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Simplified Hybrid Control Strategy for Stand-Alone DC Microgrid with Photovoltaic System to Extend Battery Lifespan

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Abstract—Conventionally, a flexible photovoltaic (PV) power control strategy is used to reduce battery utilization in stand-alone dc microgrids (dcMGs). However, conventional control schemes deploy multiple voltage controllers to regulate the dc-link voltage, causing mode transitions during the transients and complicating the controller design. This paper proposes a simplified control strategy for the PV system and the battery energy storage system in a stand-alone dcMG with a single voltage controller to regulate the dc-link voltage. The proposed control strategy enhances the transient response of the system by eliminating the mode transitions between voltage controllers and simplifying the hybrid control scheme while reducing the battery utilization. Additionally, the proposed solution does not require the knowledge of the load, which facilitates its application. The effectiveness of the proposed control strategy is validated with simulation results.

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

I. INTRODUCTION

A battery energy storage system (BESS) is often incorporated into a stand-alone dc microgrid (dcMG) with the photovoltaic (PV) system to improve the reliability as the PV generation is intermittent. Although the battery improves the system stability, its lifespan is shortened based on its operation behaviour. In lithium-ion batteries, parameters such as the battery temperature, state-of-charge (SoC), depth-of-discharge (DoD), and the calendar aging influence the battery aging rate [1], [2].

The BESS may operate at its maximum charging limit if the PV system is operated with traditional maximum power point tracking (MPPT) control [3], which degrades the battery lifespan due to high current stress. To prevent the PV excess generation in the dcMGs, a segregated MPPT with voltage regulation control is implemented, which has the ability to curtail the PV power [4], [5].

Although the control in [4] solves the PV over-generation issue, the dynamic of the control system is slow because of the constant PV voltage-step operation of the MPPT. In addition, the use of multiple proportional-integral (PI) controllers for each PV control function causes a transient whenever the control function is changed. As the PV dynamic performance is slow, the battery is forced to operate more often for regulating the dc-link voltage and consequently, the battery ages faster. Similarly, the dynamic response of the PV system in [5] is poor during the intermittent rapid irradiance changes due to the constant PV voltage-step-based MPPT operation. Hence, the battery needs to operate continuously and the prolonged period of battery operation reduces its lifespan [1].

Alternatively, flexible PV power control schemes, which integrate the MPPT and the droop control, were introduced to eliminate the PV control reconfiguration during the operation mode transitions [6], [7]. However, the battery utilization is not enhanced as the dynamic response of the PV system is still slow. Therefore, the battery is used as the primary asset to control the dc-link voltage in [3]–[7]. An advanced flexible PV power control scheme was introduced in [8], [9] to reduce the battery utilization and primarily regulate the dc-link voltage with the PV system by adjusting the PV power dynamically. However, the control strategy in [8], [9] implements two dc-link voltage controllers (one for the PV system and one for the BESS) to regulate the dc-link voltage and requires mode transitions during the transients. Hence, control limits with deadband are applied to identify the operation modes and facilitate the mode transitions between the PV system and the BESS, which increase the control complexity [8], [9]. Furthermore, the need for an extra sensor to measure the load power in the aforementioned conventional solutions is a drawback.

Fig. 1. Circuit configuration and proposed simplified control strategy of the stand-alone dcMG.

In this paper, a hybrid control strategy for the stand-alone dcMG with BESS and PV system is proposed. It simplifies the centralized control scheme by implementing a single dc-link voltage controller and eliminating mode transitions of the controller. The proposed control strategy also extends the battery lifespan by reducing the battery usage. This objective is fulfilled by considering the PV system as the primary asset to control the dc-link voltage. The BESS converter is only operative when (i) the load demand exceeds the maximum available PV power or (ii) the battery SoC falls below a pre-defined value. During these conditions, the PV generates its maximum power. Furthermore, the proposed control strategy does not require a sensor to measure the load current. The PV controller is implemented with an advanced flexible power point tracking (FPPT) algorithm [10]–[13], to rapidly respond to the intermittent irradiance changes as well as load demand variations and thus, prevent operating the battery unnecessarily.

II. PROPOSED CONTROL STRATEGY

An overview of the proposed control strategy of a stand-alone dcMG powered by a PV system and a BESS is shown in Fig. 1. As the main contribution of the paper is controlling the PV system and the BESS, the effects of other MG components (i.e. dc loads, inverters, etc) can be considered as a current source and named as “MG Loads” in Fig. 1. No extra sensor is added in the proposed solution to measure the load power. A single PI controller is used to regulate the dc-link voltage, v_{dc} , to its reference, v_{dc-ref} , as shown in Fig. 1. The load demand, p_{load} , information can be obtained from the output of this PI controller. Unlike the control scheme in [8], [9], which implements two voltage controllers with dedicated control limits, a single PI controller is used for the outerloop control of both the PV system and the BESS. Furthermore, the proposed control system does not require the deadband to identify the operation modes, which is essential for the operation of the control system in [8], [9]. Hence, it simplifies the hybrid control scheme of the dcMG while

Fig. 2. Proposed hybrid operation mode identification strategy.

providing flexibility to the load share between the PV system and the BESS.

The battery operation mode, Op , is evaluated based on the battery SoC and p_{load} information, which is given by:

$$Op = \begin{cases} 1, & \text{Discharge mode} \\ 0, & \text{Standby mode} \\ -1, & \text{Charge mode} \end{cases} \quad (1)$$

As shown in Fig. 2, the output of the PI controller p_{load} is compared with the maximum available PV power, p_{pv-max} , which is estimated using the approach in [14]. If p_{load} is larger than p_{pv-max} , Op is updated to 1 as the PV maximum generation is insufficient to supply the demand, and the battery will supply the remaining load demand. In this case, the PV power reference, p_{pv-ref} , is set to p_{pv-max} to reduce the load share of the BESS. Subsequently, the battery SoC is compared with its threshold value SoC_{th} , which is a pre-defined value and it is considered to be 100% in this paper. If SoC is smaller than SoC_{th} , Op is updated to -1 , charge mode, and similarly, p_{pv-ref} is set to p_{pv-max} so that any PV excess generation can charge the battery. Otherwise, the BESS goes into standby mode by updating Op to 0 to minimize its utilization. To achieve this, the PV generation is accordingly adjusted to the load demand (setting p_{pv-ref} to p_{load}) to balance the power flow and regulate the dc-link

TABLE I
SIMULATION PARAMETERS

Parameters	Values
DC-link voltage reference, V_{dc-ref}	180 V
PV panel maximum power-point voltage*, V_{mpp}	116 V
PV panel maximum power*, P_{pv-max}	850 W
Battery voltage rating, V_{bat}	12 V
Battery capacity, E_{bat}	84 Wh
Battery dc-dc converter inductance, L_{bat}	6.3 mH
PV dc-dc converter inductance, L_{pv}	10 mH
DC-link capacitor, C_{dc}	5 mF
PV-side capacitor, C_{pv}	0.33 mF

*Irradiance 1000 W/m^2 and temperature 25°C

voltage to its reference.

Subsequently, the determined p_{pv-ref} is provided to the FPPT algorithm [10] to generate the PV voltage reference, v_{pv-ref} . The PV voltage reference is then provided to the model-based analytical voltage controller that calculates the inductor current reference, $i_{lpv-ref}$, for the PV current controller, which is further elaborated in [15]. The switching signal, S , for the PV boost converter is then generated by the direct model predictive current controller, which is explained in detail in [8]. Similarly, the switching signals, $S1$ and $S2$, for the battery converter are also generated by the direct model predictive current controller [8]. As shown in Fig. 1, the battery current reference, $i_{ibat-ref}$, provided to the current controller is $(p_{load} - p_{pv})/v_{bat}$. The BESS will operate according to the evaluated operation mode, Op , to prolong the battery lifespan with enhanced utilization.

III. SIMULATION RESULTS

The transient performance of the proposed control strategy under different load conditions and rapid irradiance changes is investigated using MATLAB/Simulink. The simulation parameters are provided in Table. I. The PV controller operates the PV strings on the left-side of the maximum power point (MPP), which results in smaller power oscillation as compared to the right-side of the MPP [10]–[13].

Case I: This case verifies the transient performance of the proposed control strategy under different load conditions, as shown in Fig. 3. The PV maximum power, p_{pv-max} , is 850 W and the irradiance is assumed to be constant at 1 kW/m^2 in this case study. The initial load demand, p_{load} , is 450 W, which is below p_{pv-max} , and hence, the battery is not in operation ($Op = 0$) and the PV generation equals the load. At $t = 2 \text{ s}$, p_{load} increases to 1 kW, exceeding $p_{pv-max} = 850 \text{ W}$. Thus, the operation mode, Op , is updated to 1, which activates

Fig. 3. Simulation results of the proposed control strategy under different load conditions. (a) PV voltage, (b) dc-link voltage, (c) PV power, PV maximum power, load power, and battery power, (d) PV and battery currents, and (e) battery SoC.

the BESS and supplies the remaining load demand with the battery, as can be seen in Fig. 3(c). Hence, the drop in dc-link voltage, v_{dc} , (see Fig. 3(b)) due to sudden load increase is rapidly compensated and v_{dc} is regulated back to its reference by the BESS. At $t = 6 \text{ s}$, p_{load} decreases to 750 W, which is below p_{pv-max} . However, Op is updated to -1 as the battery SoC is below its reference value SoC_{th} (100 % in this case). Accordingly, PV generation remains at $p_{pv-max} = 850 \text{ W}$ and charges the battery with the surplus generation, as shown in Figs.

Fig. 4. Simulation results of the proposed control strategy under changing irradiance. (a) Irradiance, (b) PV voltage, (c) dc-link voltage, (d) PV power, PV maximum power, load power, and battery power, (e) PV and battery currents, and (f) battery SoC.

3(c) and (e). The battery is fully charged at approximately $t = 15$ s and Op is updated to 0 to put the BESS in standby mode and adjust the PV generation to the load. The results of this case confirm the capability of the proposed centralized control strategy to effectively deal with the load transients. Furthermore, the reduced battery utilization with the proposed concept is also demonstrated.

Case II: In this case, p_{load} remains constant at 550 W to investigate the intermittent irradiance effect on the proposed control strategy. Initially, as shown in Fig. 4(a), the solar irradiance is at 1 kW/m^2 with $p_{pv-max} = 850 \text{ W}$. Hence, the BESS is not in operation and the dc-link voltage is regulated solely by the PV system, as shown in Fig. 4(c). The irradiance linearly decreases to 500 W/m^2 at $t = 2$ s, causing a p_{pv-max} reduction to approximately 410 W. The battery becomes operative ($Op = 1$) to fulfill the load demand, as the PV generation is insufficient. At $t = 6$ s, the irradiance increases back to 1 kW/m^2 and the PV system has enough power for the load. As the battery has been discharged previously, it needs to restore energy before turning off. Hence, the PV generation remains at $p_{pv-max} = 850 \text{ W}$ to charge the battery with the excess generation by updating Op to -1 , as shown in Fig. 4(d). The battery then goes into standby mode after it is fully charged (see Fig. 4(f)) and correspondingly, PV generation adjusts to the load. This case study validates the transient performance of the proposed control strategy under intermittent irradiance changes, while utilizing the battery only when needed.

IV. CONCLUSION

A simplified control strategy for hybrid stand-alone dcMG with the PV system and the BESS has been proposed in this paper. Unlike conventional controls, the proposed control strategy utilizes a single dc-link voltage controller that reduces the control complexity for better dynamic performance. Furthermore, the proposed control system improves the BESS utilization by keeping it in standby mode whenever possible and thus, eliminating the micro-cycle operations. Results from the simulation case studies confirm the effectiveness of the proposed control in dealing with load transients and intermittent irradiance changes. The control is able to maintain the dc voltage under the test scenarios while reducing reliance on the BESS.

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