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Adaptive Power Management Strategies for Hybrid unit based on Decentralized Control Method

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Abstract

This investigation tried to control a standalone hybrid DC microgrid in islanded operation mode by using decentralized power management strategies. Unlike common approaches where a Photovoltaic (PV) module is controlled as current source, the proposed strategy controls PV arrays as a voltage source that follows the current/voltage adaptive characteristic curve. Proposed I/V characteristic for hybrid PV/battery adapts the hybrid unit behavior independently in accordance with the load demand. Hence, the PV module can spend its maximum power on load demand and supply the extra energy on charging the battery energy storage system (BESS), which will maintain the power balance within the DC microgrid and regulating DC bus voltage. The proposed control system can be applied on any DC microgrid to achieve control objectives through decentralized procedure, without need for 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 and validated.

Keywords: DC microgrid, power management, decentralized control, hybrid unit, droop characteristic.

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 [1]-[2]. Microgrid refers to an accumulation of loads and distributed generation (DG) resources in low and medium voltage levels functioning as a power system for power generation and if possible, as Combined Heat and Power (CHP) [3]-[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 DG along with any storage devices such as super-capacitors and batteries [5]. Due to population growth and increased demand for electrical energy, 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 DG. With the progress made in DG technology, there have been many advantages together with numerous problems in terms of network operation.
and protection. 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]:

- Not requiring too much investment, employment of public participation and average assets
- Short construction period
- Elimination of transmission losses and power distribution loss reduction compared to large centralized power plants
- Ease of use as CHP\(^1\) generation
- Portability and easy handling
- 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. The main purpose of analyzing this microgrid is to maintain the power balance between energy sources and BESS, regulating of DC bus voltage and energy management [8].

\[ \text{Figure 1: Schematic diagram of a DC microgrid.} \]

Figure 1 shows the diagram of a DC microgrid. In the above figure, \( V_{\text{ref}} \) represents the reference voltage of microgrid, \( R_d \) is source resistance, \( i_{\text{DG}} \) is current injected into the microgrid by distributed generation unit(s), \( i_{\text{Load}} \) is load current or power consumption and \( C_{\text{dc}} \) is the microgrid capacitor. This type of microgrid usually applies DG 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. Generally, the control objectives of DC microgrids in the field of power management can be divided into two categories [9]:

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

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 and flexibility of the microgrid. 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 [10]-[11]. Research and development of adaptive control systems aimed at improving the behavior and economic performance of DC microgrid through hierarchical control has been a controversial topic in the field of DC microgrid energy management. The microgrid economic performance in tertiary-level of hierarchical control involves and analysis islanding formation, load recovery and re-synchronization with the main network. The DG outputs are stabilized and delivered to the power electronic converters through internal and external control loops including PI controllers. Generally, converters are controlled through Pulse Width Modulation (PWM) based on I/V droop characteristic curve. The microgrid voltage stability and steady state error of controllers are realized at the primary and secondary levels. At the tertiary-level of control, the economic performance of the microgrid can be obtained through a centralized energy management system or through the System Control and Data Acquisition (SCADA)

\(^1\) combined heat and power
One disadvantage of this method involves centralized microgrid control and system dependency on the communication links that decreases the reliability of the system. The utilization of smart systems for droop control and local control of DC microgrids are regarded as efficient methods in this area. The smart decentralized strategy is adopted based on fuzzy logic to achieve power balance in the microgrid aimed at specifying the virtual resistance range for droop controllers in accordance with the status of each DG or the SOC in each energy storage device [14]. All modules in a decentralized control system are controlled only through local variables; as result, the microgrid can operate independently and without need for telecommunications infrastructure [15]. In order to increase the storing energy level in the microgrid and avoid the load shedding scenario in the microgrid, two or more storage systems can be applied as battery or super-capacitor. Moreover, in order to overcome the control challenges involved in coordination of energy storage sources within a microgrid, a two-layer hierarchical control strategy can be adopted [16]-[17]. To achieve this target, the primarily control layer functions through adaptive voltage-droop aiming to regulate the common bus voltage support the battery charge status close to each other in the process of recharging. The microgrid operation modes include: The process of charging and discharging batteries, DC common bus voltage and load shedding in case of non-supply of power from DG sources and energy storage systems.

In this paper a decentralized power management strategy for hybrid PV/battery unit is developed. The main contributions of this investigation are: maintaining of power balance, voltage regulation and keeping SOC in allowable range concurrently. According to the proposed strategy, hybrid unit is controlled as a voltage source following I/V multi-segment characteristic curve. These strategies establish power balance and maintain DC bus voltage and SOC level of BESS within the allowable range. All the mentioned targets will be fulfilled only through local and independent control, without any need for centralized control or communication links.

1. Hybrid structure of DC microgrid

The hybrid unit included a PV module and BESS is supposed in an adaptive droop control microgrid as shown in figure 2. The control strategy was designed and implemented so as to be generalized to a large number of hybrids and droop control units. Notably, microgrid droop control refers to the third layer of hierarchical control within microgrid energy management system.

![Figure 2: Block diagram of proposed DC microgrid.](image_url)

Figure 2 illustrates hybrid PV/battery unit and linear load in proposed DC microgrid. The PV array was regulated by a unidirectional boost converter so as to connect to microgrid common bus at the desired voltage level (feeder resistance is ignored). \(I_{pvo}\) is the current injected by PV module into the DC link.
while $I_B$ represents the output 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 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. Generally, the aim of the proposed control strategy was to coordinate the performance of hybrid PV/battery unit through droop control method, so that maximum power of PV module is delivered to the microgrid. This objective can provide the power balance, preserving battery SOC at an optimum level and DC bus voltage regulation. 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 required power will alter to charge the battery independently on the basis of load variations and available PV power, so as to supply the load demand fully in real-time.
3. If PV 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 maximum power point tracking (MPPT) controller take away PV operating point from maximum power point (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 PV. Hence, BESS establishes power balance in an isolated microgrid.

\section*{Proposed control strategy}

Converter control system in the hybrid unit is a controller 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 3. Output current ($I_H$) is regulated indirectly by controlling the battery current ($I_B$) by PI controller. It is necessary to mention that DC/DC converter of BESS 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:

\begin{equation}
  e_P = I_{B-ref} - I_B = I_{B-ref} - (I_H - I_{pvo})
\end{equation}

In order to simplify calculations, the power loss is disregarded [18]-[22]. Reference current ($I_{ref}$) is defined as follows:

\begin{equation}
  I_{ref} = I_{B-ref} + I_{pvo}
\end{equation}

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

\begin{equation}
  e_P = I_{ref} - I_H
\end{equation}

From the above equations, it can be concluded that regulation of current $I_B$ in the reference value $I_{B-ref}$ 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 $I_B$ in the reference value $I_{ref}$ using the measured of $I_{pvo}$ and the reference current value $I_{B-ref}$.
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 4. As can be seen, I_L is load demand and I_B-max is maximum current supplied or absorbed by the BESS. According to this figure, if the load demand is less than the MPPT of PV unit, this unit will behave as a voltage source and adapting its output power to the load demand. In this condition, 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 20 to 90 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 stored power in BESS. 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 discharged according to the load demand level. In the third part of the curve, the load demand is higher than the total power generation of PV and battery stored power. In this situation, the PV generates its 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 while the battery stays in discharging status until SOC_{min} has met.
Figure 4: Equivalent voltage/current characteristics of the hybrid unit.

The purpose of converter control system in the hybrid unit at any time is to charge the battery or inject the total power available in the PV module to the DC microgrid. Furthermore, PI Controller in figure 3 specified the reference current $I_{B-ref}$ 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. 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 ($I_{pv}=I_{pv-mppt}$). These scenarios will be explored in the next section.

3.1. Nominal operation scenario

This control strategy becomes operational when $SOC \geq SOC_{nom}$. In this case, battery control system zeros the $I_{B-ref}$ reference current; therefore, $I_{ref}$ is determined on the basis of $I_{pvo} = I_{pv-mppt}$. It is noteworthy that mentioned 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 I/V characteristic based on the load demand ($I_L$) and $I_{pv-mppt}$ which are divided into three subcategories:

1. $I_{pv-mppt} \leq I_L \leq (I_{pv-mppt} + I_{B-max})$: This mode is equivalent to the middle part of characteristics in Figures 4, 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 BESS, maintaining and regulating the microgrid voltage within the allowable range. Notably, $I_{pv-mppt}$ 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 5, respectively.
\[ I_L > (I_{pv-mppt} + I_{B-max}) \]: If the load demand \((I_L)\) is greater than the total generation of PV and the current of BESS, DC voltage of the microgrid tried to decrease to less than \(V_{min}\). Therefore, the hybrid unit begins to regulate the DC bus voltage in \(V_{min}\). This target is achieved by regulating the output of hybrid unit within its nominal range to establish a power balance in the microgrid. In fact, the DC-DC converter of BESS 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 discharged under 20% SOC, the load shedding scenario should be implemented, but it is beyond the scope of this paper [23].

\[ I_L < I_{pv-mppt} \]: 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, supplying the total load demand by PV 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 microgrid. 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.

### 3.2. 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 power in the microgrid. Therefore the reference current \(I_{B-ref}\) is regulated in the value of \(-I_{B-max}\) (maximum charging current) and reference \(I_{ref}\) in the value of \((I_{pv0} - I_{B-max})\). Using a constant charging curve \(SOC/I_{B-ref}\) similar to Figure 6 as Priority Controller, the battery can be analyzed and modeled within the hybrid unit [24]:

\[
I_{B-ref} = -I_{B-max} + I_{B-max}(1 - e^\frac{SOC - SOC_{nom} + \delta SOC}{\delta SOC/k})
\]
In the above equation, \( \text{SOC}_{\text{nom}} \) represents the reference battery charge level which the controller of the BESS tends to reach this SOC level. When the battery charge level reaches \( \text{SOC}_{\text{ref}} \), the constant \( K_{\delta} \) will determine how fast the reference charge current \( I_{\text{ch-ref}} \) decreases to zero (i.e., battery discharge rate). Both \( K_{\delta} \) and \( \delta_{\text{SOC}} \) are selected according to battery specification and design preference.

\[
I_{\text{ch-ref}} = \frac{S}{\text{SOC}_{\text{nom}} - I_{B_{\text{max}}}} \delta_{\text{SOC}}
\]

**Figure 6**: SOC/I\(_{B_{\text{max}}} \) characteristic curve of the battery.

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

1. \( I_{B_{\text{max}}} \leq I_{pV_{-mpt}} \): In this case, the current produced by PV unit is sufficient for BESS charging and excessive current is injected into the load. Current injection into the microgrid \( (I_0) \) is derived from the difference \( (I_{pV_{-mpt}} - I_{B_{\text{max}}}) \). Hence, the battery charging process can be fulfilled by indirectly controlling the power injected into the DC microgrid. However, the major target of control strategy in this scenario involves battery charging, top priority is to support the establishment of power balance in the microgrid for decentralized controlling of the DC microgrid.

2. \( I_{B_{\text{max}}} > I_{pV_{-mpt}} \): In this case, the reference current \( I_{\text{ref}} \) is negative and the hybrid unit absorbs the current difference \( (I_{pV_{-mpt}} - I_{B_{\text{max}}}) \) so as to charge the battery in maximum current. This is equivalent to move I/V characteristic to the left. In this situation, the hybrid unit acts as a consumer and charge battery. If the load demand is increased and the SOC of BESS is decreased to 20%, PV unit should be supplied the load.

4. DC-DC converter control system in hybrid unit

Generally when the PV unit 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 \( \text{SOC}_{\text{max}} \) limit. This condition occurs when the excess power of PV \( (I_{pV_{-mpt}} - I_L) \) is greater than the current \( I_{B_{\text{max}}} \) of the battery unit. This can impair the battery voltage and destroy its cells [25]. It is necessary to adopt a suitable controller for monitoring the battery charge status. Since this paper intended to coordinate the performance of the hybrid unit, 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. 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 \( I_{\text{ch-limit}} \) based on battery voltage. When the battery voltage is reduced to less than \( V_{B_{\text{lim}}_{\text{lim}}} \), the PI controller output will regulate the charging current \( I_{\text{ch-limit}} \) 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 \( V_{B_{\text{lim}}_{\text{lim}}} \), the PI controller curtails the reference charging current \( I_{\text{ch-limit}} \) in order to adjust the battery voltage. If the load decreases or the battery voltage increases, so that \( I_B \) exceeds reference \( I_{\text{ch-limit}} \), the PI controller will adjust the charge current of PV module so as to
follow the reference charge current $I_{\text{ch-limit}}$. In fact, the controller transfers the operating point of the PV unit outside the 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, MPPT algorithm is disabled and the range of $V_{\text{mppt}}$ stays in the last fixed value before disabling the algorithm. 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 $I_{\text{ch-limit}}$ 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 $I_{\text{ch-limit}}$. 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.

5. Simulation Results

A DC microgrid composed of a PV/battery hybrid unit and linear resistive 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 battery charging.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC bus voltage Ref.</td>
<td>$V_{\text{dc-ref}}$</td>
<td>500 V</td>
</tr>
<tr>
<td>Maximum PV power</td>
<td>$P_{\text{pv-max}}$</td>
<td>100 KW</td>
</tr>
<tr>
<td>Low voltage threshold</td>
<td>$V_L$</td>
<td>485 V</td>
</tr>
<tr>
<td>High voltage threshold</td>
<td>$V_H$</td>
<td>515 V</td>
</tr>
<tr>
<td>Nominal battery capacity</td>
<td>$C_{\text{bat}}$</td>
<td>40 A.h</td>
</tr>
<tr>
<td>Initial SOC of battery</td>
<td>$\text{SOC}$</td>
<td>% 65</td>
</tr>
<tr>
<td>Minimum value of SOC</td>
<td>$\text{SOC}_{\text{min}}$</td>
<td>%20</td>
</tr>
<tr>
<td>Maximum value of SOC</td>
<td>$\text{SOC}_{\text{max}}$</td>
<td>%90</td>
</tr>
</tbody>
</table>

Figure 7 shows the power/voltage characteristic curve of PV module. According to this curve, the PV arrays can generate and deliver maximum power of 100 kW at 1000 W/m² of radiation level at 275 volt. The red circles on the curve represent the 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 $\frac{dP}{dV}$ becomes zero at the MPP, before which the value of power becomes positive and then will be negative. Also, if $\frac{dP}{dV}$ is positive, the algorithm progresses on the power-voltage curve by increasing the voltage until it reaches $\frac{dP}{dV} = 0$; and if $\frac{dP}{dV}$ is negative, the algorithm moves in the opposite direction to the point where the power-voltage variations are zero, selecting that point as MPP.
Figure 7: Power characteristic curve of PV module in 25 °C temperature and different radiation levels.

Figure 8 illustrates the performance of control strategy in response to the load changes. In this part of the simulation, solar radiation is fixed in 1000 w/m², accordingly the output power of the PV unit will be 100 KW based on figure 7 characteristic curve and PV unit acts as a controlled power source. In this scenario and at the first step, load demand is 100 KW and the load is completely supplied by the PV unit. Also the initial SOC level of the battery is 65%; therefore it’s unnecessary to charge the battery. At t=0.4s, load demand is increased to 140 KW and that is 40 KW more than maximum power generation of the PV unit. Hence the battery unit started to discharge and battery supplied the shortage value of the load demand. At t=0.8s, load demand is decreased to initial value (100 KW) again and it can be supplied by the PV unit. In this situation battery will be in floating mode till t=1.5s. At t=1.5s the load demand is decreased again and its level is stabilized in 60 KW. Therefore the PV unit supplied the load demand and excess power (40 KW) is spent to charge the battery to increase the SOC level of the unit until 90%.

Figure 8: Performance of proposed control strategy in response to load changes.
Figure 9 shows the voltage of common bus on the output of hybrid unit. After running on the transients, the DC bus voltage is stabilized on 500 V and the BESS regulated DC voltage in order to establish power balance in the DC microgrid. Also in the other scenarios, the DC bus voltage is stabilized in 500 V and the variations of load demand or battery charging scenario have no major effect on DC voltage. Hence \( V_{dc} \) is controlled well, according to the desired control strategy and in all the scenarios; it is in the allowable range.

Figure 10 illustrates the performance of proposed control strategy in response to PV power generation and load changes. In this scenario, the solar radiation and load demand is changed simultaneously. In fact, MPPT controller of PV unit is disabled and power generation of PV unit changed according to the load demand; therefore PV unit acts as a voltage source. At the first step, load demand is 20 KW and PV unit supplied the load completely. At \( t=0.5\) s, load demand increased to 80 KW and MPPT controller of PV unit is activated to generate maximum power of the unit. As shown in this figure, at \( t=0.8\) s there is 20 KW excess power in the system; hence battery unit started to charge to increase SOC level. At \( t=1.5\) s, load demand decreased to 20 KW again, therefore the MPPT controller of PV unit is deactivated again to superpose power generation with the load demand and after \( t=2\) s, generation and load is met each other.
Figure 10: Performance of proposed control strategy in response to PV power generation and load changes.

Figure 11 shows the simulation results of proposed control strategy during nominal operating scenario. In this scenario solar radiance is fixed to 500 w/m², hence the generation power of PV unit is 50 KW constantly and this unit acts as a controlled power source. In the first step, there’s not any load in the system and all the power charged the battery unit. At t=0.5s, 120 KW linear load is connected to common bus, that is 70 KW more than maximum power generation of the PV unit. Therefore BESS started to discharge and supplied the shortage of load demand. At t=1.5s, load demand is decreased to zero again, hence the delivered power by battery unit is decreased too. As mentioned before, PV unit generates 50 KW power constantly, therefore battery unit started to charge again until SOC level reached to 90%.

Figure 11: Simulation results of proposed control strategy during nominal operating scenario.

Figure 12 illustrates simulation results of proposed strategy during transition from charging state to the nominal operating scenario. Similar to the previous scenario, solar radiance is fixed in 500 w/m² and PV unit generates 50 KW power constantly; in fact PV unit act as a controlled power source. At the
first step, load demand is zero and all the PV power generation charged battery unit. At t=1s, load demand is increased to 50 KW. Hence battery unit transferred from charging state to floating mode according to the characteristic curve presented in figure 6. Therefore load demand is completely supplied by PV unit and battery unit will be in floating state.

![Figure 12: Simulation results of proposed strategy during transition from charging scenario to nominal operating scenario.](image)

**Conclusion**

A multi-loop control strategy for controlling a PV/battery hybrid system has been developed and simulated. The decentralized strategies control the PV power converter and the bidirectional battery power converter in the presence of operating constraints. Based on the battery SOC, the PV maximum power and the load demand operation has been categorized into two operating scenarios to smoothly manage the power flow within the DC microgrid under battery charging current and capacity limits. Simulation results from a DC microgrid system with 500 V common bus voltage has been presented and validated the proposed control strategies under different operating scenario.

**References**


