Electrical Power and Energy Systems 87 (2017) 109–120

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

# Cooperative control of battery energy storage systems in microgrids

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ARTICLE INFO

*Article history:*
Received 19 January 2016
Received in revised form 28 November 2016
Accepted 5 December 2016

*Keywords:*
Microgrid
Distributed Energy Resource (DER)
Dynamic power sharing
Virtual impedance

ABSTRACT

This paper proposes a cooperative control of battery energy storage (BES) units within a microgrid (MG) which includes two control subsystems for charge and discharge operation mode of the BES. In addition, the proposed cooperative control strategy provides accurate reactive power sharing among the BES units. During discharge operation, the proposed strategy utilizes a SoC-based droop control in order to avoid promptly depleting of the BES units, by dedicating the highest priority to their SoC level and respecting their power rating. This is achieved without any disturbance in the power balance of the MG. In addition, during charge operation of the BES units, the proposed control method uses a proportional-integral (PI) controller to limit the BES absorbing power and match it with the available surplus power from the renewable energy sources (RESs). This in turn avoids any power imbalance within the system. Finally, to utilize the extra capacity of the BES converters and also to avoid overloading of RESs, a new adaptive virtual impedance (AVI) strategy is proposed here which provides accurate reactive power sharing by imposing a virtual impedance in series with the coupling impedance of each BES and RES unit. The system performance is validated through extensive simulations carried out in PSCAD/EMTDC software.



## 1. Introduction

Microgrids (MGs) include clusters of loads and renewable energy sources (RESs), which can operate in either grid-connected mode or autonomous mode as shown in Fig. 1. Energy storage systems such as batteries are widely used in MGs in order to compensate the power imbalance between the RES units and loads in the autonomous mode [1]. To achieve this, battery energy storage (BES) units are charged by absorbing the surplus power of the RES units during off peak hours. Additionally, they can operate as a back-up in the autonomous MG by delivering active and reactive power during peak hours of demand. Several researches have studied the performance of the BES units in autonomous MGs. In [2], the frequency variations reflect the power imbalance within the MG and the BES operation mode is decided, accordingly. Also, in [3] BES units are utilized to compensate the power fluctuations due to the intermittent nature of RESs. Additionally, the performance of different types of batteries has been investigated in several researches as [4–7].

Different control strategies are proposed, in the literature, for the BES units within an MG. In some researches the BES units are controlled to supply a constant power to the MG to maintain the frequency above a threshold value. Alternatively, some other studies conduct the BES units with the droop control strategy along with the RES units of the MG [8–10]. In simple droop control, the droop coefficients are defined based on the capacity of the distributed energy sources (DERs) including RES and BES units. This denotes that, delivered power by the BES units is determined without considering the BES state of charge (SoC). Therefore, this may result in promptly depleting of the BES units and in turn it causes BES disconnection. However, it is desired for the BES units to stay in the system as a backup in case of any power imbalance.

To address this issue, one solution is to modify the traditional droop control of the BES units such that their power ratios correlate with their state of charge (SoC) instead of their nominal capacity [11–13]. In this method, the output active power of each BES unit is modified dynamically overtime according to its instantaneous SoC level. The main problem with the above modified droop control is that the output power of each BES unit is related to the SoC level of other BES units as well as its own SoC level. To avoid this, in this paper, a new dynamic control strategy is proposed for the BES units which update the droop coefficients of the RES units according to the BES units SoC variations.

The proposed strategy in this paper consists of two control subsystems, one for charge and the other for discharge operation mode of the BES unit. During discharge operation, the proposed strategy utilizes a SoC-based droop control in order to avoid

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http://dx.doi.org/10.1016/j.ijepes.2016.12.003
0142-0615/

**Nomenclature**

| | |
|---|---|
| $P, Q$ | average active and reactive power |
| $V, \delta$ | magnitude and angle of the voltage across the filter capacitor |
| $V_{pcc}, \delta_{pcc}$ | magnitude and angle of the PCC voltage |
| $C_f, L_c, X_c$ | filter capacitor, coupling inductance and its impedance |
| $P_{max}, V_{max}$ | maximum active power capacity and maximum acceptable voltage of the MG |
| $P^l_{RES}, Q^l_{RES}$ | average active and reactive power of RES-$l$ |
| $m, n$ | angle and voltage droop coefficients |
| $E^k_{BES}(t), P^k_{BES}(t)$ | instantaneous stored energy and power of BES-$k$ |
| $m_0$ | global droop coefficient designated to $P_0$ and $SoC_0 = 1$ |
| $E^k_{BES,init}, E^k_{BES,max}$ | initial and maximum stored energy of BES-$k$ |
| $Q_{max}, S_{max}$ | maximum available reactive power and maximum capacity of each BES converter |
| $SoC^{k/l}_{BES}(t), SoC^{k/l}_{BES-d}(t)$ | instantaneous and discrete SoC level of BES-$k/l$ |
| $I, \theta$ | magnitude and angle of the phase-$a$ current of the coupling inductance |
| $X^k_{c-BES}, X^k_{AVI-BES}$ | coupling and virtual impedance of BES-$k$ |
| $V_{ref-\alpha}, V_{ref-\beta}$ | $\alpha\beta$ coordinates of the reference voltage |
| $X^l_{c-RES}, X^l_{AVI-RES}$ | coupling and virtual impedance of RES-$l$ |
| $V_{ref}, \delta_{ref}$ | magnitude and angle of the reference voltage |
| $Q^{k/l}_{actual}, Q^{k/l}_{desired}$ | actual and desired reactive power of DER-$k/l$ |
| $v_a, v_b, v_c$ | instantaneous reference voltage across the filter capacitor |
| $X^k_c, X^k_{AVI}$ | coupling and virtual impedance of DER-$k$ |
| $Q_{ratio-err}$ | reactive power ratio error between any two DERs |
| $v^k_{ref}, v^k_{droop}, v^k_{AVI}$ | reference voltage, original droop voltage and voltage drop across the AVI of VSCs |
| $V^k_{droop}, \delta^k_{droop}$ | magnitude and angle of the original droop voltage |

promptly depleting of the BES units, by dedicating the highest priority to their SoC level and respecting their power rating. Therefore, the output active power of each BES unit is modified dynamically according to its SoC level variations. In addition, in order to avoid power imbalance within the system during charge operation of the BES units, the proposed control method limits the BES absorbing power to the surplus power available from the renewable energy sources (RESs).

Active power sharing among the BES units within an MG has been thoroughly investigated in [14,15]. However, none of them considers reactive power sharing among the BES units. It is worth noting that reactive power exchange of the BES units does not relate on their SoC level and is available due to their converters extra/unused capacity. Here, along with the SoC-based droop control for active power sharing of the BES units, a reactive power sharing strategy is proposed, in order to utilize the extra capacity of the BES converters. The proposed reactive power sharing strategy uses the BES extra converter capacity and also avoids overloading the RES units. Based on the proposed reactive power sharing algorithm, the BES unit with lower SoC (i.e. lower output active power) which reflects its higher unused converter capacity supplies a greater amount of reactive power. To achieve this, a virtual impedance is imposed in series with coupling inductance of the BES units converters and as a result, the desired active and reactive power sharing ratios are achieved [16].

This paper is organized as follows. Section 2 describes the problem statement and objectives of the control strategy. MG structure and control is introduced in Section 3. Section 4 discusses the cooperative control of the BES units for both charge and discharge mode of operation. In Section 5, a new virtual impedance method is introduced to accomplish the reactive power sharing. Section 6 summarizes the BES control structure in charge and discharge mode. Performance evaluation is discussed in Section 7, considering different case studies simulated in PSCAD/EMTDC. At last, Section 8 concludes the research.

## 2. Problem statement

The paper contributions are highlighted as below, and are achieved by the proposed comprehensive control strategy of the BES units in charge and discharge modes.

- The BES units contribute in supplying the load as long as their SoC levels are within the nominal range of operation ($SoC_{min} < SoC < SoC_{max}$).

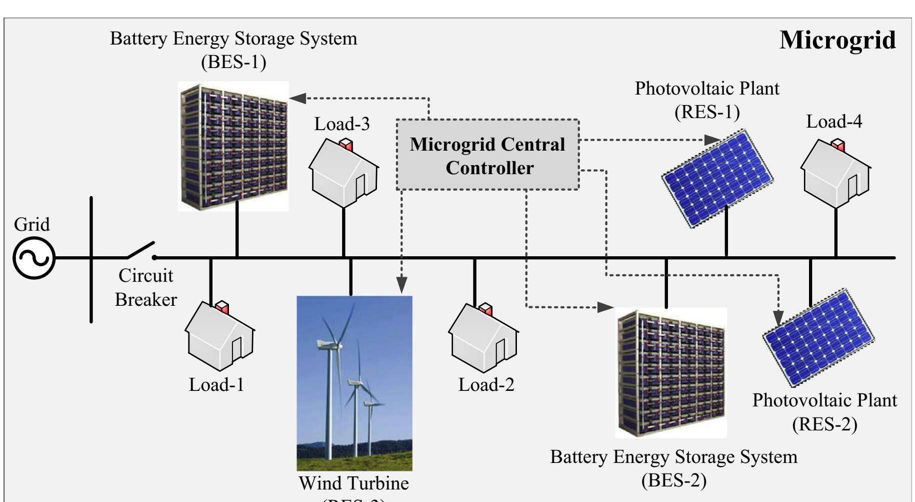


**Fig. 1.** A microgrid consisting of several distributed BESSs, DERs and loads.