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Published in:
Proceedings of the 40th Annual Conference of IEEE Industrial Electronics Society, IECON 2014

DOI (link to publication from Publisher):
10.1109/IECON.2014.7048804

Publication date:
2014

Document Version
Early version, also known as pre-print

Multiagent Based Distributed Control for State-of-Charge Balance of Distributed Energy Storage in DC microgrids

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***Abstract*—In this paper, a distributed multiagent based algorithm is proposed to achieve SoC balance for DES in the DC microgrid by means of voltage scheduling. Reference voltage given is adjusted instead of droop gain. Dynamic average consensus algorithm is explored in each agent to get the required information for scheduling voltage autonomously. State-space analysis on a single energy storage unit and simulation verification shows that the proposed method has two advantages. Firstly, modifying the reference voltage given has less impact on system stability compared to gain scheduling. Secondly, by adopting multiagent methodology, the proposed distributed control has less communication dependence and more reliable during communication topology changes.**

Keywords— Multiagent; Distributed Control; State-of-Charge Balance; Distributed Energy Storage; DC microgrids; Dynamic Average Consensus

I. INTRODUCTION

Microgrid, is basically a small grid which gathers local loads and distributed generations, energy storage systems and may operate in both grid-connected and islanded modes [1]. MG concept emerged as one of possible resolutions for efficient integration of a growing number of DGs scattered throughout the network. With the trend that increasing adoption of direct-current (DC) systems at generation and consumption level, DC microgrid is gaining more and more attention in both academia and industry [2]. This trend is powered, for the first, by the outburst of various DC loads and generations (such as photovoltaic panels, batteries, fuel cells, LEDs, etc.); for the second, by the facts that DC microgrid has relatively higher efficiency, easier connection to the DC bus, higher power quality (i.e. no reactive power, no harmonics, no unbalance current, no inrush current to transformers, etc.); for the third, by the struggle to meet the high set goals of utilizing more renewable energy resources (RESs), which operate either inherently at DC or have a DC bus within the system.

To maintain the power quality in both grid-connected mode and islanded mode, distributed energy storage (DES), consisted of distributed energy storage units and relative controllers, is an indispensable part for DC microgrid. For one thing, the availability of the renewable energy source is intermittent in nature, without precise prediction and enough inertia of the system, the balance of power and demand cannot be achieved without DES buffering either the power surplus or shortage. For another, to make the system more reliable through DES redundancy, more than one set of energy storage unit might be needed, and thus the coordination of DES becomes a need for the DC microgrid.

Assuming all the energy storage units in the DES of the DC microgrid are the batteries of the same type, and overlooking the efficiency difference and network topology (usually, the line impedance is very small), it has many benefits to make stage-of-charge (SoC) of DES balanced. As it is well known, it is desirable to maintain the SoC of the battery at a certain range (e.g. between 20% and 80%). Since in this case, the battery has higher efficiency and State-of-Health (SoH) [3]. If the SoC of all the energy storage units is kept the same all the time, no single units tend to go outside of this range compared with the case which doesn't use SoC balancing. Thus, the power capacity of the whole DES can be guaranteed, i.e., there is lower possibility that one of the units is forced offline due to very high or very low SoC. Several previous works have been done to achieve SoC balance [1], [4]]–[[7]. In [4], the authors propose a screening process for the battery management system (BMS) to improve the performance of output voltage and SoC balancing. However, it is only for balancing the SoC of each cell in a battery string, it is not eligible for the balancing the SoC of energy storage units in the DES. In [5], a SoC-based droop control is proposed to achieve SoC balance for DES through making the droop gain inversely proportional to the *n*th order of SoC. In [6], fuzzy control is used to modify the droop gain to balance the SoC. However, they have larger influence on the system in terms of stability. In [7], a fuzzy method is proposed to balance stored energy, but this needs the information from other energy storage units, which will cause intensive communication workload if centralized control is used. Recently, multiagent system becomes one of the most popular distributed control solutions, and it has been applied widely to the grid energy management [8]. Multiagent based average-consensus is just one of the effective ways to overcome the drawbacks of some control algorithms which need control parameters from other local controllers in the system.

In this paper, a distributed multiagent based algorithm is proposed to achieve SoC balance of DES by means of voltage scheduling. Every energy storage unit is taken as an agent and

they schedule their own reference voltage given to keep SoC balance of the whole DES, using the parameter information obtained through average consensus algorithm. During the information discovery process, only communication between direct neighboring agents is needed. The proposed method has two advantages. Firstly, modifying the reference voltage given has less impact on system stability compared to gain scheduling. Secondly, by adopting multiagent methodology, the system becomes a distributed control and thus need less communications and more reliable.

The rest of the paper is organized as follows. Section II elaborates the proposed multiagent based distributed control for SoC balance of DES, and at the end of this section the advantages of voltage scheduling compared to gain scheduling in terms of stability is shown using state-space analysis. In Section III, the proposed control strategy is verified in a DC microgrid with 4 energy storage units in DES through simulation. The simulation results show that, agents can not only achieve SoC balance, but also have a certain immune to the communication topology changes. Finally, Section IV concludes the paper.

II. Proposed Distributed Control for SoC Balance of DES Based on Multiagent

In this work, we take a DC microgrid with a DES having 4 energy storage units as an example. The configuration of the test DC microgrid is shown in Fig.1. Normally, the load is fed by RES when there is sufficient amount of power from RES, and DES is working on the charging mode. When the output power from the RES is not enough, the DES turns to discharging mode if none or only part of the power comes from the grid. It is desirable, that during discharging, the storage unit with higher SoC will provide more power than the others, and accordingly, during charging, ones with lower SoC will absorb more power. With the proposed multiagent based method, the SoC balance of each unit can be achieved.

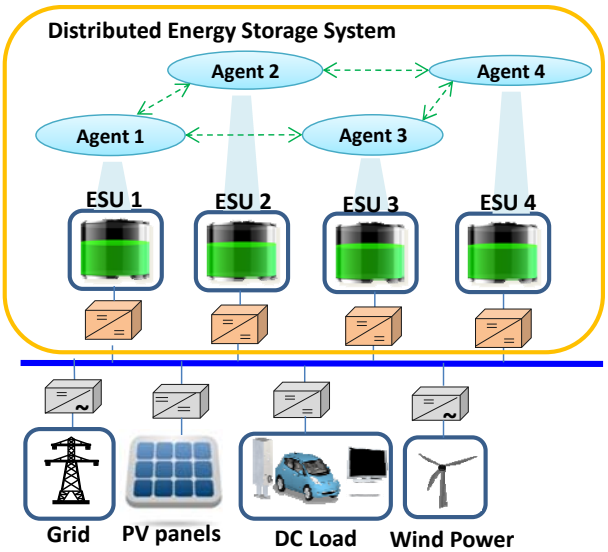


Fig. 1. DC microgrid with DES controlled by multiagent system

A. Estimation of the SoC

Before describing the proposed control method to achieve SoC balance, the SoC estimation method adopted here is introduced firstly. Although many techniques have been proposed to measure or monitor the SoC of a cell or the battery, charge counting or current integration is the most commonly used technique [3]. Here we use this method to estimation SoC of each energy storage unit for the sake of simplicity, since this is not the emphasis of this paper. The arithmetic of this method is showed as below.

$$SoC_i = SoC_i^* - \frac{1}{C_{e\_i}} \int i_{b\_i} dt \tag{1}$$

where i_{b_i}, SoC_i^*, and C_{e_i} are the output current, initial value of SoC, and battery capacity for unit i respectively.

If the power loss in the converter can be omitted and assume the output voltages of the batteries are the same, there are following equations for each battery.

$$P_i = P_{in\_i} = V_{in} i_{b\_i} \tag{2}$$

Where V_{in}, P_i and P_{in_i} are the input voltage of the converter, output power of the converter, and input power of the converter, for unit i, respectively. Here we assume that values of the input voltage of all the converters are the same, i.e., the DC bus voltage.

So combining the (1) and (2), the SoC calculation can be written as

$$SoC_i = SoC_i^* - \frac{1}{C_{e\_i} V_{in}} \int P_i dt \tag{3}$$

B. Voltage Scheduling for SoC Balance

One of the novelties of this paper is that, instead of adjusting the droop gain in the control of energy storage units, we try to control the power sharing to achieve SoC balance by modifying the reference voltage given in the droop control. This goal is achieve by a simply equation added to the traditional droop control method. The traditional droop control for the converter in the DC microgrid is introduced as

$$V_o = V_{ref,MG} - R_d i_o \tag{4}$$

Where V_o is the voltage command to the converter, $V_{ref,MG}$ is the reference voltage in the droop control, i_o is output current to the grid from the converter. R_d is the virtual impedance in the droop control.

Previous work has make R_d reversely proportional to the order of SoC [1][5], here the control method is by modifying

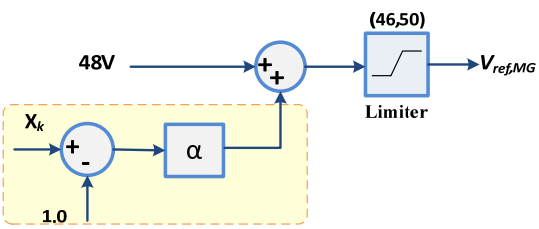


Fig. 2. Voltage scheduling for SoC of DES

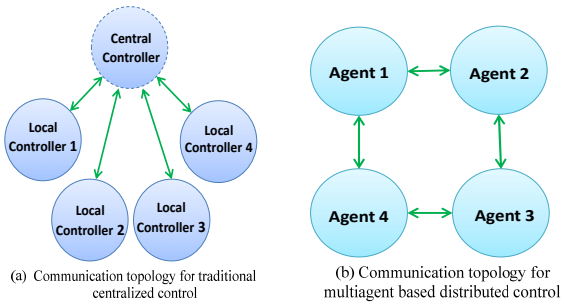
the reference voltage given, and the control diagram is shown in Fig.2.

where α is a proportional coefficient and X_k is the radio of the SoC of unit k to the average SoC of all the other uints. α is chosen as 2 in this work and the X_k is defined as below.

$$X_k = \frac{SoC_k}{\frac{1}{n-1}\cdot(\sum_{i=1}^{n} SoC_i - SoC_k)} \tag{5}$$

C. *SoC Information Discovery Based on Dynamic Average Consensus Algorithm*

As it is can be seen in (5), the proposed voltage scheduling droop control need the information of SoC from other energy storage units, and thus it will heavily rely on the communication if centralized communication is adopted which is shown in Fig.3. (a). Here, by using multiagent based dynamic average consensus method to obtain the information from other units, only communications between immediate neighboring agents are used, and there is no strict reliance on any of a single local controller. The structure of the system is show in Fig.3. (b).



(a) Communication topology for traditional centralized control

(b) Communication topology for multiagent based distributed control

Fig. 3 Communication topology for two different control methodologies

The consensus used here is based on [9], which is the discrete time algorithm of [10].The information discovery process for agent i is represented as follows.

$$SoC_i(\mathrm{k}+1) = SoC_{\mathrm{ini}\_i} + \lambda \sum_{j \ni N_i} \delta_{ij}(\mathrm{k}+1) \tag{6}$$

$$\delta_{ij}(\mathrm{k}+1) = \delta_{ij}(\mathrm{k}) + SoC_j(\mathrm{k}) - SoC_i(\mathrm{k}) \tag{7}$$

Where SoC_{int_i} is the initial SoC of energy storage unit i, λ is a scaling factor, which is designed according to the stability. In this work λ is choose as *1/3*.

Through this dynamic average consensus algorithm, each agent can get the average SoC of the DES SoC_{AVG} at the end of information discover stage, and only the communication between direct neighboring agents is need in the process. Then (5) can be rewritten as

$$X_k = \frac{SoC_k}{\frac{1}{n-1}\cdot(\mathrm{n}\, SoC_{\mathrm{AVG}} - SoC_k)} \tag{8}$$

By now, the necessary information to implement voltage scheduling droop control is ready, each agent can now make their own decision in the same way simultaneously, and the

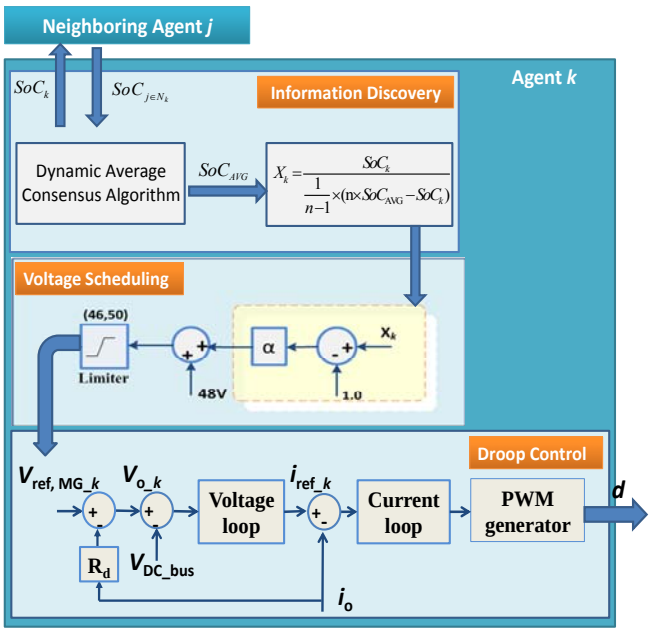


Fig. 4 Control diagram of proposed multiagent based method

overall control diagram of the proposed method for DES is shown in Fig. 4.

D. *Stability Improvement Using Voltage Scheduling*

In this section, the comparison of the impact of R_d and $V_{ref,MG}$ on system stability has been done using state-space analysis for one energy storage unit, to show the advantages of scheduling voltage instead of modifying droop gain.

If a lossless and non-isolated BUCK DC/DC converter is considered, droop control system in Fig. 4. can be modeled with coupled differential equations:

$$\dot{x}_1 = -I_v R_d x_3 - I_v V_c + I_v V_{\mathrm{ref,MG}} \tag{9}$$

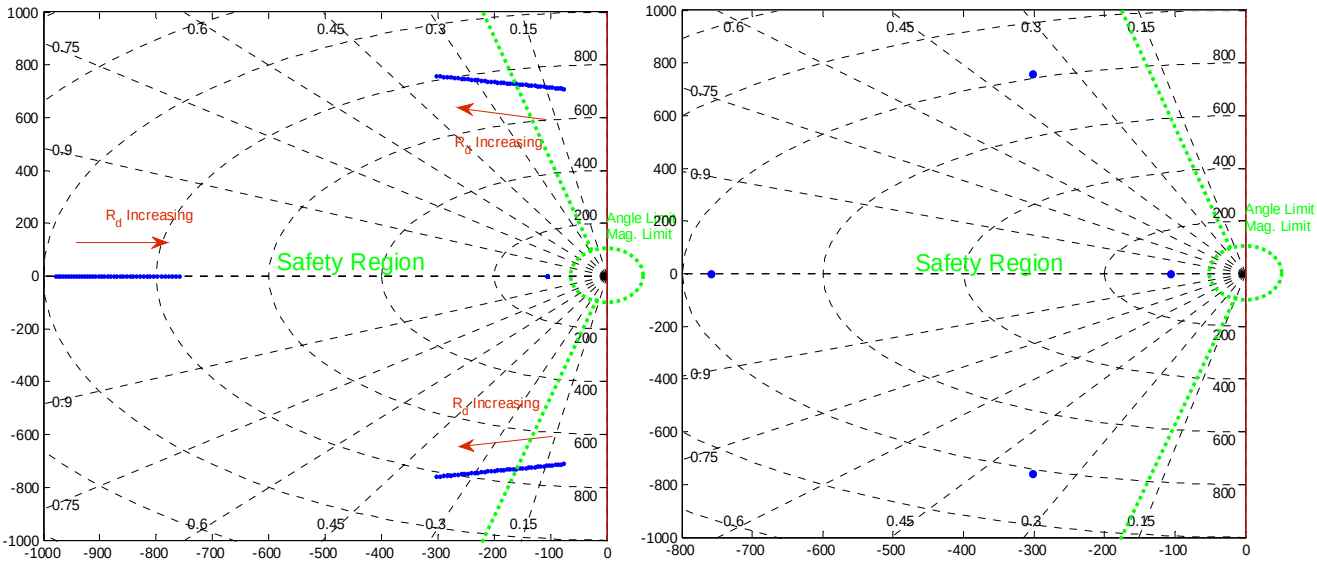
$$\dot{x}_2 = I_c x_1 - I_c(R_d P_v + 1)x_3 - I_c P_v V_c + I_c P_v V_{\mathrm{ref,MG}} \tag{10}$$

$$\dot{x}_3 = \frac{P_c V_{in}}{L} x_1 + \frac{V_{in}}{L} x_2 - \frac{P_c V_{in}(\mathrm{R}_d \mathrm{P}_v + 1)}{L} x_3 - \frac{V_{in} P_v P_c + 1}{L} V_c + \frac{V_{in} P_v P_c + 1}{L} V_{\mathrm{ref,MG}} \tag{11}$$

$$\dot{v}_c = \frac{1}{C} x_3 - \frac{1}{R_L C} V_c \tag{12}$$

x_1 denotes the output of the integrator of the voltage loop, x_2 denotes the output of the integrator of the current loop, x_3 denotes the filter inductor current, v_c denotes the filter capacitor voltage (equal to the common bus voltage if unit is directly connected). P_v, P_c, P_{sc}, I_v, I_c and I_{sc} are the control parameters of voltage and current loop and voltage secondary control PI controllers, L and C are inductance and capacitance of the converter output filter, R_L is the equivalent resistance of the connected load, V_{in} is the source voltage and $V_{ref,MG}$ is the reference voltage given.

The routes of eigenvalues of the system at the R_L as 3 Ω, under the case of changing R_d from 0.1 Ω to 0.5Ω and the case of changing $V_{ref,MG}$ from 46V to 50V is shown in Fig. 5, where the initial value of the system is as listed in TABLE I.



(a)Impact of R_d on system stability (b) Impact of V_{ref} on system stability

Fig.5 Comparison of impact of Rd and Vref on system stability

It can be seen that when changing $V_{ref,MG}$, all the eigenvalues of the system are within the safety region, while changing Rd, the eigenvalues of the system will lie out of the safety region when the R_d is too small. We can say from this analysis results that modifying $V_{ref,MG}$ is preferable than R_d in term of the stability.

TABLE II

PARAMETERS OF A VOLTAGE-DROOP CONTROLLED ENERGY STORAGE

Fixed parameters	
L	1.8e-3 H
C	2.2e-3 F
R_d	0.2Ω
$V_{ref,MG}$	48V
P_c	1
Ic	97
P_v	0.5
I_v	993
P_{sc}	0.02
I_{sc}	70

III. SIMULATION VALIDATION

Simulation based on Matlab/Simulink is accomplished to evaluate the performance of proposed control method based on a DC microgrid with a DES having 4 energy storage units, which is the same as Fig. 1. The parameters of each energy storage unit are the same as is shown in TABLE III. Both the effectiveness of balancing SoC of DES and the immunization of a certain communication fail.

Initially, the four energy storage units have the initial SoC as 90%, 80%, 70% and 60% respectively. At the beginning, the DES is discharging at the rate of 480W to fill the generation shortage. At the time of 12s, the DES is charging at the rate of 50W to absorb the generation surplus. During this process, the communication topology of the multiagent system also changes during this process. Initially, the topology of the communication is the same as Fig.1, i.e., 4 agents communicate with their two neighbors in a ring; at the time of 2.5s and 15s, the communication connection between agent 1 and agent 4 is disconnected and connected respectively.

Fig.6 shows the results of information discovery stage. It can been seen that using dynamic average consensus algorithm, the discovered SoC_{AVG} remains very closed to the real value, even during the transients of communication topology changes. Fig. 7 shows the $V_{ref,MG}$ for each energy storage unit, which indicates that it is variant alongside the simulation period. The curve of SoC, output current of each unit and the common DC bus voltage at the load side is shown in Fig. 8. It shows the proposed method is effective to balance SoC of the DES, and at the same time, maintain the bus voltage within the permitted range.

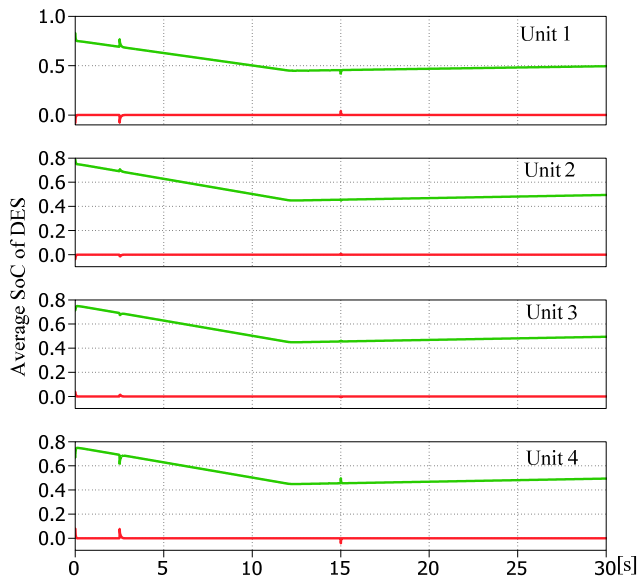


Fig. 6. SoCAVG from consensus algorithm and its difference with real value

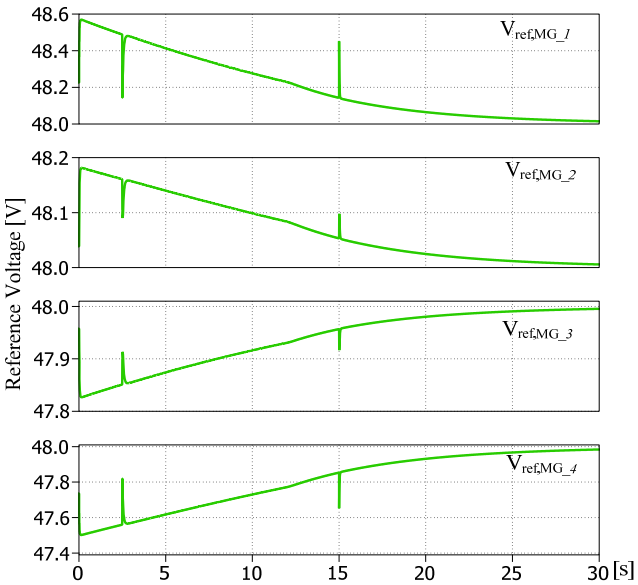


Fig. 7. Vref,MG for each energy storage unit

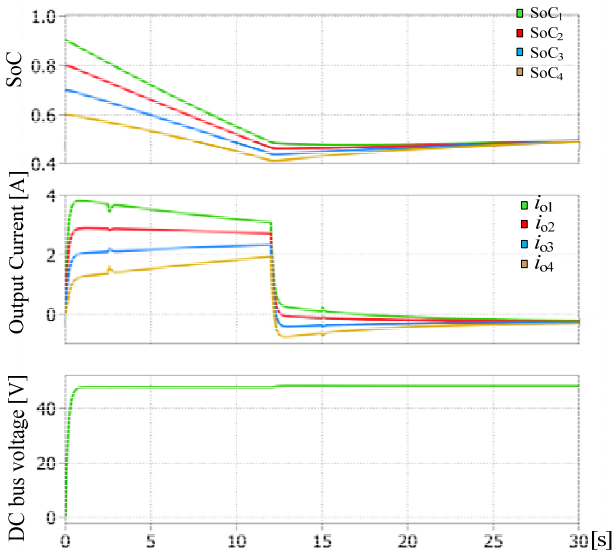


Fig. 8 SoC, output current of each unit and the common DC bus

IV. Conclusion

This work proposed a distributed control method to achieve SoC balance for DES using voltage scheduling based on multiagent system. Dynamic average consensus algorithm is explored in each agent to get the necessary information for scheduling voltage autonomously. By using this method, SoC of the DES can be balanced without jeopardizing the quality of the DC bus voltage. The advantage of this method in terms of stability is demonstrated through state-space analysis, and the advantage of less communication dependence is shown through its immunization to a certain communication topology changes.

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