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Multiobjective Distributed Secondary Control of Battery Energy Storage Systems in Islanded AC Microgrids

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Abstract: The control of storage devices plays an important role in stable operation of distributed AC microgrids. A multi-objective distributed secondary control scheme of storage devices is proposed. Firstly, to maintain the frequency and voltage regulation and ensure proportional reactive power sharing, a distributed consensus scheme is adopted for the operation of battery energy storage systems. Secondly, to prolong the cycle life of the battery, an improved droop control strategy combined with state of charge balancing is proposed, where each battery agent only requires and shares information with its networked neighbors in the communication topology. Finally, an islanded AC microgrid model with four battery energy storage systems is built and simulation results demonstrate the effectiveness of the proposed consensus strategy.

Key Words: Distributed control, Islanded microgrids, Battery energy storage systems, State of charge balancing

1 Introduction

With the rapid development of low-carbon electrical power systems[1], more and more microgrids are connected to the power grid [2],[3]. These microgrids are featured with distributed renewable energy [4] such as wind turbine (WT), photovoltaic (PV), and battery energy storage systems (BESSs) [5].

The control structure of microgrids is often complex [6], the output voltage and frequency regulation is a particular challenging issue [7]. Distributed consensus control of the voltage and frequency of microgrids based on the BESSs is studied [8],[9] and other researches consider the islanded microgrid mode [10]. To achieve more stable the output voltage and frequency regulation using BESSs, secondary control of voltage and frequency for distributed microgrid is proposed [11]. Meanwhile, considering the energy level of BESSs and enhancing battery cycle life [12], a secondary control strategy of frequency and voltage is analyzed on the IEEE14-node system [13].

Storage devices such as batteries plays an important role in the output voltage and frequency regulation of microgrids, and the state of charge (SoC) influences the cycle life of batteries [14]. To make the charged power control of distributed BESSs more stable and accurate, optimization control of battery in the charged state is achieved [15],[16] and adaptive droop control is proposed to ensure the SoC balancing of batteries [17]. To prolong the cycle life of battery and support stable operation of microgrids, a scheme combining the PI controller with SoC optimization of BESSs is analyzed and a frequency and voltage control of battery under different scenarios is presented [18]. However, most of the existing BESS operation and control schemes only consider the frequency and voltage regulation, whilst the SoC balancing is large ignored.

This paper proposes a novel distributed consensus control of battery energy storage systems in islanded AC microgrids. The main contributions of this paper include: (1) An improved droop control model by considering the SoC of BESSs is developed to prolong their cycling life. (2) A multi-objective distributed secondary control scheme is proposed to achieve the frequency restoration, voltage and reactive power regulation, and SoC balancing with different initial SoC values of BESSs.

The remainder of this paper is organized as follows: section II mainly establishes an improved droop control based on battery SoC. A distributed secondary controller is designed for stable regulation of the output voltage and frequency of BESSs in section III. Section IV details the experimental simulations and analysis of the designed control strategy, and conclusions and prospects are given in section V.

2 Battery Energy Storage System

To maintain the stable operation of battery, primary control and secondary control are used in the microgrid. The primary control can adjust the output voltage and frequency while the secondary control compensates the deviations of frequency and voltage using the BESS. The block diagram of a BESS unit consisting of voltage-source inverter, LC filter and output connector is shown in Fig.1. The primary control loops mainly includes power calculation, voltage and current controller. The power calculation provides the output active and reactive power to obtain the voltage reference v_{oref} for the voltage controller. After the adjustment using the PI, the output line current reference i_{ref} is generated and applied to the inner loop current controller. Finally, the duty cycle is formed to drive the inverter to work.

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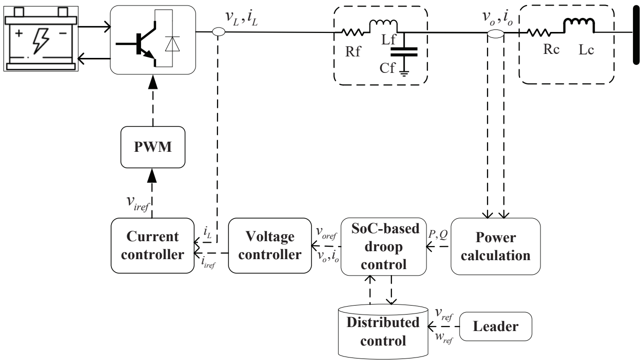

Fig. 1: Block diagram of an BESS unit

2.1 The Battery SoC Model

The ampere-hour integral method is most widely used for SoC estimation, and SoC model of the i-th battery is given as

$$SoC_i = SoC_{0i} - \frac{\int i_{Bi}dt}{Ce_i} = SoC_{0i} - \frac{\int P_{Bi}dt}{E_{Bi}} \qquad (1)$$

where E_{Bi}=$Ce_i V_{\mathrm{B}i}$, SoC_i and E_{Bi} are the current and initial value of the i-th SoC respectively, P_{Bi} is the output active power of inverter, Ce_i ,i_{Bi} and $V_{\mathrm{B}i}$ are the capacity, current and voltage of the corresponding battery i-th, respectively.

When the input voltage of all inverters are equal, the auxiliary model of the i-th battery SoC can be described as

$$\dot{SoC_i} = -P_{Bi}/E_{Bi} \qquad (2)$$

2.2 SoC-based Droop Control

To better reveal the relationship between the frequency and SoC of BESS unit, the primary control of BESSs is analyzed, and an droop control model combined with SoC is established.

The conventional $P - f$ droop method of i-th distributed BESS unit is given by

$$f_{ni} = f_i + m_i P_{Bi} \qquad (3)$$

where f_{ni} is the nominal frequency, f_i is the frequency of i-th battery, m_i is the corresponding droop coefficients. Then, taking the derivation of f_{ni}, and it follows that

$$\begin{aligned} \dot{f}_{ni} &= \dot{f}_i + m_i \dot{P}_{Bi} = \dot{f}_i + m_i \left(-E_{Bi} \ddot{SoC} \right) \\ U_{fi} &= U_{f1i} + U_{f2i} \end{aligned} \qquad (4)$$

where U_{fi} is an auxiliary control to be designed. To design distributed secondary controller of frequency and voltage, the following two definitions are given

$$\begin{aligned} U_{f1i} &= \dot{f}_{ni} \\ U_{f2i} &= -m_i \dot{P}_{Bi} \end{aligned} \qquad (5)$$

The $Q - V$ droop control can be obtained

$$v_{ni} = v_i + n_{qi} Q_{Bi} \qquad (6)$$

where v_{ni} is the nominal output voltage, v_i is the direct component of the output voltage magnitude while quadrature one is zero, Q_B is reactive power of battery, n_{qi} is the corresponding droop coefficient. Then

$$\begin{aligned} \dot{v}_{ni} &= \dot{v}_i + n_{qi} \dot{Q}_{Bi} \\ U_{vi} &= U_{v1i} + U_{v2i} \end{aligned} \qquad (7)$$

where U_{vi} is an auxiliary control to be designed as well.

$$\begin{aligned} U_{v1i} &= \dot{v}_i \\ U_{v2i} &= n_{qi} \dot{Q}_{Bi} \end{aligned} \qquad (8)$$

Now we integrate both sides with respect to the auxiliary control variable to obtain f_{ni} and v_{ni}

$$f_{ni} = \int (U_{f1i} + U_{f2i}) ds \qquad (9)$$

$$v_{ni} = \int (U_{v1i} + U_{v2i}) ds \qquad (10)$$

3 Distributed Secondary Controller Design

A multi-objective distributed secondary control scheme of BESSs is proposed for the frequency and voltage regulation, synchronizing the reactive power sharing, and achieving SoC balancing. The communication topology is firstly analyzed. Then, the convergence of the proposed control strategy is proved.

3.1 Graph Theory

To achieve the consensus control of microgrid, the BESS unit is regarded as a node in the communication topology [19]. The communication network can be described by a spare communication graph $\mathcal{G}\,(v, \varepsilon)$, v is the set of nodes, and ε refers to the set of edges formed by these nodes. The elements of ε can be described as (i, j), and the graph adjacency matrix is given by

$$\mathrm{A} = [a_{ij}] \in \Re^{N \times N}, a_{ij} = \begin{cases} 1 & (j,i) \in \varepsilon \\ 0 & otherwise \end{cases} \qquad (11)$$

The Laplacian matrix is $L = D - A$, and $D = diag\{d_i\}$. $d_i = \sum_{j=1}^{N} a_{ij}$ is the in-degree of the communication topology.

3.2 Distributed Frequency and SoC Balancing Controller of BESSs

To better describe the connection structure of communication network, the consistency control of output frequency and SoC balancing with auxiliary control of BESSs can be transformed into a synchronization problem of a multi-agent system.

Lemma 3.1 (cf. [4]) Zero is a simple eigenvalue of L if and only if the directed graph $\mathcal{G}$ have a spanning tree. Further, $L * 1_N = 0$, and 1_N is the vector of ones with the length of N.

Theorem 3.1 For a communication graph defined in (11), if there exists $c_f > 0, b_{ij} > 0, \forall i = 1, 2...N$, and the distributed secondary controller is designed as

$$\begin{aligned}&U_{fi}=-c_f\left[\sum_{j\in N_i}a_{ij}\left(f_i-f_j\right)+b_{ij}\left(f_i-f_{ref}\right)\right]\\&-c_f\sum_{j\in N_i}a_{ij}\left(m_{pi}P_{Bi}-m_{pj}P_{Bj}\right)\\&=-c_f\left[\sum_{j\in N_i}a_{ij}\left(f_i-f_j\right)+b_{ij}\left(f_i-f_{ref}\right)\right]\\&-c_f\sum_{j\in N_i}a_{ij}\left(m_{pi}\left(-E_{Bi}\,S\ddot{o}C_i\right)-m_{pj}\left(-E_{Bi}\,S\ddot{o}C_j\right)\right)\end{aligned}\tag{12}$$

where

$$U_{f1i}=-c_f\left[\sum_{j\in N_i}a_{ij}\left(f_i-f_j\right)+b_{ij}\left(f_i-f_{ref}\right)\right]\tag{13}$$

$$\begin{aligned}&U_{f2i}=-c_f\sum_{j\in N_i}a_{ij}\left(m_{pi}P_{Bi}-m_{pj}P_{Bj}\right)\\&=-c_f\sum_{j\in N_i}a_{ij}\left(m_{pi}\left(-E_{Bi}\,S\ddot{o}C_i\right)-m_{pj}\left(-E_{Bi}\,S\ddot{o}C_j\right)\right)\end{aligned}\tag{14}$$

then the operating frequency converges to f_{ref} and the SoC balancing of BESSs in a microgrid can be achieved.

Proof To conduct convergence analysis of the proposed controller, the leader following consensus can be designed as

$$\bar{f}_i=f_i-f_{ref}\tag{15}$$

Then, taking the derivation of $\bar{f}_i$

$$\begin{aligned}&\dot{\bar{f}}_i=\dot{f}_i\\&=\dot{f}_{ni}-m_{pi}\dot{P}_i\\&=-c_f\sum_{j\in N_i}a_{ij}\left(f_{ni}-f_{nj}\right)-c_f b_{ij}\left(f_i-f_{ref}\right)\\&-c_f\sum_{j\in N_i}a_{ij}\left(m_{pi}\left(-E_{Bi}\,S\ddot{o}C_i\right)-m_{pj}\left(-E_{Bi}\,S\ddot{o}C_i\right)\right)\\&=-c_f\sum_{j\in N_i}a_{ij}\left(f_i-f_j\right)-c_f b_{ij}\left(f_i-f_{ref}\right)\\&=-c_f\sum_{j\in N_i}a_{ij}\left(\bar{f}_i-\bar{f}_j\right)-c_f b_{ij}\bar{f}_i\\&=c_f\left[-\bar{f}_i\sum_{j\in N_i}a_{ij}+\sum_{j\in N_i}a_{ij}\bar{f}_j\right]-c_f b_{ij}\bar{f}_i\\&=c_f\left\{-d_i\bar{f}_i+\begin{bmatrix}a_{i1}&\dots&a_{iN}\end{bmatrix}\begin{bmatrix}\bar{f}_1\\\dots\\\bar{f}_N\end{bmatrix}\right\}-c_f b_{ij}\bar{f}_i\end{aligned}\tag{16}$$

Define the global vector $\bar{f}=\begin{bmatrix}\bar{f}_1&\dots&\bar{f}_N\end{bmatrix}^T$ and the pinning gain matrix $B=diag\left\{b_{ij}\right\}$. Then the global dynamics is given by

$$\begin{aligned}&\dot{\bar{f}}=c_f\left(-D\bar{f}+A\bar{f}\right)-c_f B\bar{f}\\&=-c_f L\bar{f}-c_f B\bar{f}\\&=-c_f\left(L+B\right)\bar{f}\end{aligned}\tag{17}$$

According to [20], there exist eigenvalues $\lambda\left(L+B\right)\geq 0$, which together with $c_f>0$ yields

$$\lim_{t\to\infty}\left|f\left(t\right)-f_{ref}\right|=0\tag{18}$$

3.3 Distributed Voltage and Reactive Power Sharing Controller of BESSs

With the similar design process of distributed secondary frequency and active power controller, a distributed secondary voltage and reactive power controller of BESSs is proposed.

Theorem 3.2 For a communication graph defined in (11), if there exists $c_v>0, g_{ij}>0, \forall i=1,2...N$, and the distributed secondary controller is designed as

$$\begin{aligned}&U_{vi}=-c_v\left[\sum_{j\in N_i}a_{ij}\left(v_i-v_j\right)+g_{ij}\left(v_i-v_{ref}\right)\right]\\&+\sum_{j\in N_i}a_{ij}\left(n_{qi}Q_i-n_{qj}Q_j\right)\end{aligned}\tag{19}$$

where

$$U_{v1i}=-C_v\left[\sum_{j\in N_i}a_{ij}\left(v_i-v_j\right)+g_{ij}\left(v_i-v_{ref}\right)\right]\tag{20}$$

$$U_{v2i}=-C_v\sum_{j\in N_i}a_{ij}\left(n_{qi}Q_i-n_{qj}Q_j\right)\tag{21}$$

then the voltage converges to v_{ref} and reactive power sharing of BESSs in a microgrid can be achieved.

Proof The leader following consensus can be designed as

$$\bar{v}_i=v_i-v_{ref}\tag{22}$$

Then, taking the derivation of $\bar{v}_i$

$$\begin{aligned}&\dot{\bar{v}}_i=\dot{v}_i\\&=\dot{v}_{ni}-n_{qi}\dot{Q}_i\\&=-c_v\sum_{j\in N_i}a_{ij}\left(v_{ni}-v_{nj}\right)-c_v g_{ij}\left(v_i-v_{ref}\right)\\&-c_v\sum_{j\in N_i}a_{ij}\left(n_{qi}Q_i-n_{qj}Q_j\right)\\&=-c_v\sum_{j\in N_i}a_{ij}\left(v_i-v_j\right)-c_v g_{ij}\left(v_i-v_{ref}\right)\\&=-c_v\sum_{j\in N_i}a_{ij}\left(\bar{v}_i-\bar{v}_j\right)-c_v g_{ij}\bar{v}_i\\&=c_v\left[-\bar{v}_i\sum_{j\in N_i}a_{ij}+\sum_{j\in N_i}a_{ij}\bar{v}_j\right]-c_v g_{ij}\bar{v}_i\\&=c_v\left\{-d_i\bar{v}_i+\begin{bmatrix}a_{i1}&\dots&a_{iN}\end{bmatrix}\begin{bmatrix}\bar{v}_1\\\dots\\\bar{v}_N\end{bmatrix}\right\}\\&-c_v g_{ij}\bar{v}_i\end{aligned}\tag{23}$$

Define the global vector $\bar{v}=\begin{bmatrix}\bar{v}_1&\dots&\bar{v}_N\end{bmatrix}^T$ and the pinning gain matrix $G=diag\left\{g_{ij}\right\}$. Then the global dynamics is given by

$$\begin{aligned}&\dot{\bar{v}}=c_v\left(-D\bar{v}+A\bar{v}\right)-c_v G\bar{v}\\&=-c_v L\bar{v}-c_v G\bar{v}\\&=-c_v\left(L+G\right)\bar{v}\end{aligned}\tag{24}$$

According to [20], there exist eigenvalues $\lambda\left(L+G\right)\geq 0$, which together with $c_v>0$ yields

$$\lim_{t\to\infty}\left|v\left(t\right)-v_{ref}\right|=0\tag{25}$$

4 Simulation Verification Studies

The effectiveness of the proposed multi-objective distributed secondary control strategy is verified in an island microgrid by MATLAB/simulink. The control parameters and load specifications are provided in Table 1. The microgrid consists of four BESSs and two loads. The $load_1$ is connected to BESS unit 1 and $load_2$ is connected to BESS unit 3. The rated capacity of BESS unit 1 is equal to BESS unit 2 while BESS unit 3 is equal to BESS unit 4, which is used to verify that the proposed control scheme can balance SoC with heterogeneous batteries. The communication topology of the four BESSs is shown in Fig.2.

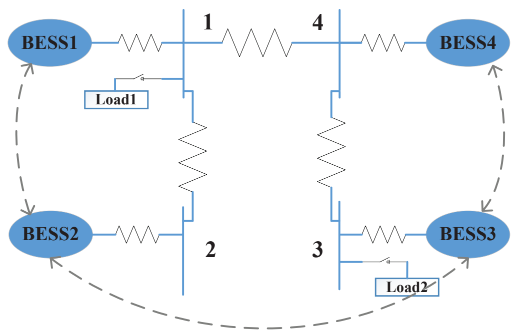

Fig. 2: An AC microgrid structure with four BESSs

The robustness of the proposed control strategy under loads changes is further analysed. The microgrid is running from 0s to 10s in island mode. After loads are connected to the system at t=3s, the frequency has small fluctuations in Fig.3, and the output voltage also oscillates as shown in Fig.4. After a period of adjustment, the frequency and voltage maintain stable. To highlight the proposed control strategy performance, loads are removed from the system after t=6s. The frequency and output voltage of BESSs can change accordingly, which demonstrates the remarkable handling ability of the proposed control scheme.

Further, SoC balancing of all BESSs is quickly achieved to 75% at about t=1s as shown in Fig.5. Approximately at t=3s and t=6s, there exists fluctuations due to the connection and removal of loads. Especially at t=3s, results can be obtained at t=6s. When loads are cut off from BESSs, the SoC amplitude also has small fluctuations, which illustrates that the proposed strategy can make all batteries vary at the same rate.

The reactive power ratio of BESSs can be observed in Fig.6. At t=3s, the output power distribution of the system changes due to loads changes. The power flow begins to redistribute, and the fluctuation of reactive power ratio is significantly reduced. At t=6s, the sudden removal of the loads causes changes of the reactive power ration, and BESSs keeps stable after rapid adjustment. Simulation results demonstrate that the proposed control strategy is effective to adopt to the loads change of the microgrid system.

5 Conclusion

This paper addresses the problem of consensus control of the frequency and voltage, and reactive power sharing of BESSs in islanded microgrids. A multi-objective distributed secondary control strategy combined with SoC balancing is proposed. Theoretical analysis is conducted to prove illustrate the convergence of the consensus control method and simulation experiments conducted to verify its effectiveness. The consensus control with heterogeneous BESSs under attacks does not take in consideration, which will be the future work.

Table 1: Control parameters of the microgrid system

Item	Symbol	Value
LC Filter	Lf Rf Cf	1.35mH 0.1Ω 50μF
Coupling	Lc Rc	0.35mH 0.03Ω
Droop coefficients of BESS 1 and 2	mP nQ	9.4×10^{-5} 1.3×10^{-3}
Droop coefficients of BESS 3 and 4	mP nQ	12.5×10^{-5} 1.5×10^{-3}
Voltage loop	K_{PV} K_{IV}	0.15 300
Current loop	K_{PC} K_{IC}	10 10000
Line1, Line3	Ll1,Ll3 Rl1,Rl3	318μH 0.23Ω
Line2	Ll2 Rl2	1847μH 0.35Ω
Load1	PL1 QL1	12kW 12kvar
Load2	PL2 QL2	15.3kW 7.6kvar
SoC (%)	BESS 1,2 BESS 3,4	70,60 80,90

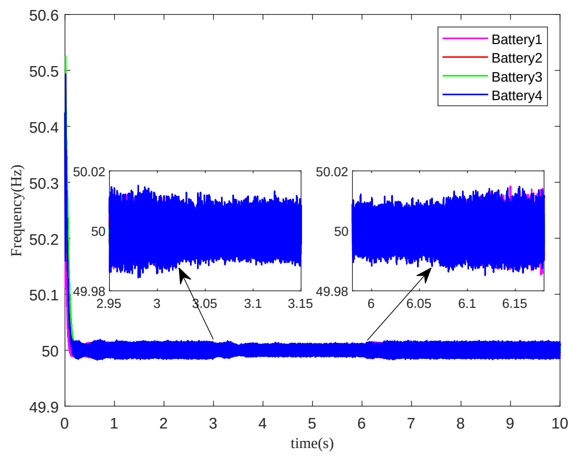

Fig. 3: Operating frequency of four BESSs

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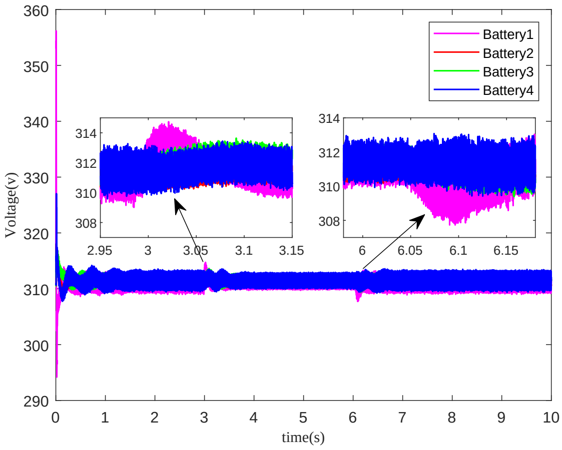

Fig. 4: Output voltage of four BESSs

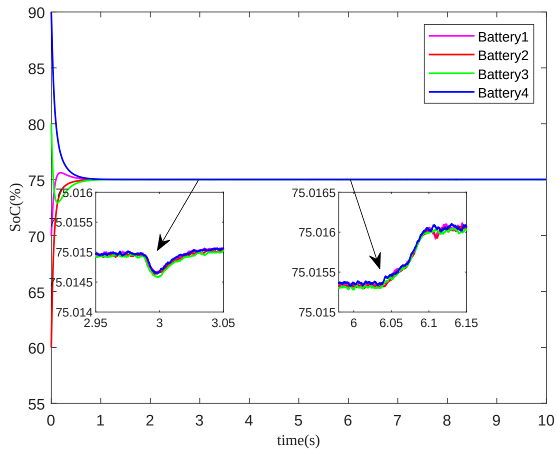

Fig. 5: The SoC balancing of four BESSs

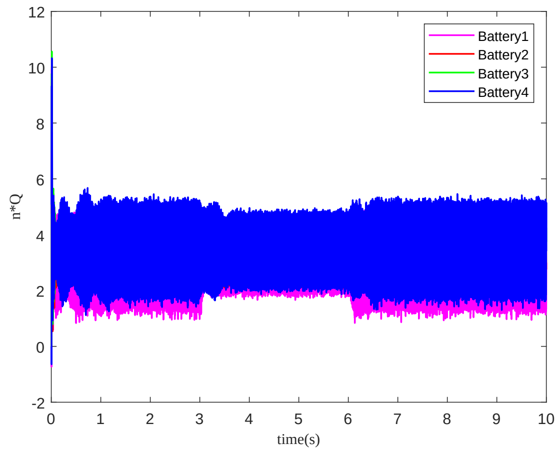

Fig. 6: Reactive power ratios of four BESSs

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