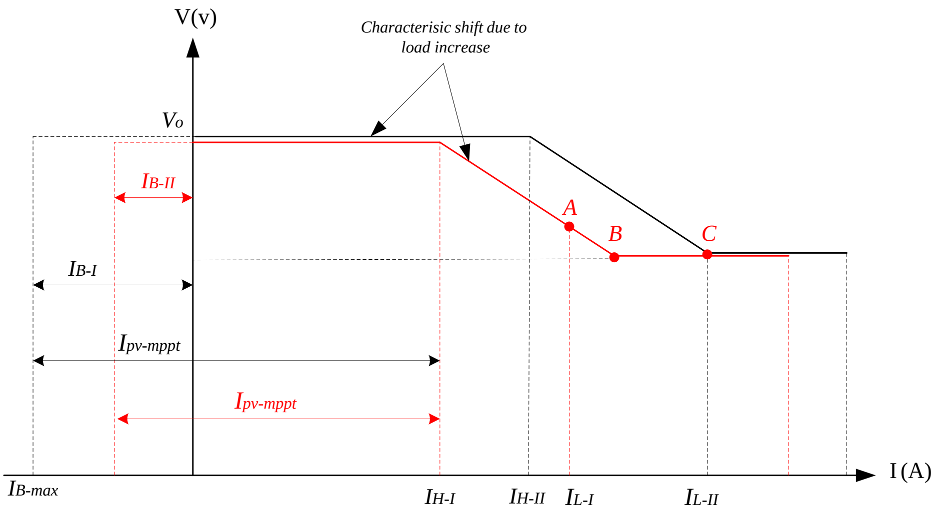


Fig. 10. I/V characteristic illustrating the battery charging scenario when the load increases

As shown in above figure, the battery is first charged separately by PV Unit with current I_{B-I}=I_{B-max} as remaining current of PV supplies the load demand I_{L-I}. The rest of the load demand will be supplied by wind turbine according to its droop characteristic (point A). Wind turbine can supply any load rise until to the point B and V_{min}. If the load demand increases beyond this point and to I_{L-II}, the WTG will attempt to decrease the voltage based on the characteristic droop to below V_{min}. Therefore, the hybrid unit in this scenario increases its output from I_{H-I} to I_{H-II} in order to stabilize and regulate the voltage range. Furthermore, the battery charge current decreases to I_{B-II} in order to regulate the DC link voltage. The hybrid unit continues to supply the load demand until the maximum current injection ($I_{pv-mppt}$) into the microgrid; therefore the charge current becomes zero. Any increase in the load demand will be supplied by the battery in order to support the power balance in the microgrid as described in Figure 6.

2- $I_{B-max} > I_{pv-mppt}$: In this case, the reference current I_{ref} is negative and the hybrid unit absorbs the current difference ($I_{pv-mppt}$ – I_{B-max}) so as to charge the battery in maximum current. This is equivalent to move the I/V characteristic to the left according to Figure 11. In this situation, the hybrid unit acts as a consumer. The wind turbine will supply the battery charge current and any increase in the load demand up until its nominal current.

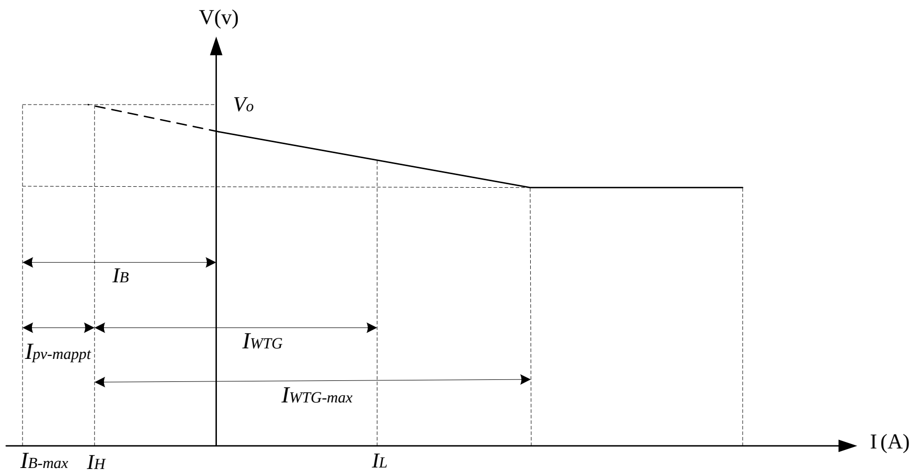


Fig. 11. I/V characteristic during battery charging scenario when $I_{pv\text{-}mppt} < I_{B\text{-}max}$

5. DC-DC CONVERTER CONTROL SYSTEM

In the scenario where the PV module power generation is greater than the load demand, the hybrid unit stores the excess power in the battery, which might lead the SOC level exceed the SOC_{max} limit. This condition occurs when the excess power of PV ($I_{pv\text{-}mppt} - I_L$) is greater than the current $I_{B\text{-}max}$ of the battery unit. This can impair the battery voltage and destroy its cells [37]. It is crucial to adopt a suitable controller for monitoring the battery charge status. Since this paper intended to synchronize the performance of the hybrid unit in DC microgrid, there was a two-stage charge controller involved to achieve that target. This controller is able to combine different charging curves through the battery SOC or DC link voltage so as to adjust the reference charge current [38]-[39]. Since the available power for battery charging varies depending on the PV power generation and load demand, therefore the proposed controller was implemented only to regulate $I_{ch\text{-}limit}$ based on battery voltage as shown in Figure 4.

Moreover, the internal control loop I_B in Figure 4 was adopted to control the charging current within the allowable range and prevent its value exceeding $I_{ch\text{-}limit}$ at every moment. When the battery voltage is reduced to less than $V_{B\text{-}limit}$, the PI controller output will regulate the charging current $I_{ch\text{-}limit}$ on the value of $-I_{B\text{-}max}$. This behavior will continue until the battery voltage is increased to the reference value. When the battery voltage exceeds the value of $V_{B\text{-}limit}$, the PI controller curtails the reference charging current ($I_{ch\text{-}limit}$) in order to adjust the battery voltage. If the load decreases or the battery voltage increases, so that I_B exceeds reference $I_{ch\text{-}limit}$, the PI controller will adjust the charge current of PV module so as to follow the reference charge current $I_{ch\text{-}limit}$. In fact, the controller transfers the operating point of the PV module outside the maximum power point (MPP) so as to reduce the power generation of PV, thus stabilizing the battery charge current in the value of $I_{B\text{-}ref.}$ Throughout this process, the MPPT algorithm is disabled and the range of V_{mppt} stays in the last fixed value before disabling the algorithms.

It is noteworthy that MPPT algorithm in this paper is based on Perturb & Observe method that follows and monitors the MPP point in the power-voltage curve of PV module. Now, if the battery current falls again below $I_{ch\text{-}limit}$ due to increased load demand, the PI controller will transfer the operating point of PV unit to the MPP region, so as to increase the power generation of PV, thus stabilizing the current I_B in $I_{ch\text{-}limit}$. In both the above processes, the hybrid unit supplies the load demand. If the load demand increases or power generation of PV decreases according to the reduced solar radiation, then the controller will transfer the PV operating point to the MPP point, thus zeroing the PI controller output. Any increase in load demand beyond the maximum power of PV module will be supplied by the wind turbine generator (WTG).

6. SIMULATION RESULTS

A DC microgrid composed of a PV/battery hybrid module, wind turbine generator (WTG) and constant dc power load was simulated in MATLAB/SIMULINK so as to evaluate the performance of proposed control strategy. Microgrid parameters have been presented in Table 1. The proposed strategy was assessed through several operational scenarios such as applying changes in the level of power generation, load demand and the solar radiation level.

Table 1. DC microgrid parameters

Parameter	*Symbol*	*Value*
DC bus voltage Ref.	$V_{dc\text{-}ref}$	250 *V*
Maximum PV power	$P_{pv\text{-}max}$	10 *KW*
Maximum WTG power	$P_{WTG\text{-}max}$	4 *KW*
Nominal virtual resistance	R_d	0.8 *Ω*
Low voltage threshold	V_L	230 *V*
High voltage threshold	V_H	260 *V*
Nominal battery capacity	C_{bat}	40 *A.h*
Initial SOC of battery	*SOC*	% 65
Minimum value of SOC	SOC_{min}	%40
Maximum value of SOC	SOC_{max}	%80

Figure 12 shows the power/voltage curve of PV module. According to this graph, the PV array can generate and deliver maximum power of 10 kW at 1000 watts per square meter (w/m^2) of radiation level at 55 V. The red circles on the curve represent the maximum power point (MPP) traced and generated by the MPPT algorithm. This study involved the MPPT algorithm based on conventional Perturb & Observe method in order to extract the maximum power of PV array. According to this algorithm, it can be shown that *dP/dV* becomes zero at the maximum power point, before which the value of power becomes positive and then will be negative. Also, if *dP/dV* is positive, the algorithm progresses on the power-voltage curve by increasing the voltage until it reaches *dP/dV=0*; and if *dP/dV* is negative, the algorithm moves in the opposite direction to the point where the power-voltage variations are zero, selecting that point as the maximum power point.

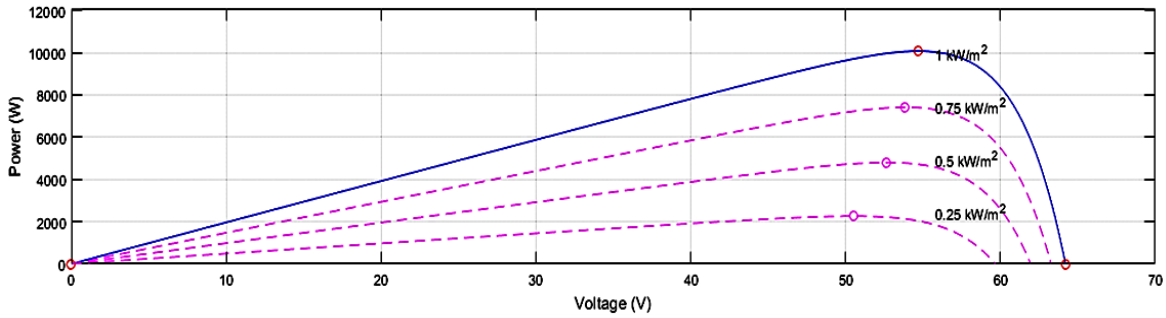
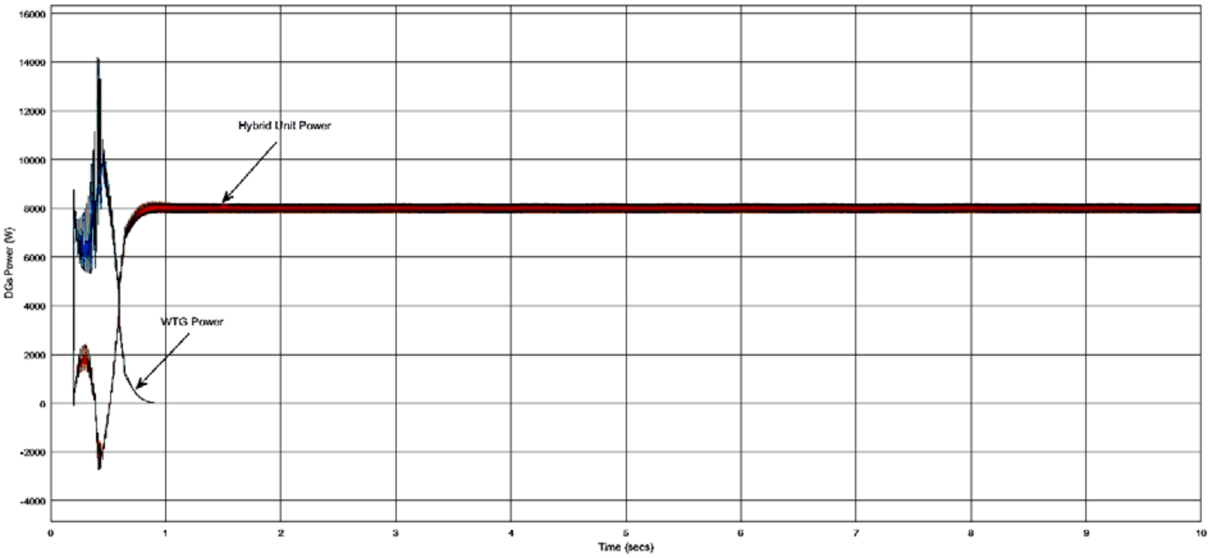


Fig. 12. Power characteristic curve of PV module in 25 ◦C temperature and different radiation levels

Figure 13 shows the results of DC microgrid performance in fixed power load of 8 kW. Figure 13 (a) shows the power generation of the hybrid unit and wind turbine. According to this figure, after running on the DGs transients and stabilization of output power, since the load demand is less than maximum power of PV module, the MPPT controller unit is deactivated and its output power is adapted by the DC/DC converter to the load demand. The PV module acts as a voltage source in the microgrid. In this mode, the power generation of wind turbine (P_{WTG}) will become zero. In other words, this mode doesn't require maximum power output of PV (10 kW), because the load demand is less than the MPPT power of PV array, and since the initial SOC level was assumed to be 65%, there was no need to charge the battery system. Therefore the MPPT controller transfers the operating point of PV module away from MPP point and adapts output power to the load demand. Figure 13 (b) shows the voltage and current of PV array. According to level of load demand, the PV module supplies the total load demand in a current about 130 amps and voltage of 60 V. Figure 13 (c) displays the variations of DC bus voltage. The common bus voltage will be stabilized on 255 volt after load implementation and the variations are allowable within the range of 230 to 260 volts. Notably, the load increasing trajectory and maximum power delivery of WTG unit will drop the voltage of common bus to the minimum level according to the droop characteristic of the unit. Therefore, the output of PI controller will not be zero in these cases and with discharging of battery system; the common bus voltage will be regulated within the allowable range, thus establishing power balance in the microgrid. Since the primary battery SOC was assumed to be 65%, there was no significant change in the battery SOC given the levels of generation and consumption, putting the battery in floating status.



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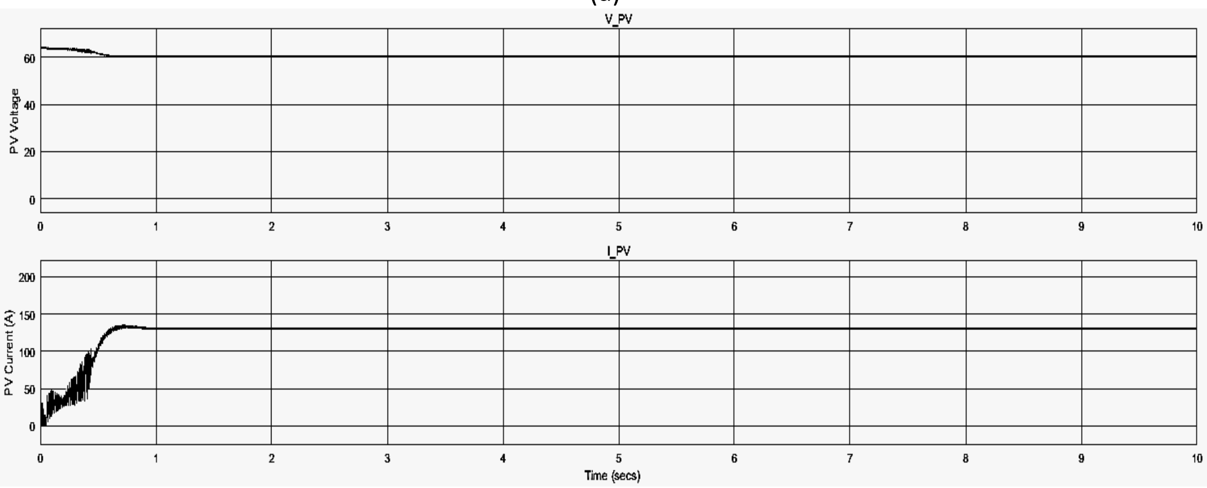

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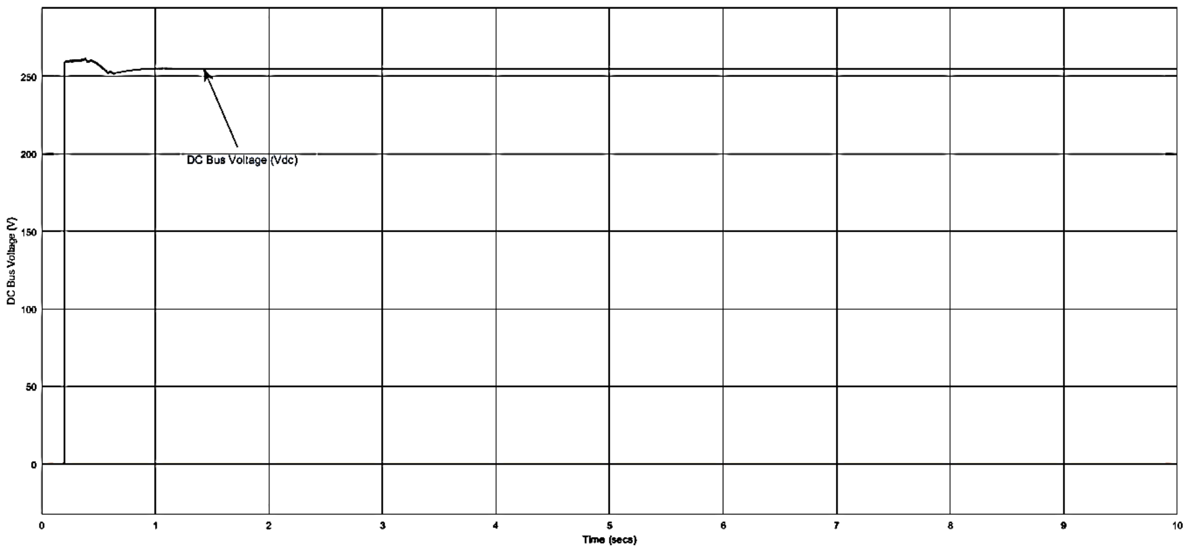

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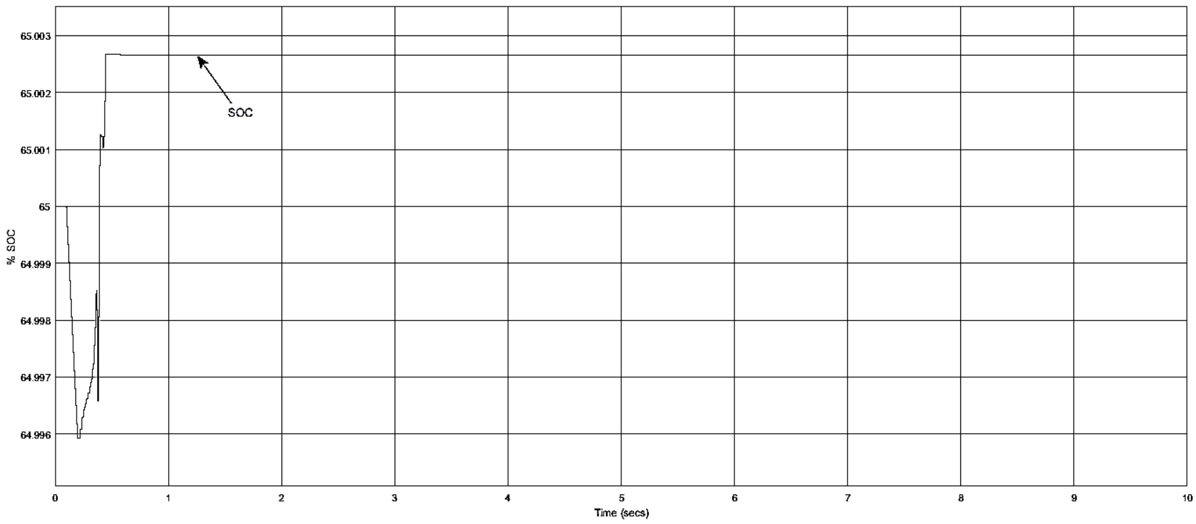
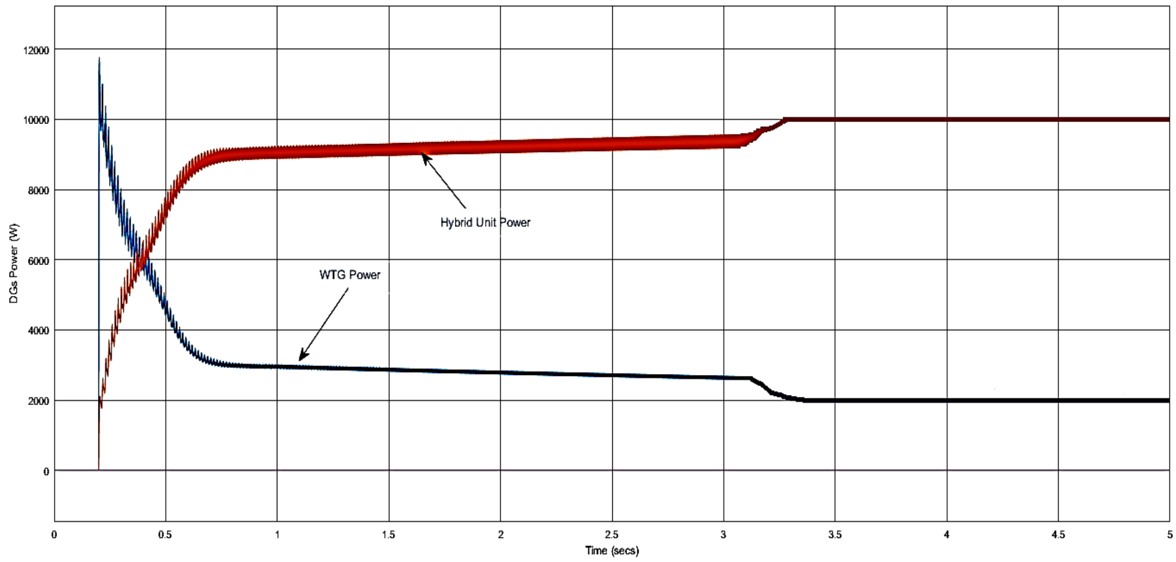


(d)

Fig. 13. Simulation results in 8 KW load: (a) Generation power of PV and WTG unit, (b) Voltage and current of PV module, (c) Common DC bus voltage, (d) Battery SOC level

Figure 14 shows the results of DC microgrid performance in fixed power load of 12 kW. Figure 14 (a) shows the power generation of the hybrid module and wind turbine. According to this figure, after DGs running on transients and stabilization of output power, since the load demand is higher than maximum power of the PV module, the MPPT controller unit is reactivated and the its output power reaches the maximum of 10 kW within 3.5 seconds as the PV module acts as a controlled power source in the DC microgrid. In this case, the wind turbine generator supplies the rest of load demand (2 kW) on the basis of its droop characteristic.

Moreover, it is noteworthy that until the output power of PV unit reaches to maximum power, the WTG temporarily delivers more than 2 kW of power for adaptive control and coordination between units. From the time of t=3.6s, the hybrid module will deliver the MPPT power of PV module and wind turbine generator stabilizes its output at 2 kW. The battery unit is slightly discharged for a period of time to prevent the PV delay destabilizing the unit output power. In this case, the hybrid module acts as a controlled power source according to droop curve shown in Figure 6. Some achievement of the newly proposed control strategy was coordinated performance of hybrid unit and wind turbine according to the adaptive droop curve, undertaking the supply of load demand within the allowable range of common bus voltage, thus establishing a power balance and preventing circulating currents in the DC microgrid. Figure 14 (b) shows the voltage and current of PV array. According to the load demand, the PV module injects total power generation in MPP point at a current about 155 amps and voltage of 60 V. Figure 14 (c) displays the range variations of DC common bus voltage. Since a portion of the load demand is supplied by the wind turbine, the common bus voltage decreases according to its droop characteristic, thereby V_{dc} has been stabilize on 245 volts. The maximum power delivered by wind turbine generator (WTG) led to reduction of common bus voltage to 230 V, which was not observed in this scenario because of the production level in wind turbine. Notably, according to the proposed control scheme in Figure 4, if the DC link voltage drops to 230 volts due to increased levels of load demand, then the output of PI controller of battery system will not be zero, since the discharging of the battery can support the DC link voltage and establish the power balance in the microgrid. Figure 14 (d) illustrates the SOC level of the battery system, which is discharged due to the time required for the PV module to reach the maximum power and establish a power balance in the hybrid module. After the PV module deliver the MPPT power, the battery system will remain in floating status. In this case, the hybrid unit acts as a power controlled source according to the proposed droop curve and adapting its maximum output power to the load demand.



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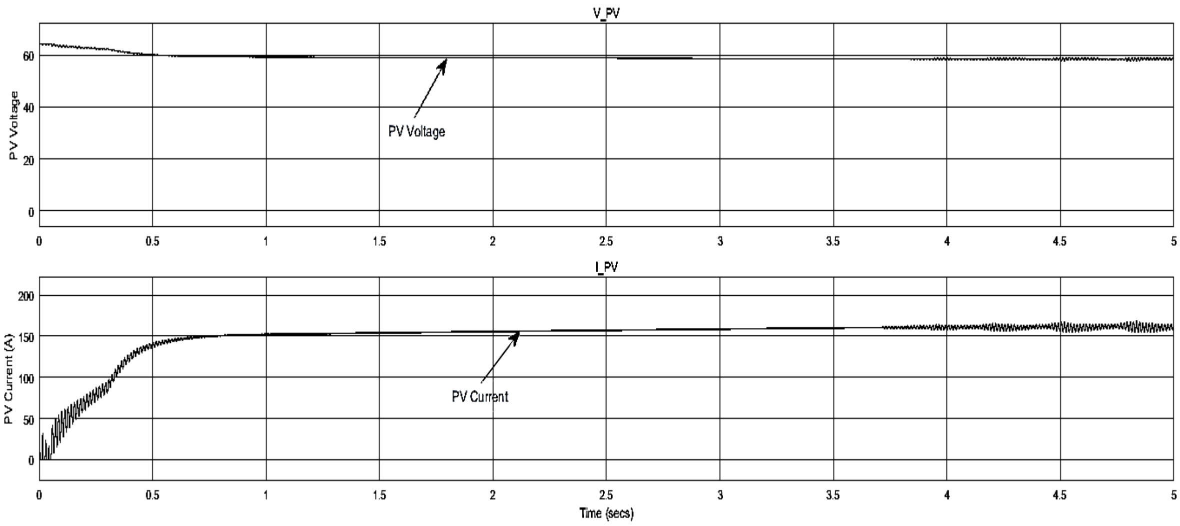

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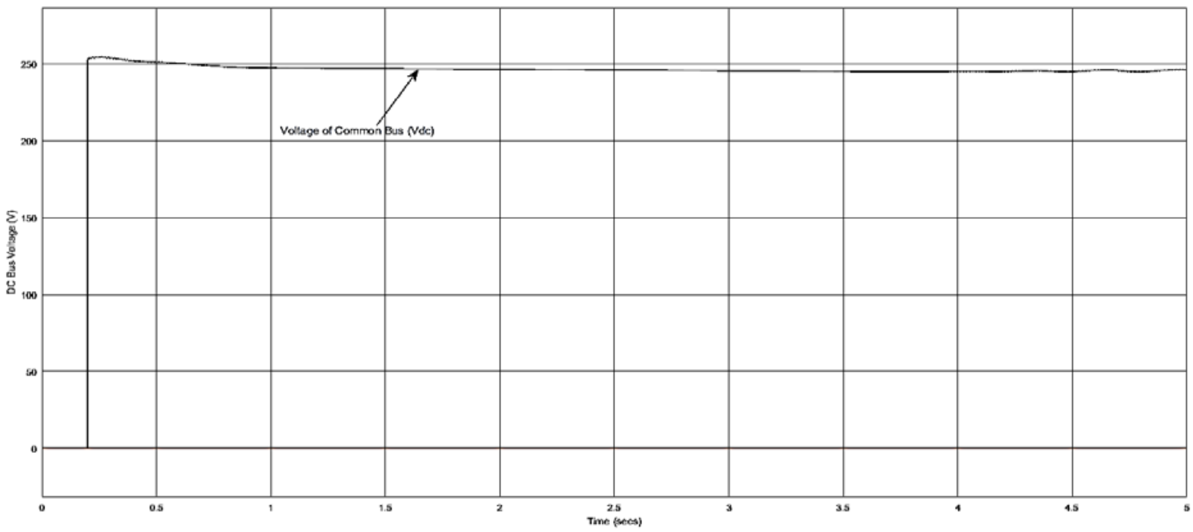

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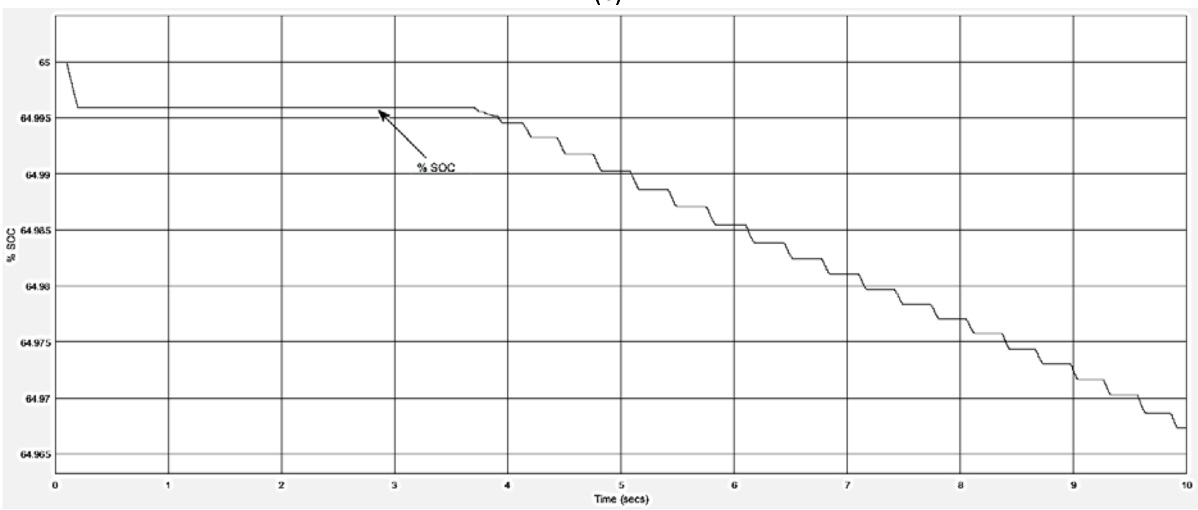


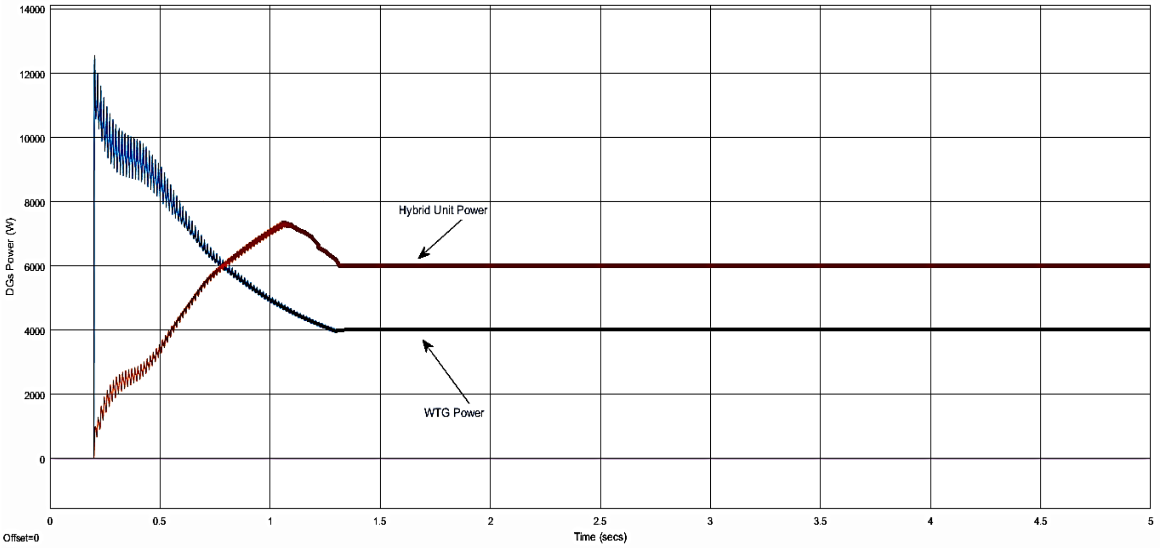
(d)

Fig. 14. Simulation results in 12 KW load: (a) Generation power of PV and WTG unit, (b) Voltage and current of PV module, (c) Common DC bus voltage, (d) Battery SOC

Figure 15 illustrates the results of DC microgrid performance by decreasing the amount of solar radiation from 1000 w/m^2 to 500 w/m^2. In this scenario, the power generation of PV is decreased according to the power/voltage characteristic curve shown in Figure 12. In the MPPT mode, the output power will be maximum 5 kW. In this scenario, the dc constant power load of 10 kW is applied on the microgrid. Figure 15 (a) displays the power generation of the hybrid unit and WTG. PV module will supply 5 kW of 10 KW load demand according to the existing radiation level as the wind turbine generates maximum power equivalent to 4 kW. In this mode, according to the droop characteristic of the wind turbine, the common bus voltage will begin to decrease.

As the voltage value reaches the lower limit of the allowed range (230 V), the PI controller is activated discharging the battery system and reducing the SOC, so as to regulate and maintain the voltage value within the allowable range. In fact, in this situation, the battery system undertakes to supply 1 kW of load demand shortage in the DC microgrid, thus establishing a power balance in the microgrid. In this situation, the hybrid unit behaves similar to a controlled power source according to the proposed droop curve and delivering maximum power of PV array based on the MPPT algorithm. It is noteworthy this situation could continue until the battery SOC level reaches its lowest threshold to %40, in which case the battery discharge status is disabled and the battery status will be floating or charging. In this case if the total power generation of DGs is lower than the load demand, the load shedding scenario should be implemented which is outside the scope of this paper. Figure 15 (b) shows the voltage and current of PV array. In accordance with the reduced levels of radiation, the PV can supply maximum power of 5 kW according to the MPPT algorithm in approximately 78 amperes and 58 volts. Figure 15 (c) shows the range variations of DC common bus voltage. As described in Section (a), the common bus voltage drops as the wind turbine supplies a portion of the load demand. Hence, the battery unit controller decreases the share of wind turbine by injection the current of I_B into the DC link, supplying a major portion of load demand, and stabilizing the range of V_{dc} on 235 volts.

Moreover, Figure 15 (d) shows the SOC level of the battery system. The battery will start to discharge because of reduction in the power generation of PV module aimed at establishing the power balance in the hybrid unit. After delivering of 5 kW by the PV, the battery system will supply the rest of load demand. Reduced level of battery SOC continues to minimum 40%, at which point it goes to floating or charging status according to the control scenario defined for the battery based on the power generation of the DGs. In this case, the hybrid unit acts according to the proposed droop curve similar to the controlled power source, adapting its maximum output to the load demand. Notably, the allowable range of 40 to 80 percent was assigned for the battery SOC in order to avoid full discharge of capacitors and extend the life of the system.



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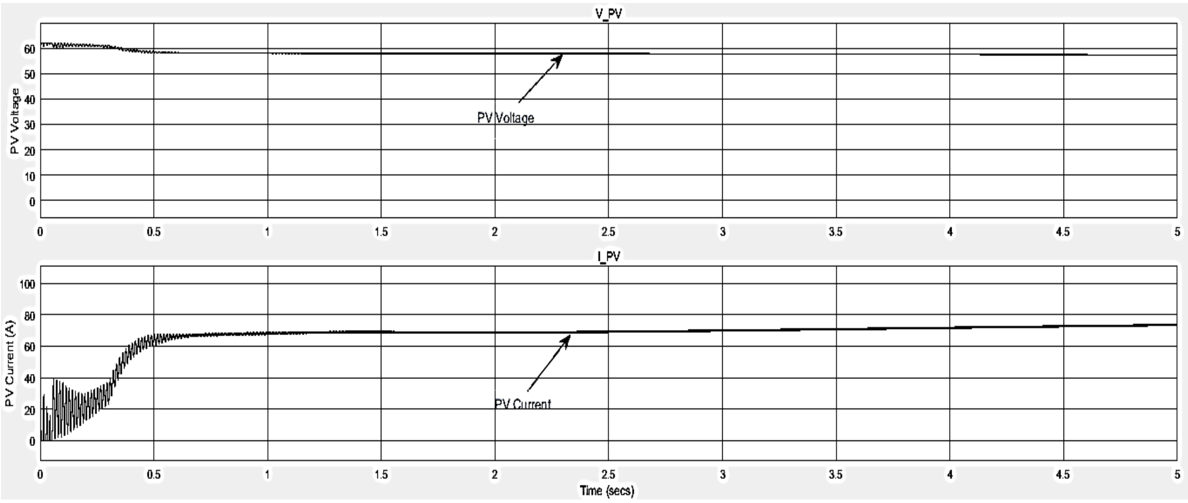

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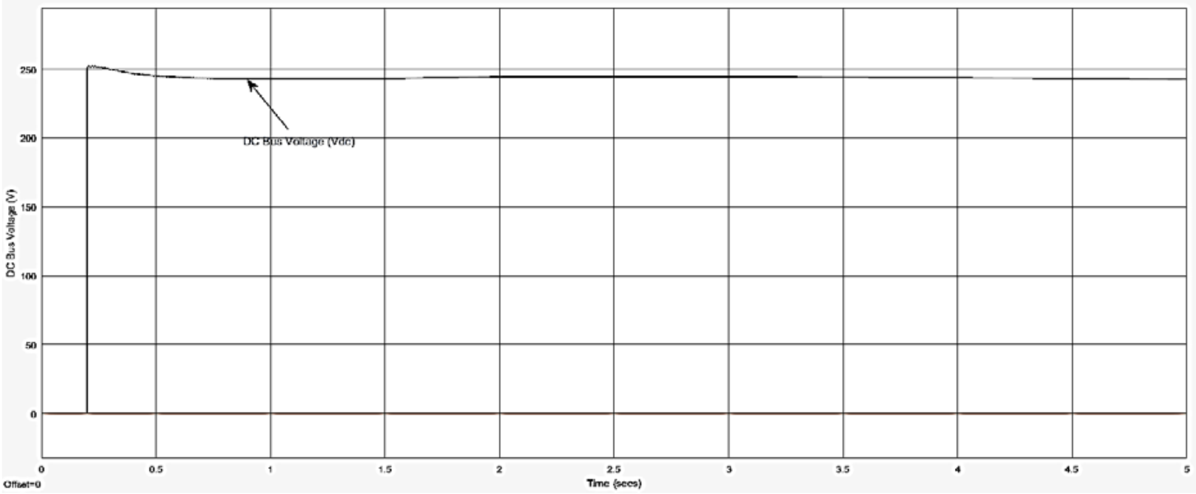

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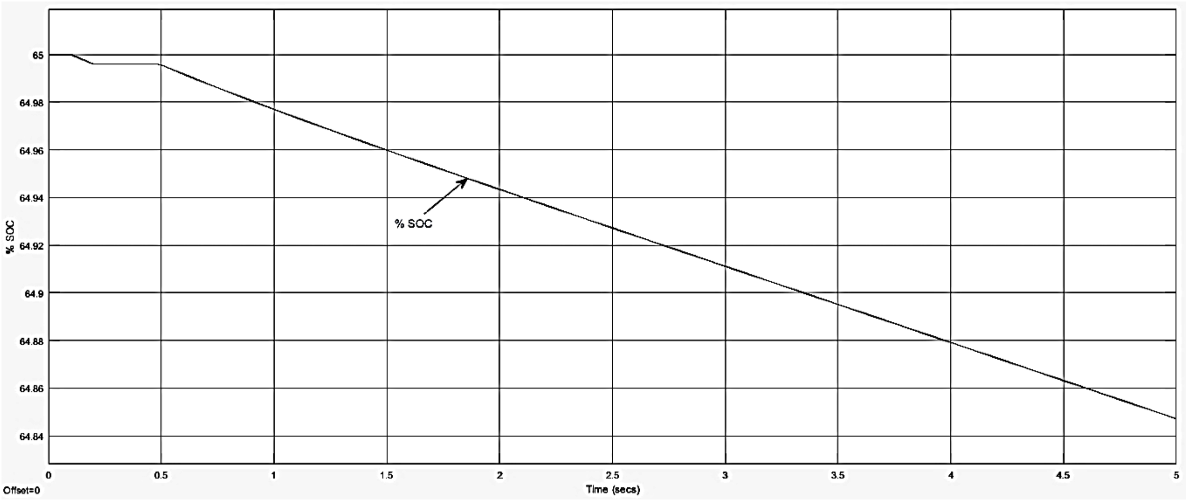

(d)

Fig. 15. Simulation results in 10 KW load and decreasing solar radiation from 1000 w/m^2 to 500 w/m^2: (a) Generation power of PV and WTG unit, (b) Voltage and current of PV module, (c) Common DC bus voltage, (d) Battery SOC

CONCLUSION

This paper proposed a decentralized control strategy for DC microgrid composed of a hybrid PV/battery unit and wind turbine generator so as to establish a power balance in isolated function of microgrid. Unlike the conventional methods of PV control as a current source, the hybrid PV/battery was controlled as a voltage source following the adaptive I/V characteristic curve, which realized the decentralized control of the hybrid unit and WTG in the DC microgrid. Based on the system simulation and newly proposed control strategy in MATLAB/SIMULINK, it was found that the I/V characteristic can be applied independently to the microgrid. Hence, the hybrid unit and WTG can inject their maximum powers into the microgrid, supplying the load demand and charging the battery. Moreover, it supported the power balance in the DC microgrid, fulfilling the battery's SOC constraints. In the case of load demand exceeds the maximum PV power generation; the WTG will supply the power shortage. Also in the case of load demand is more than the total power generation of DGs, the battery will begin to discharge in order to regulate the DC bus voltage. The entire proposed operation can take place without the need for communication links or any centralized energy management and validation system.

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