Fuzzy-Logic-Based Gain-Scheduling Control for State-of-Charge Balance of Distributed Energy Storage Systems for DC Microgrids

Aldana, Nelson Leonardo Diaz; Dragicevic, Tomislav; Quintero, Juan Carlos Vasquez; Guerrero, Josep M.

Published in:
2014 IEEE Applied Power Electronics Conference and Exposition (APEC 2014) . Proceedings of a meeting held 16-20 March 2014, Fort Worth, Texas, USA.

DOI (link to publication from Publisher):
10.1109/APEC.2014.6803606

Publication date:
2014

Document Version
Early version, also known as pre-print

Citation for published version (APA):
Aldana, N. L. D., Dragicevic, T., Vasquez, J. C., & Guerrero, J. M. (2014). Fuzzy-Logic-Based Gain-Scheduling Control for State-of-Charge Balance of Distributed Energy Storage Systems for DC Microgrids. In 2014 IEEE Applied Power Electronics Conference and Exposition (APEC 2014) . Proceedings of a meeting held 16-20 March 2014, Fort Worth, Texas, USA. (pp. 2171-2176). IEEE Press. (I E E E Applied Power Electronics Conference and Exposition. Conference Proceedings). DOI: 10.1109/APEC.2014.6803606

Diaz, N.L.; Dragicevic, T.; Vasquez, J.C.; Guerrero, J.M., "Fuzzy-logic-based gain-scheduling control for state-of-charge balance of distributed energy storage systems for DC microgrids," Applied Power Electronics Conference and Exposition (APEC), 2014 Twenty-Ninth Annual IEEE , vol., no., pp.2171,2176, 16-20 March 2014

Fuzzy-Logic-Based Gain-Scheduling Control for State-of-Charge Balance of Distributed Energy Storage Systems for DC Microgrids

Nelson L. Diaz[1,2], Tomislav Dragičević[1], Juan C. Vasquez[1], Josep M. Guerrero[1]
[1]Department of Energy Technology, Aalborg University, Denmark
[2]Universidad Distrital Francisco José de Caldas, Bogotá, Colombia
Email: {nda, tdr , juq, joz}@et.aau.dk

***Abstract*— A microgrid is an integration of distributed energy sources, loads and energy storage systems. Indeed, energy storage systems are required in order to ensure reliability and power quality because of the intermittent nature of renewable energy sources and changes of load demand. Apart from that, the use of distributed energy storage units provides redundancy to the system and support possible increments in load consumption. In consequence, the control strategy used in the microgrid must take into account the stored energy balance between distributed energy storage units in order to avoid over-charge or deep-discharge in one of the energy storage units. Primary control in a microgrid is responsible for power sharing among units; and droop control is typically used in this stage. This paper proposes a modular and decentralized gain-scheduling control strategy based on fuzzy logic that ensures balanced stored energy among distributed energy storage units, as well as low voltage deviation in a DC microgrid. Hardware in the loop simulations show the performance of the proposed control strategy.**

Keywords*— *Fuzzy logic control, gain-scheduling, energy storage system (ESS), DC microgrids

I. INTRODUCTION

A microgrid is an aggregation of renewable energy sources (RES), loads and energy storage systems (ESS), which may operate both in grid-connected or islanded mode, and in AC and/or DC configuration [1].

Hierarchical operation has been defined in order to standardize the control of microgrids [2]. The first layer, termed primary control, is basically a local control that allows power electronics converters to operate independently, and at the same time enabling cooperation among them. This stage includes inner current control loops and voltage droop controllers in order to ensure power balance between units [3]. Secondary control is in charge of removing any steady-state error introduced by the droop control [1], [2]. And, tertiary control takes care of global decisions related to energy generation, demand, storage, and power flow between the microgrid and the main grid [1]. Commonly, primary control uses distributed control strategies meanwhile, centralized control strategies are more commonly applied in secondary and tertiary stages in order to coordinate, supervise and modify the different variables of primary controllers [1], [3].

Another important fact is the use of ESS into a microgrid. An ESS is required in order to overcome the power quality problems associated to the intermittent nature of the energy generated from RES and common changes in the load [4]. Indeed, decentralization of energy storage systems has emerged as a promising strategy for overcoming the problems related to renewable energy generation and additionally add redundancy to the energy storage system [5], [6].

In a microgrid, like in an ecosystem, ESS and RES units have to coexist. Traditionally, and according to [1], RES (e.g. photovoltaic or wind turbines) normally will use algorithms to inject the maximum power, behaving like current/power sources, while ESS (e.g. battery sets) will be responsible to keep the voltage level of the microgrid. This structure is possible in a grid connected microgrid since the energy can be balanced thanks to the injection/absorption of power to/from the main grid. However, in an islanded system, real-time internal power balancing is mandatory, which point out that RES/ESS may work as voltage or power sources depending on different conditions. In this sense, voltage signaling principle has been previously used to coordinate the operation between RES and ESS in DC microgrids [18]. However in this approach only one ESS unit takes the role to control the voltage bus level.

When more than one ESS takes part into a microgrid, coordination is required to ensure stored energy balance among the units in order to avoid deep-discharge or overcharge in one of the ESS. Therefore, during the process of charging, it is desirable to prioritize the charge of the storage unit with the smallest state of charge (SoC), and similarly, during the process of discharge, the storage unit with the highest SoC should provide more power to the microgrid than the others. However, a centralized coordination may cause limitation if more ESS or RES have to be integrated to the microgrid. Precedent approaches have proposed several strategies for energy storage balance based on centralized strategies in secondary controllers [3], [6]-[7]. Additionally, the aforementioned proposals rely on centralized supervisory control which may include secondary controllers to restore voltage levels [11], [12] or tertiary control levels that takes care on the energy management and efficiency optimization [13], [14]. Therefore, there is a single point of failure in the system and the addition of new ESS units may be complicated.

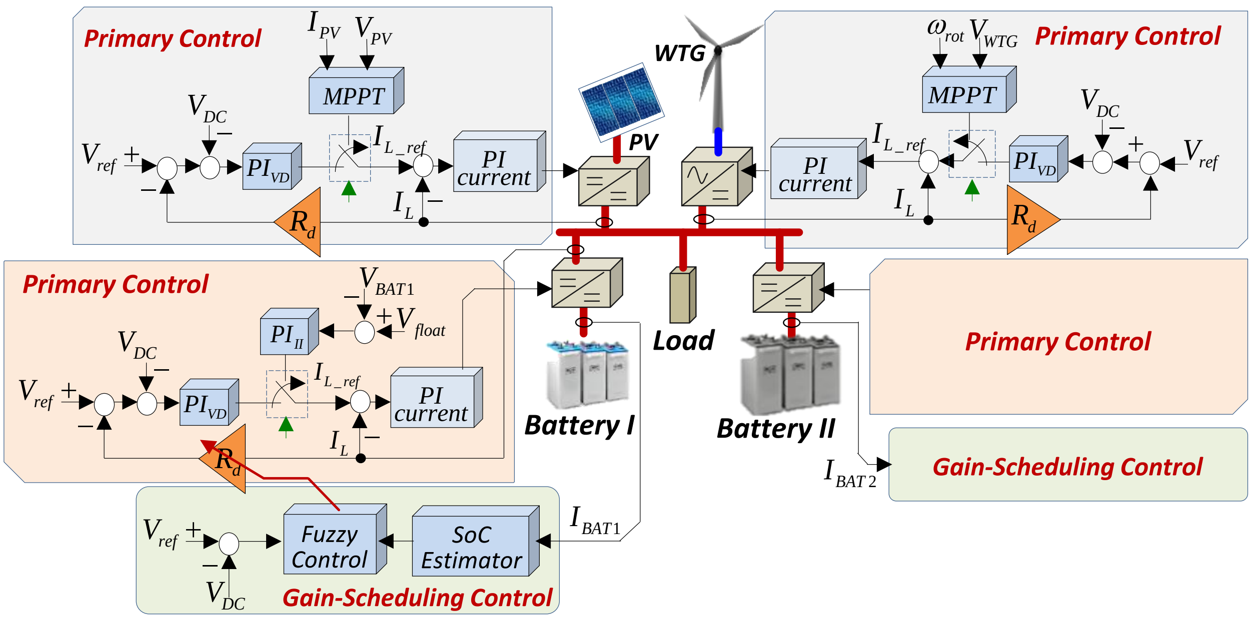

Fig. 1. Scheme of the DC microgrid with gain-scheduling control.

In [15] a decentralized controller to balance SoC's among ESS units in a DC microgrid was proposed by using adaptive voltage droop controllers. In this approach the virtual impedance value depend on the SoC value raised by an exponent. However this exponent is hard to adjust, due to trade-off SoC between balance accuracy and voltage deviation. In this paper we propose a control method that deals with this trade-off by using fuzzy logic. Fuzzy logic has already been proposed for control of inner control loops in power electronics converters [19]. However, the slightly improved performances do not justify the use in such a situations in which the control designer knows perfectly the plant model. Nevertheless, when the system is complex and with many uncertainties, such as a microgrid, fuzzy logic can be well justified to adjust external control loops. In our case, each unit does not know about the characteristics or operation of the rest of the system [6], so they have to solve the control problem by using only local information [8].

This paper proposes a decentralized gain-scheduling controller based on fuzzy logic that adjusts the droop coefficient of the primary controller in order to ensure stored energy balance between distributed ESS [8]. In particular, this proposal is focused on a DC microgrid under islanded operation, so the gain-scheduling control also reduces the voltage deviation in the DC common bus, thus behaving as an alternative to secondary controller. However, it should be noted that, unlike the case with conventional secondary control, the steady-state error cannot be completely cancelled by this method.

The paper is organized as follows. Section II presents the configuration of a DC microgrid including the different elements and controllers. Section III proposes two operation modes for each ESS and RES units, which are selected according to local measurements. Section IV presents the fuzzy-logic-based gain-scheduling controller that adapts the virtual resistance value included in each ESS unit controller. Hardware in the loop results are presented in Section V in order to show the good performance of the control architecture proposed. Section VI gives the conclusions.

II. CONFIGURATION AND CONTROL OF THE DC MICROGRID

The diagram of a DC microgrid composed by several RES, DC loads, and two batteries, is shown in Fig. 1. The presented DC microgrid is always operated in islanded mode, and two operational sub-modes have been identified based on the SoC of batteries and the amount of power generated by the RES. Only local variables are required by the controllers that have been used in this configuration, thus avoiding any communication link among units.

A. RES control loops

The RES (photovoltaics or wind turbine generators, PV/WTG) control architecture consists of a maximum power point tracker (MPPT) that calculates the reference inductor current (I_{L_ref}) to the inner current loop ($PI_{current}$) that controls the PWM unit of the PV/WTG. In case of PV unit, the MPPT uses the voltage and current of the PV array (V_{PV} and I_{PV}) to provide I_{L_ref}. The WTG's MPPT uses the rotor speed (ω_{rot}) and the voltage in terminals of the generator (V_{WTG}). By using an MPPT, maximum power extraction can be guaranteed. However, RES/ESS units can also contribute in voltage regulation by using an external voltage loop (PI_{VD}) that provides I_{L_ref} and a droop control loop that emulates virtual resistance loop R_d. The switch between MPPT and voltage control depend locally on the locally measured microgrid voltage level (V_{DC}), as will be described in the following Section.

B. ESS control loops

In case of ESS units, the local control consists of a similar inner current control as described in previous Subsection. Current reference I_{L_ref} is generated from either a voltage droop controller (PI_{VD}) or a regulator (PI_{II}) that tries to maintain the battery terminals voltage ($V_{BAT1,2}$) to a certain floating voltage level (V_{float}). In this particular case, the voltage droop controller includes an adaptive virtual resistance value that is determined by a gain-scheduling control loop, which includes a fuzzy-logic controller with rules that takes into account the voltage error ($V_{ref} - V_{DC}$) and the estimated value of the battery SoC. In this paper, a coulomb counting method has been implemented for simplicity reasons, however sophisticated techniques such as extended Kalman filters can be used as well in order to enhance the accuracy of this method [16], [17].

III. OPERATION MODES OF RES AND ESS UNITS

As described in previous Section, both RES and ESS units can operate in two different operation modes, depending on the locally measured microgrid voltage (V_{dc}), according to Fig. 2.

A. Mode I

In this mode, the RES operates in MPPT. Meanwhile, the converters of the batteries operate under voltage droop control. Notice that a prolonged unbalance between available and consumed power will finally lead the batteries to low levels of SoC. On the contrary, when the power generated by RES is higher than load consumption, the batteries are charged until they reach their float voltage V_{float}. At this time, the control of the battery, switches to a voltage regulation mode, in which, the battery, draws as much current as needed to keep its voltage at V_{float} [3]. When both batteries reach the float voltage, the RES continues operating in MPPT mode until a voltage threshold $V_H = 1.05 \times V_{ref}$ is reached in the DC bus. Then, the RES changes to a voltage regulation mode (*Mode II*).

B. Mode II

In this mode, the DC bus voltage is regulated by the RES, while both batteries are in voltage regulation mode. The microgrid continues operating in this mode until a voltage threshold $V_L = 0.95 \times V_{ref}$ is reached at the DC buss. This occurs if the consumption of the load is bigger than the power generated by the RES. Then, the system changes to operation (*Mode I*).

Notice that in order to switch between modes but to avoid intermittent glitches, a hysteresis window of 0.1V (±0.05V) has been implemented here. This window can be adjusted depending on the admissible voltage regulation levels and the voltage drop due to the voltage drop in the power lines. In case of a microgrid low voltage drop values are expected due to the reduce scale of the electrical system and the short line distances. The operation modes of RES and ESS are summarized in Table I.

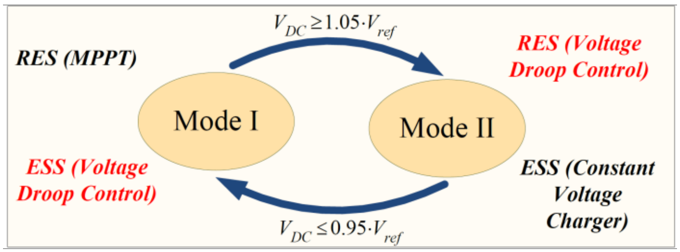

Fig. 2. Transition diagram between operation modes.

TABLE I. RES AND ESS OPERATION MODES

	Mode I	***Mode II***
RES	Maximum power point tracking	Voltage droop control
ESS	Voltage droop control	Constant voltage charging

IV. GAIN-SCHEDULING CONTROL BASED ON FUZZY LOGIC

When batteries are in the process of charge or discharge, the power balance is managed by droop controllers [3]. By using these controllers, the output voltage is given by

$$V_{DC} = V_{ref} - I_L R_d \tag{1}$$

where R_d is the virtual resistance (VR) value of each droop controller, V_{DC} is the voltage at the common DC bus, V_{ref} is the voltage reference of the common DC bus, and I_L is the output current at each converter.

It can be seen from (1) that depending on the value of the *VR*, each battery will inject or extract corresponding amount of current in order to keep the power balance in the microgrid. Consequently, the ESS with the lowest VR will be charged and discharged faster than the other. Therefore, the main objective of the gain-scheduling controller is to adjust the value of the VR in order to ensure stored energy balance between distributed energy storage units. In addition, it is advisable that the gain-scheduling controller avoids high voltage deviation in the common DC bus. In light of the above, to prevent high voltage deviation at the DC bus the smaller VR for both batteries are desirable when V_{DC} is far from V_{ref}, rather than when V_{DC} is close V_{ref}.

In particular, one of the main advantages of fuzzy logic controllers is that they can manage different control objectives simultaneously [9]. Therefore, the proposed fuzzy system adjusts the VR of the droop controllers in accordance with the SoC at each ESS and at the same time, the VR is adjusted in accordance to the voltage deviation (*VE*) in order to reduce it, as follows

$$VE = V_{DC} - V_{ref} \,. \tag{2}$$

Fig. 3 shows the parametric behavior of the gain-scheduling controller. Figs. 3(a) and 3(b) show the way in which R_d is adjusted in accordance to the SoC for different values of *VE*, for charging and discharging respectively. Fig. 3(c) shows the way in which R_d is adjusted in accordance to *VE* for different values of SoC.

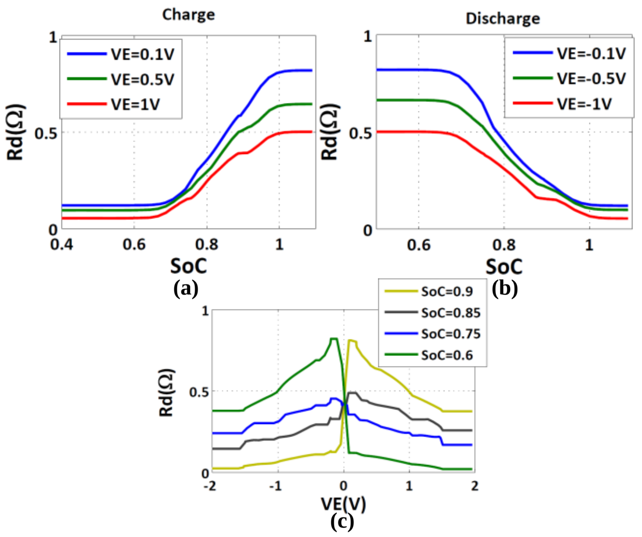

Fig. 3. Gains-schedule response: (a) under charge, (b) under discharge, (c) under voltage deviation.

V. HARDWARE-IN-THE-LOOP RESULTS RESULTS

The DC microgrid under study in this proposal is composed by two RES: a PV array and a wind turbine generator (WTG); DC loads, and two banks of batteries (see Fig. 1). In Fig. 1, two control loops at each distributed energy resource can be seen. As a matter of fact, each RES can operate under maximum power point tracking (MPPT) control or in voltage droop control. Apart from that, the most effective way of charging a battery is by using a two stage procedure, current-limited followed by a constant voltage charging [3], [10]. The transition between controllers and operation modes will be explained in deep in the final paper. Fig. 2 illustrates the way in which the gain-scheduling fuzzy controller modifies the virtual resistance of the droop controller.

The performance of the microgrid with the gain-scheduling was tested and compared to a microgrid with fixed virtual resistance. Hardware in the loop simulations were performed by using a dSPACE and *control desk*. Fig. 4 shows the behavior of the SoC at each battery and V_{DC} in the common DC bus when the gain-scheduling control is used (a) and when a fixed Rd is used (b). It can be seen that by using the gain-scheduling control the SoC of the batteries approaches one to the other. Additionally, it is possible to reduce the output voltage deviation. What is more, it is possible to see in Figure 3(a) that the SoC of battery 2 is bigger at the end of the simulation in comparison to the SoC of battery 2 in Figure 3(b). In this case (V_{ref} = 48V), the maximum power generated by RES is 300W and the nominal power of the load is 250W.

Fig. 5 shows a comparison of the time of charge when the gain-scheduling control is used (a) and when a fixed R_d is used (b). An initial SoC of 75% for battery 1 (*BAT 1*) and 58% for battery 2 (*BAT 2*) has been established. Each figure shows the voltage at the batteries and the SoC for each battery. The simulation time is split into four stages in order to indicate the behavior of the system clearly. During the first stage (*T1*), the batteries are under the process of charge. It can be seen that in the system that uses the fuzzy controllers (see Fig. 5(a)) the SoC of battery 2 approaches the SoC of battery 1 asymptotically. At the end of T1, battery 1 reaches its float voltage therefore; battery 1 changes its inner control loop from voltage droop control to constant voltage charger. During the second stage (*T2*), battery 2 reaches its float voltage. Hence, it changes its inner control loop from voltage droop control to constant voltage charger.

It is possible to see that despite *battery 1* is charged faster at the beginning in the system with fixed virtual resistance (see Fig. 5(b)) the total time of charge of both batteries (*T1+T2*) is less in the system with gain-scheduling control (see Fig. 5(a)), thanks to the approach in the SoC of both batteries.

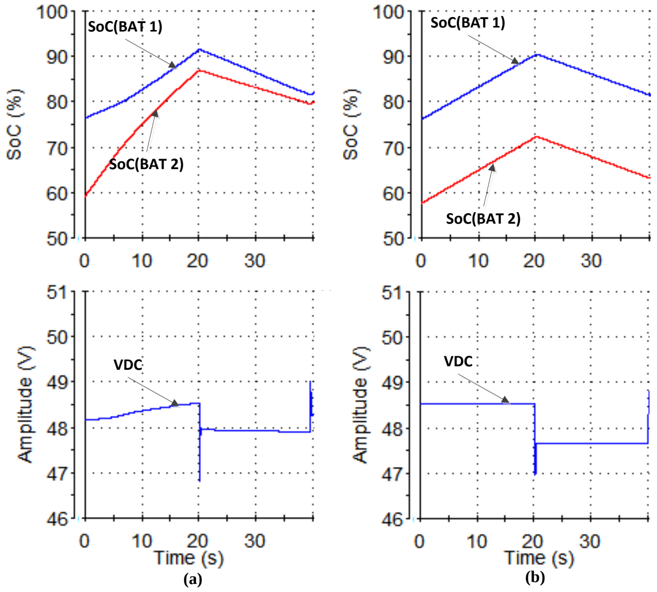

Fig. 4. Response of the system with: (a) fuzzy control, (b) fixed virtual resistance.

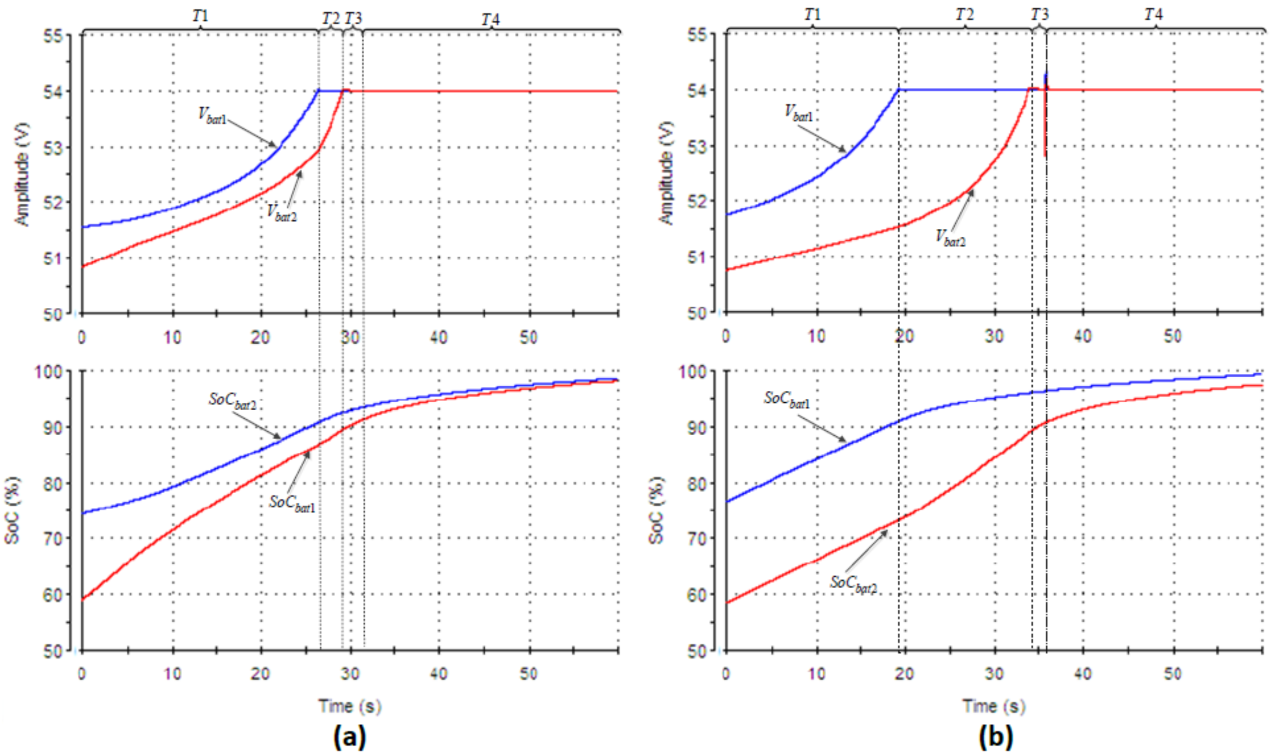

Fig. 5. Time of charge with: (a) fuzzy control, (b) fixed virtual resistance.

During third stage (*T3*), both batteries are under constant voltage charge and the RES are still in MPPT control. At this point, the voltage in the DC bus (V_{DC}) increases until a threshold value $V_{DC} = 1.05\ V_{ref}$ and the system changes its operation mode. At the new operation mode, the RES operates under voltage droop control in order to regulate the voltage at the DC bus. Then, during forth stage (*T4*), batteries are under constant voltage charge and RES are under voltage droop control.

VI. CONCLUSION

The proposed gain-scheduling control technique assures good stored energy balance and small voltage deviation. Additionally, this strategy is absolutely modular and no centralized control is required. Fuzzy logic has been already proposed for energy management of ESS in microgrids. However, just a single battery has been analyzed and the stored energy balance together with voltage deviation has not been studied. In general, the fuzzy gain-scheduling scheme proposed in this paper shows comparative advantages in dealing with different control objectives. Another advantage of the fuzzy system is that the same fuzzy controller can be easily scaled to different values of R_d. The good performance of the proposed approach has been presented through hardware in the loop simulation results of a DC microgrid. The results points out its potential applicability in real microgrid sites.

REFERENCES

[1] J. Vasquez, J. Guerrero, J. Miret, M. Castilla, and L. de Vicuna, “Hierarchical control of intelligent microgrids,” *Industrial Electronics Magazine*, IEEE, vol. 4, no. 4, pp. 23–29, 2010.

[2] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuna, and M. Castilla, “Hierarchical control of droop-controlled AC and DC microgrids – a general approach toward standardization,” *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 158–172, Jan. 2011.

[3] T. Dragicevic, J. Guerrero, J. Vasquez, and D. Skrlec, “Supervisory control of an adaptive-droop regulated dc microgrid with battery management capability,” *Power Electronics, IEEE Transactions on*, vol. 29, no. 2, pp. 695-706, Feb. 2014.

[4] Zhou Haihua, T. Bhattacharya, Tran Duong, T. S. T. Siew, A. M. Khambadkone, "Composite Energy Storage System Involving Battery and Ultracapacitor With Dynamic Energy Management in Microgrid Applications," *IEEE Transactions on Power Electronics*, vol. 26, no. 3, pp. 923-930, March 2011.

[5] M. Fazeli, G. M. Asher, C. Klumpner, Yao Liangzhong, M. Bazargan, "Novel Integration of Wind Generator-Energy Storage Systems Within Microgrids," *Smart Grid, IEEE Transactions on*, vol. 3, no. 2, pp. 728,737, June 2012.

[6] H. Kakigano, Y. Miura, and T. Ise, “Distribution voltage control for dc microgrids using fuzzy control and gain-scheduling technique,” *Power Electronics, IEEE Transactions on*, vol. 28, no. 5, pp. 2246–2258, 2013.

[7] Y. Zhang, H. J. Jia, and L. Guo, “Energy management strategy of islanded microgrid based on power flow control,” in *Innovative Smart Grid Technologies (ISGT)*, 2012 *IEEE PES*, pp. 1–8, 2012.

[8] Zhihong Ye; Boroyevich, D.; Kun Xing; Lee, F.C., "Design of parallel sources in DC distributed power systems by using gain-scheduling technique," *Power Electronics Specialists Conference*, 1999. PESC 99. 30th Annual IEEE , vol.1, pp. 161,165 vol.1, Aug 1999.

[9] H. Zhang, F. Mollet, C. Saudemont, and B. Robyns, “Experimental validation of energy storage system management strategies for a local dc distribution system of more electric aircraft,” *IEEE Transactions on Industrial Electronics*, vol. 57, no. 12, pp. 3905–3916, 2010.

[10] “IEEE guide for optimizing the performance and life of lead-acid batteries in remote hybrid power systems,” 2008.

[11] Anand, S.; Fernandes, B. G.; Guerrero, J. M., "Distributed Control to Ensure Proportional Load Sharing and Improve Voltage Regulation in

Low-Voltage DC Microgrids," *Power Electronics, IEEE Transactions on*, vol. 28, no. 4, pp. 1900-1913, April 2013.

[12] Xiaonan Lu; Guerrero, J.M.; Kai Sun; Vasquez, J.C., "An Improved Droop Control Method for DC Microgrids Based on Low Bandwidth Communication With DC Bus Voltage Restoration and Enhanced Current Sharing Accuracy," *Power Electronics, IEEE Transactions on*, vol. 29, no. 4, pp. 1800-1812, April 2014.

[13] Meng, Lexuan; Dragicevic, Tomislav; Guerrero, Josep M.; Vasquez, Juan C., "Optimization with system damping restoration for droop controlled DC-DC converters," *Energy Conversion Congress and Exposition (ECCE), 2013 IEEE*, pp.65-72, 15-19 Sept. 2013.

[14] Dragicevic, T.; Guerrero, J.; Vasquez, J., "A Distributed Control Strategy for Coordination of an Autonomous LVDC Microgrid Based on Power-Line Signalling," *Industrial Electronics, IEEE Transactions on*, IEEE Early Access, 2014.

[15] Lu, X.; Sun, K.; Guerrero, J.M.; Vasquez, J.C.; Huang, L., "State-of-Charge Balance Using Adaptive Droop Control for Distributed Energy Storage Systems in DC Micro-Grid Applications," *Industrial Electronics, IEEE Transactions on*, IEEE Early Access, 2014.

[16] Dragicevic, T.; Sucic, S.; Guerrero, J.M., "Battery state-of-charge and parameter estimation algorithm based on Kalman filter," EUROCON, 2013 IEEE , vol., no., pp.1519,1525, 1-4 July 2013

[17] Auger, F.; Hilairet, M.; Guerrero, J.M.; Monmasson, E.; Orlowska-Kowalska, T.; Katsura, S., "Industrial Applications of the Kalman Filter: A Review," *Industrial Electronics, IEEE Transactions on*, vol.60, no.12, pp.5458,5471, Dec. 2013.

[18] Schonberger, J.; Duke, R.; Round, S.D., "DC-Bus Signaling: A Distributed Control Strategy for a Hybrid Renewable Nanogrid," *Industrial Electronics, IEEE Transactions on*, vol. 53, no. 5, pp. 1453-1460, Oct. 2006.

[19] Bose, B.K., "Expert system, fuzzy logic, and neural network applications in power electronics and motion control," *Proceedings of the IEEE*, vol.82, no.8, pp.1303-1323, Aug 1994.