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Reduced Battery Usage in a Hybrid Battery and Photovoltaic Stand-Alone DC Microgrid with Flexible Power Point Tracking

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Abstract—A hybrid control strategy for photovoltaic (PV) system and energy storage system (ESS) in a dc microgrid is proposed in this paper. The proposed control strategy minimizes the utilization of ESS in order to prolong the battery lifetime, reduce the total system power losses, and maintain the state-of-charge (SoC) of the battery within a desired range as long as the required power from PV is available. In contrast to the conventional control strategies that regulate the dc bus voltage with the ESS, the proposed control strategy exploits the use of both PV and ESS in regulating the dc bus voltage. It also employs an advanced flexible power point tracking algorithm for the PV system to further enhance the dynamic performance of the system by adaptively adjusting the PV output power according to the load profile.

Index terms—Battery state-of-charge (SoC), dc microgrid (dcMG), energy storage system (ESS), flexible power point tracking (FPPT), photovoltaic (PV) systems.

I. INTRODUCTION

The over-extraction of fossil fuels during the past few decades has led to increased fuel costs due to the limited amount of natural resources. This fact considerably impacts the cost of electricity production using conventional resources. Consequently, renewable energy resources have been slowly replacing conventional fuels to generate electricity and obtain a more sustainable natural resource utilization and reduce the carbon footprint [1]. Among the renewable energy sources, solar energy is renowned to be one of the most abundantly available resources and hence, photovoltaic (PV) power plants produce nowadays more electricity compared to geothermal and tidal wave energies [1].

DC microgrid (dcMG) power systems are drawing great attention due to a steady growth in dc load demand and distributed renewable energy generation. The majority of modern consumer electronics, energy-efficient lighting systems and energy-saving electronics are operated with dc supply. If these dc loads are supplied from the ac grid, the supply needs to be converted to dc, which contributes to power conversion losses. Such conversion losses can be eliminated via dc power supply. Also, synchronization and reactive power flow issues do not exist in dcMGs [2], [3].

However, issues such as dynamically changing weather conditions and dc bus over-voltage may lead to instability in microgrids and hence, dcMGs require a robust control scheme. It is crucial for the dcMG system to operate efficiently

and reliably with the power conversion control systems. The majority of existing PV controllers aim to extract maximum power from PV arrays using maximum power point tracking (MPPT) algorithms [4], [5]. The overall control of the microgrid is achieved with the support of energy storage systems (ESSs) such as batteries and super-capacitors, which help to regulate the dc bus voltage. When the PV penetration increases, MPPT operation may cause dc bus over-voltage and ESS overcharging issues. Hence, the MPPT method alone is insufficient to control the PV generation and additional features are needed to maintain the dc bus voltage [6]–[9].

The excessive PV penetration issue is solved with MPPT-droop dual-mode control strategy with the ESS [7]–[9]. However, the controller for PV generation in [7] generates transient disturbance during operation mode transitions and the transition criteria further complicates the control algorithm. The PV controller in [8] only focuses on the MPPT operation mode and the algorithm in [9] only focuses on the dc bus voltage regulation. Therefore, the additional outer-loop control technique is required to regulate the dc bus voltage in [8] and to extract the maximum power from PV [9]. [10] and [11] introduced the MPPT and droop integrated control method to avoid the transition criteria during mode transitions and to remove the system disturbances. The dp/dv regulator is the key element in the control that provides a duty ratio for the dc-dc converter by calculating the change in power with the droop coefficient. However, this strategy suffers from slow dynamic response under rapid environmental changes as the PV voltage-step is constant. The control systems for dcMGs introduced in [6], [12], [13] do not optimize the battery usage and the extensive use of battery to regulate the dc bus voltage drastically shortens the battery lifetime.

To solve the above mentioned drawbacks, this paper proposes a dcMG system with a hybrid control strategy for PV and ESS. The proposed hybrid control strategy minimizes the utilization of the ESS and it keeps the state-of-charge (SoC) of the ESS within the desired range, if the required power is available from the PV, to prolong the ESS lifetime. The aims of the proposed control strategy are achieved by keeping the battery ESS in standby mode, if the PV has sufficient power to cater the load demand. The ESS converter is put into operation only in the case of: (i) load demand exceeds

Fig. 1. Circuit configuration and proposed control strategy of the islanded dcMG.

the maximum available PV power, (ii) transient dc bus voltage deviates beyond the allowed operational limits and (iii) the SoC of the battery becomes smaller than a desired minimum range. During this operating condition, the PV generates its maximum power. In order to regulate the PV power to the required power from loads, a flexible power point tracking (FPPT) algorithm with adaptive voltage-step calculation, [14]–[17], is implemented in the PV controller, which enhances the dynamic response of the system.

The structure of this paper is as follows. The details of the proposed control strategy with PV and ESS controllers are introduced in Section II. The simulation results are presented in Section III, and Section IV concludes the study.

II. PROPOSED CONTROL STRATEGY

The circuit configuration of an islanded dcMG powered by a PV and the ESS is shown in Fig. 1. The proposed control strategy, and the controllers of the dc-dc converters connected to the PV array and the ESS are explained in details in the following subsections.

A. Proposed Hybrid Control Strategy

The battery serves as the secondary source in the islanded dcMG when the PV system is not able to fulfil the load demand. It also helps to regulate the dc bus voltage v_{dc} when its deviation exceeds the allowable control limits. In the proposed hybrid control strategy, a control voltage range is defined in which only the PV controller regulates the dc bus voltage and the ESS converter remains idle. If the v_{dc} is not within this allowable range, or if the MPPT operation mode is on, the ESS converter will operate. Here, V_{dcUL} and V_{dcLL} are the upper and lower limits of the control range, respectively, as shown in Fig. 2. Furthermore, there is a deadband around each of these control limits, V_{dcUL1} and V_{dcUL2} for V_{dcUL} and V_{dcLL1} and V_{dcLL2} for V_{dcLL} as shown in Fig. 2. The reason for setting the deadband across each main control limit is to prevent the battery to turn on and off recursively around the boundary limits.

p_{pv-max} is the rated maximum power of the PV power plant which can be estimated using the technique provided in [18], Op is the battery operation mode which is provided from the battery controller, and p_{load} is the load demand power. If the SoC is within the range of SoC_{min} and SoC_{max} , shown in

Fig. 2. Proposed operation control limits.

Fig. 3. Proposed hybrid operation mode calculation strategy.

Fig. 3, the operation condition Op will not be updated. If the SoC is lower than SoC_{min} , Op is updated to 1 and the battery is put into operation in order to be charged by the PV excess power generation. When the load power p_{load} is larger than the maximum available power p_{pv-max} ($p_{load} > p_{pv-max}$), the

Fig. 4. Proposed algorithm for the calculation of the PV power reference.

battery has to operate as the load demand is higher than the maximum available power from the PV.

Subsequently, if v_{dc} is greater than V_{dcUL1} or smaller than V_{dcLL2} , as shown in Fig. 2, the battery operates as the v_{dc} deviation is out of the allowable range and thereby, v_{dc} is regulated by the ESS. If the v_{dc} is within the innermost boundaries, i.e. V_{dcUL2} and V_{dcLL1} , the battery controller is switched off and only the PV converter controller is responsible for regulating v_{dc} to its reference value. If v_{dc} is within the outermost boundaries, V_{dcUL1} and V_{dcLL2} , and not within the innermost boundaries, the operation mode will not be updated. With this control methodology, the ESS utilization is carefully minimized.

After the operation mode is identified as mentioned above, the PV reference power p_{pv-ref} , is calculated accordingly, as shown in Fig. 4. The PV controller uses the Op , p_{pv-max} and p_{load} information to determine p_{pv-ref} . If Op is 1, the battery is in operation and thus, p_{pv-ref} is set to p_{pv-max} so that the PV operates at its maximum power point. This will trim down the load sharing from the ESS or restore the SoC of the ESS to the optimal range when the load demand is smaller than the p_{pv-max} . If Op is 0, it translates that the battery is not in operation. Hence, the PV system completely takes control of the load sharing and regulates v_{dc} by constantly adjusting p_{pv-ref} to be $p_{load} + dp$, in which, dp is the output of the proportional integral (PI) controller that regulates the dc bus voltage v_{dc} to its reference value V_{dc-ref} .

B. PV Connected DC-DC Converter Controller

As shown in Fig. 1, the amount of power supply from the PV system is controlled by the dc-dc boost converter. The PV power reference p_{pv-ref} is fed to the FPPT algorithm from the proposed hybrid control strategy, as shown in Fig. 4. Then, it calculates the PV voltage reference v_{pv-ref} , as shown in Fig. 1. The PV voltage reference is given to a model-based analytical voltage controller that generates the PV inductor current reference, $i_{Lpv-ref}$ [19]. A model predictive control (MPC) current controller is applied to determine the duty cycle D of the dc-dc boost converter based on the inductor current

TABLE I
SIMULATION PARAMETERS

Parameters	Values
DC-link voltage reference, V_{dc-ref}	400 V
DC-link voltage upper limit, V_{dcUL}	408 V
DC-link voltage lower limit, V_{dcLL}	392 V
Voltage at maximum power point, V_{mpp}	232 V
PV maximum power, P_{pv-max}	5.115 kW
Battery voltage rating, V_{bat}	48 V
Battery capacity, E_{bat}	5 kWh
Battery dc-dc converter inductance, L_{bat}	0.5 mH
PV dc-dc converter inductance, L_{pv}	1.5 mH
PV-side capacitor, C_{pv}	0.2 mF
DC-link capacitor, C_{dc}	4 mF

and its reference [19]. The switching signals of the boost converter are then generated with the help of the pulsewidth modulation (PWM) technique. The main advantage of this control scheme is its fast transient response, which enables the PV system to adapt the PV power based on the load demand.

C. ESS Connected DC-DC Converter Controller

A bi-directional boost dc-dc converter is deployed to charge/discharge the battery. The dc-link voltage v_{dc} is regulated according to the V_{dc-ref} by utilizing a PI controller that imposes the battery inductor current reference value, $i_{Lbat-ref}$. The switching signals for the converter are calculated by a MPC to predict the future signal that minimizes the error. When $S2$ is on, $V_2 = v_{bat}$ and when $S1$ is on, $V_1 = v_{bat} - v_{dc}$. V_1 and V_2 are the voltages across the inductor of the dc-dc converter in the mentioned switching states, as shown in Fig. 1.

$$i_L(k) = i_{Lbat}, \quad (1)$$

$$i_{L1}(k+1) = (V_1 \times T_{step})/L + i_L(k), \quad (2)$$

$$i_{L2}(k+1) = (V_2 \times T_{step})/L + i_L(k), \quad (3)$$

$$i_{ESSoutput} = (\Delta i_{Lbat} + (p_{load} - p_{pv})/v_{dc}) \times v_{dc}/v_{bat}, \quad (4)$$

where v_{bat} is battery voltage, i_{Lbat} is battery inductor current, $i_{L1}(k+1)$ and $i_{L2}(k+1)$ represent the predicted currents at the next time-step $(k+1)$, and p_{pv} is the PV output power. Then, $J_1 = (i_{ESSoutput} - i_{L1}(k+1))^2$ and $J_2 = (i_{ESSoutput} - i_{L2}(k+1))^2$ are calculated to determine which contributes the lesser error. If $J_1 < J_2$, J_1 provides the predicted value nearer to the desired value and hence, $S1$, the switch corresponding to the lesser error will be on and $S2$ off. Similarly, an opposite switching state will take place if J_2 is smaller. The switching signals are then applied to the converter to control the battery supply.

Fig. 5. *Case I*. Verification of the proposed ESS lifetime optimization control strategy under different loading conditions: (a) DC bus voltage, (b) PV power, load power and battery power, and (c) SoC of the battery.

III. SIMULATION RESULTS

The performance of proposed control system is evaluated using MATLAB/Simulink under different dc loading conditions and irradiance changes. All the simulations are carried out with the assumption of *Cell temperature* = 25 °C and the simulation parameters are shown in Table I. Solar irradiance is kept constant at 1 kW/m² and $P_{pv-max} = 5.115$ kW in *Case I* and *Case II*. Three test cases are performed, as follows.

Case I: In this case study, the performance of the proposed control strategy for the PV system and the ESS under different loading conditions is examined and the results are shown in Fig. 5. Initially, the PV is supplying power according to the load demand and the battery is not in operation. At $t = 0.1$ s, p_{load} suddenly increases from 2 kW to 4 kW, and because of that, v_{dc} drops as shown in Figs. 5(a) and (b), respectively. The voltage drop is within the control limits and load power p_{load} is smaller than P_{pv-max} , therefore, the operation status of the battery is not updated. Then, the PV increases its output power to the new load demand at $t = 0.1$ s and it is able to regulate v_{dc} to V_{dc-ref} .

The load power p_{load} surges from 4 kW to 8 kW at $t = 0.35$ s. Since p_{load} is greater than P_{pv-max} , the PV generates the maximum power and it is no longer able to regulate v_{dc} . Subsequently, the battery is put into operation in order to supply the remaining load demand and participate in v_{dc}

Fig. 6. *Case II*. Preserving the SoC of the ESS within the optimal operation range: (a) DC bus voltage, (b) PV power, load power and battery power, and (c) SoC of the battery.

regulation. The load power p_{load} reduces to 6 kW at $t = 0.6$ s and the battery is still operating as the load demand is still exceeding P_{pv-max} . p_{load} reduces to 2 kW at $t = 0.8$ s and hence, the battery stops operating as the PV has sufficient capacity to supply the load demand and v_{dc} deviation also does not go beyond the outermost control limits. Hence, this case study demonstrates the proposed hybrid control strategy supplying the load demand by minimizing the ESS utilization.

Case II: This case study demonstrates the effectiveness of the proposed control strategy in maintaining the SoC in the optimal range as shown in Fig. 6. The initial SoC is approximately 89.9% and the load demand is 8 kW. The PV system is generating the maximum power and the battery is also operating to fulfill the excess load demand. p_{load} reduces to 2 kW at $t = 0.3$ s. The PV continues to operate at maximum power point despite the load change, since SoC is below 90%. Hence, the surplus generation of 3.115 kW is supplied to the battery. The operation continues till SoC is more than 90%. Once the SoC is more than 90%, p_{pv} is re-adjusted according to the load demand and the PV controller is now operating in FPPT mode. In this case, it can be observed that the proposed hybrid control strategy is able to keep the SoC within the desired range so that the ESS has enough capacity to cater for the load demand whenever the PV generation is insufficient.

Case III: The performance of the proposed hybrid control strategy is investigated under irradiance changes as depicted

Fig. 7. Case III. Demonstration of the proposed control strategy under intermittent irradiance changes: (a) DC bus voltage, (b) PV power, load power and battery power, and (c) irradiance.

in Fig. 7. The load demand is constant at 4kW and the initial irradiance is 1 kW/m^2 . Hence, the PV is producing the load demand and the ESS does not operate. At $t = 0.2$ s, the irradiance drops to 0.6 kW/m^2 and consequently, the PV supply is reduced, as shown in Fig. 7(b). Since the PV supply is not able to fulfil the load, the battery operates and supplies the remaining load demand. Similarly in Fig. 7(c), the irradiance drops again to 0.4 kW/m^2 at $t = 0.6$ s. Hence, the PV output power further decreases and the battery increases its supply power, respectively. When the irradiance increases back to 1 kW/m^2 , the PV has sufficient power to cater for the load and thus, the battery stops operating. This case study demonstrates the dynamic performance of the proposed control strategy under rapid irradiance changes.

IV. CONCLUSION

A novel hybrid control strategy for PV and ESS converters in an islanded dcMG system has been introduced in this paper. The proposed control strategy minimizes the utilization of the ESS by changing the control operation mode according to the dc-link voltage range and load demand power, while upholding the SoC of the battery within a desired range. The effectiveness of the proposed control strategy is demonstrated with simulation results. The results show that the proposed strategy is able to regulate the dc bus voltage even during transients of load demands and solar irradiance, delicately

considering the SoC of the battery, and prolonging the battery lifetime by reducing the ESS uptime.

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