An Adaptive Control Strategy for Dynamic Response of an Autonomous DC system

Norouzi, Farshid; Ramirez Elizondo, Laura ; Hoppe, Thomas; Bauer, Pavol

DOI
10.1109/UPEC50034.2021.9548156

Publication date
2021

Document Version
Accepted author manuscript

Published in
2021 56th International Universities Power Engineering Conference (UPEC)

Citation (APA)
Norouzi, F., Ramirez Elizondo, L., Hoppe, T., & Bauer, P. (2021). An Adaptive Control Strategy for Dynamic Response of an Autonomous DC system. In *2021 56th International Universities Power Engineering Conference (UPEC): Proceedings* (pp. 1-5). Article 9548156 IEEE. https://doi.org/10.1109/UPEC50034.2021.9548156

An Adaptive Control Strategy for Dynamic Response of an Autonomous DC system

Farshid Norouzi
Faculty of Electrical Engineering, Mathematics and Computer Science, Delft University of Technology
Delft, The Netherlands
F.norouzi@tudelft.nl

Laura Ramirez Elizondo
Faculty of Electrical Engineering, Mathematics and Computer Science, Delft University of Technology
Delft, The Netherlands
L.M.RamirezElizondo@tudelft.nl

Thomas Hoppe
Department of Technology, Policy and Management, Delft University of Technology,
Delft, The Netherlands
T.Hoppe@tudelft.nl

Pavol Bauer
Faculty of Electrical Engineering, Mathematics and Computer Science, Delft University of Technology
Delft, The Netherlands
P.Bauer@tudelft.nl

***Abstract*—The dynamic behaviour - steady-state and transient - of the DC Microgrids during power disturbance can affect the system's general performance. A hybrid combination of energy storage devices with slow frequency response, like a Fuel Cell, and with a fast dynamic response, like a Super-Capacitor, provides an improved dynamic response to stabilise DC bus voltage. However, control parameters should be designed based on the preferences of the system. This paper proposes a fuzzy-based controller to determine the Virtual Capacitor Droop controller to achieve the desired transient response. The proposed dynamic control method is validated through MATLAB/Simulink.**

***Index Terms*—DC Microgrids, Dynamic behaviour, Energy Storage, Fuzzy-based controller**

I. Introduction

Recently, the performance and technical barriers to Microgrids (MGs) have been studied comprehensively [1, 2]. Compared to AC MGs systems DC MGs show more adaptability with distributed generators, more efficiency, no reactive power losses, and no skin effect. However, they suffer, among other things, from a lack of general guidelines and standards to design efficient protection schemes. In addition, they also suffer from the lack of inertia [2].

In both AC and DC MGs, the rapid integration of clean, renewable energy resources with intermittent nature has urged the need for large scale deployment of Energy Storage Systems (ESSs). Although ESSs with different capabilities are generally considered as an attractive potential solution to deal with reliability and power quality issues in MGs, it is important that ESSs are selected and used according to systems requirements since they have certain specific (and different) characteristics. For instance, comparing a typical Fuel Cell (FC) with a Super-Capacitor (SC) reveals that while an SC cannot store as much energy as a comparable FC, SC having the advantage of a higher speed of charge. Furthermore, SC has a wider range in operating temperature but is considered a relatively expensive option for those considering to adopt it (See Table I).

TABLE I
Comparison of selected properties of Fuel Cells and Super Capacitors

Property	Fuel Cells	Super Capacitors
Charge/Discharge Time	10 to 300 hrs	Picoseconds to Milliseconds
Operating Temperature	25 °C to 90 °C	−20 °C to 100 °C
Energy Density	300 to 3000 Wh/kg	0.01 to 0.05 Wh/kg
Life	$>$ 100000 cycles	1500 to 10000 hrs
Cost per kWh	1500$ to 2000$	2500$ to 5000$

In traditional control methods of distribution systems, voltage and frequency are maintained by adjusting the active (P) or reactive (Q) power in generation or consumption [3]. However, multiple Distributed Generation (DG) units should work in a parallel configuration to provide sufficient power in MGs. Traditional methods cannot control these parallel units. In this regard, power-frequency ($Q - F$) and active power-voltage ($P - E$) droops are widely used to control MGs. These methods are based on proper load sharing between Renewable Energy Sources (RESs). Therefore, droop methods in islanded (autonomous) MGs are highly affected by the nature of loads and distribution system lines. Consequently, a secondary controller is added to the primary controller to restore the frequency and voltage deviation.

DGs are interfaced with power converters, and there is no direct connection between rotating generators and the electric bus in MGs. This can cause a lack of inertia, particularly in the DC autonomous systems. Consequently, the system cannot handle the power variation properly [4]. In many studies that address the solution to the inertia problem, the virtual impedance droop controller is implemented [5, 6]. The integration of various resources with slow and fast response time has also been studied [7, 8]. These studies emphasise the emulation of the inertia in both AC and DC systems. For instance, the Virtual Synchronous Machine (VSM) method is widely used to solve this problem in AC MGs. Similar approaches are applied to solve the lack of inertia in DC systems [2, 8]. Inertia emulation techniques are implemented in the system's primary control loop, and their effects are analysed with different approaches (e.g., frequency-coordination with virtual impedance [9]). To the best of the authors' knowledge, there is no systematic method to determine virtual elements' values (e.g., the virtual capacitor). An adaptive method is proposed to address this issue based on the required dynamic response and power deviation limitations.

The research goal central to this paper is to improve the transient behaviour of an autonomous DC system. Implementation of the proposed methods can help designers in determining the optimal values of virtual elements according to systems requirements.

In the proposed DC system hybrid ESSs are combined. It consists of an FC and an SC due to their complementary characteristics. In contrast with similar studies [8, 9], the DC bus is not connected to other power sources such as solar PVs or wind turbines. This eases the analysis of the bus voltage fluctuation during the transient mode. After introducing the system with the Virtual Resistor-Capacitor Droop(VRCD) controller, the dynamic of the system will be investigated to understand the effect of the virtual elements on the time response. Then a fuzzy controller is proposed to improve its dynamic response and address power imbalances.

II. Methodology

The existence of the rotating generator in AC systems results in more kinetic energy and therefore inertia in AC MGs can be shown as [10]:

$$E_k = \frac{1}{2} J \omega_m^2 \tag{1}$$

Where J is the inertia of the whole system, ω_m is the angular velocity, and E_k is kinetic energy. There is an equivalence between energy stored in AC and DC systems. The stored energy in DC systems is equal to capacitors' energy as:

$$E_c = \frac{1}{2} C V_c^2 \tag{2}$$

Here E_c is the inertia in the DC system, C is the equivalent capacitance of the DC system, and V_c is nominal DC voltage.

TABLE II
Designed parameters of hybrid system

Component (Symbol)	Designed values
Rated power (P)	1225 (W)
DC bus voltage (V_{ref})	350 (V)
Virtual resistor (R_1)	1.3 (Ω)
FC voltage (V_{FC})	100 (V)
SC voltage (V_{SC})	150 (V)
Boost converter inductor (L_{FC})	20 (mH)
Bidirectional converter inductor (L_{SC})	5 (mH)
Boost converter capacitor (C_{FC})	200 (μF)
Bidirectional converter capacitor (C_{SC})	600 (μF)
Initial value of Virtual Capacitor (C_2)	1 F

Comparing (1) and (2) shows that to emulate the inertia in a DC system, a Virtual Capacitor Droop (VCD) should be introduced to the system. A promising way to integrate such a capacitor into the system is adding that in the primary control loop [11, 12].

Fig. 1 shows the proposed hybrid ESSs with the control loops connected to an autonomous DC system to handle the power imbalance. This system consists of an FC as the primary energy source with a slow dynamic response. To compensate for its slow dynamics, an SC with fast dynamics is connected to the system. A boost converter is used to connect the FC to the DC bus. A bidirectional Buck-Boost converter is used to connect the SC to the DC bus.

In the control scheme, droop loops provide a new voltage value for each branch of the system. These voltages are compared with actual output voltages from converters, and the PIs control the voltage output. The voltage controllers' outputs are the current reference values for current controller loops. In this system, the resistance droop controller inherently acts as a proportional controller ,and the capacitor droop controller acts as an integral controller. Therefore, their values can affect the system's dynamics in different ways. Component values for the proposed DC system are summarised in Table II.

A resistance-based droop approach is suitable for the steady-state condition when there is no power fluctuation. However, during the transient mode, when the system suffers from a lack of inertia, any power disturbance can impose voltage instability on the DC system.

To explain our approach, the equivalence DC system is shown in Fig.2. The output voltage of the DC system (V_o) in the frequency domain can be calculated as:

$$V_o(s) = V_r - Z_c I_o(s) \tag{3}$$

Where I_o is current output from parallel converters connected to the DC bus. Z_c is the virtual impedance coefficient and V_r is the nominal DC voltage. According to (3), voltages of FC and SC branches can be expressed as:

$$V_{o1}(s) = V_r - R_1 i_{o1}(s) \tag{4}$$

$$V_{o2}(s) = V_r - \frac{C_2}{s} i_{o2}(s) \tag{5}$$

Where $v_{o1}(s)$, $i_{o1}(s)$, $v_{o2}(s)$, and $i_{o2}(s)$ are voltage and current output of boost and bidirectional buck-boost converters respectively.

Two converters supply the current of the load in a complementary way. In each time, the sum of these two currents equals the demanded load. However, most of the current is supplied by $i_{o2}(s)$ in the transient mode. In the steady-state condition, $i_{o1}(s)$ is responsible for the power supply.

A. Virtual resistor and capacitor values

For selecting a virtual droop resistor value, there is a trade-off between better load sharing and voltage deviation. Although, a larger value of resistor helps load sharing, this

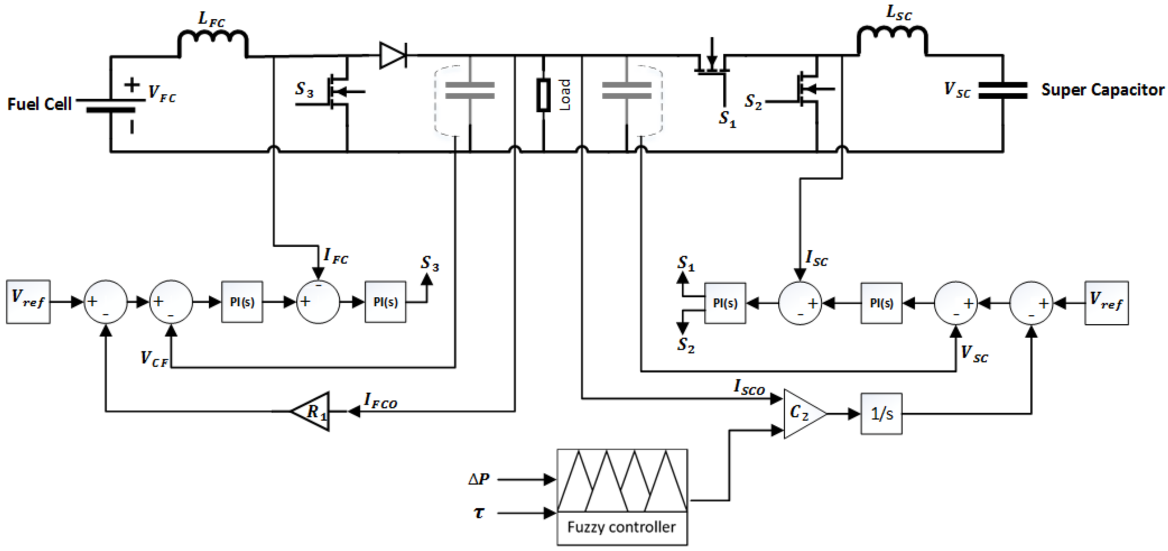

Fig. 1. Hybrid energy resources with control loops

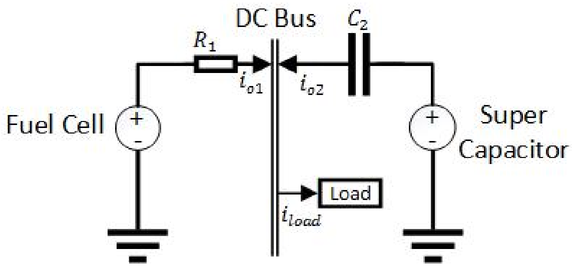

Fig. 2. Equivalence of DC system

value is limited by the maximum acceptable voltage deviation in the steady state condition as:

$$R_1 = \frac{\Delta V_{max}}{I_{max}} \tag{6}$$

Where ΔV_{max} is the maximum acceptable voltage deviation in DC bus, and I_{max} is the maximum output current from the boost converter.

Considering the virtual resistor's constraint, the virtual capacitor's value provides more freedom to satisfy the system's dynamic response. Although the system's stability analysis provides an accurate range of freedom to select virtual resistor and capacitor values, this is out of the scope of the study presented in the present paper. The range of these values for the present study was chosen with the aim not to violate the stability of the system.

Considering the parallel connection of converters, the current and voltage can be derived as:

$$v_{o1}(s) = v_{o2}(s) \tag{7}$$

$$i_{o1}(s) + i_{o2}(s) = i_{load} \tag{8}$$

Moreover, the current for each branch can be derived as:

$$i_{o1} = i_{load}.\frac{C_2/s}{C_2/s + R_1} \tag{9}$$

$$i_{o2} = i_{load}.\frac{R1}{C_2/s + R_1} \tag{10}$$

Considering general transfer functions of the first order low pass and high pass filters, it can be deduced that the system has a time constant (τ) as:

$$\tau = \frac{C_2}{R_1} \tag{11}$$

Therefore, the value of C_2 can be controlled to satisfy the system dynamics. In addition, the virtual capacitor's value is inversely proportional to the time response in high frequencies, which means that increasing capacitor values speeds up the transient response [8].

B. *Fuzzy Based Virtual Capacitor Droop Controller*

A fuzzy system is designed to regulate the virtual capacitor coefficient. The inputs of the fuzzy controller are absolute imbalanced power and the time response of the current system. The fuzzy interface updates the value of the virtual capacitor according to fuzzy rules (See Table III). These rules and the range of membership function are chosen based on our presented hybrid system, and they can vary according to systems requirements. For instance, this study assumes power imbalances that are over 950 W as a pure " large". In fact, this would give the idea to define membership functions and rules.

The membership functions for inputs are shown in Figs 3-5. The imbalanced power range is defined as ΔP= (0, 1.2 kW) based on the rate of the converters. The rules consider up to 570 W as small, between 325 and 975 W as medium, and more than 730 W as large values. The maximum time

TABLE III
FUZZY RULES

Time response (τ) \ Power Imbalance (ΔP)	Small	Medium	Large
Slow	L	L	L
Moderate	S	M	L
Fast	S	S	S

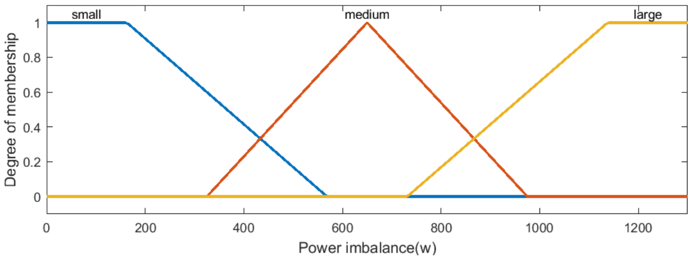

Fig. 3. Membership functions for power imbalance

response for the system is set to τ= (0, 10 s) which can vary according to system components and PI controllers' values. To this end, time response up to 4.5 s is fast, between 2.5 and 7.5 s as moderate, and more than 5.5 s as slow. We considered up to 2 F as small for the coefficient values, between 1 and 4 F as medium, and more than 3 F as large.

III. SIMULATION RESULTS

The overall system's performance with the fuzzy implemented controller was simulated. The results show the system's effectiveness. The system is designed to stabilise the bus voltage at 350 V. The maximum voltage variation in the steady-state condition is ΔV_{max}=5 V. Therefore, the maximum rated output current for the boost converter is 3.6 A, and the value for the virtual resistance (R_1) is chosen to be 1.3 Ω.

At T=3 s, a medium power of 600 W is applied to the system. This imbalanced power lasts until T=25 s. Fig. 6 shows how FC and SC complement each other and provide the necessary power at nominal current (3.5 A). During the transient mode, the FC output power cannot handle the required power, and therefore the SC is responsible for supplying the load. Due to the SC's fast dynamics, the output current of SC increases very fast in this time interval and reaches its maximum. Then after the FC takes responsibility during the steady-state, and the current of the SC converges to zero. This procedure continues when imbalance power is removed from the system at T=25 s. The bidirectional converter begins to charge the SC in the opposite direction, and gradually the FC's current reduces.

Implementing the fuzzy controller requires τ and ΔP inputs. Given the imbalanced power to the system (ΔP= 600 W), response time can be considered as the time when the current reaches 63.2 % of the final value (1.7 A).

First, the system is run without the fuzzy controller to obtain the time response of the system. Then fuzzy controller is implemented to improve the system dynamics. Based on the systems' response time and power imbalance applied to the

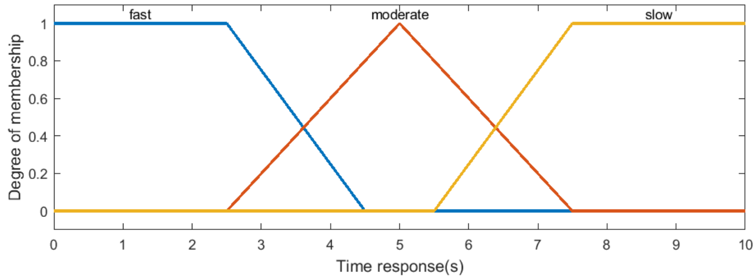

Fig. 4. Membership functions for time response

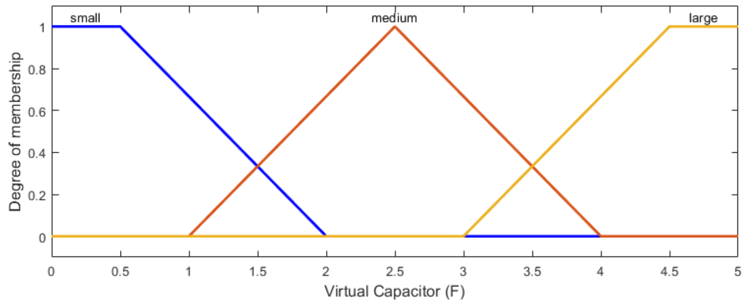

Fig. 5. Membership functions for virtual capacitors

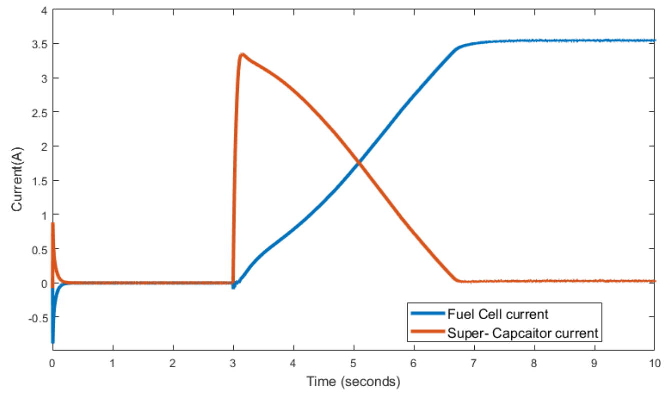

Fig. 6. Complementary behaviour of FC and SC

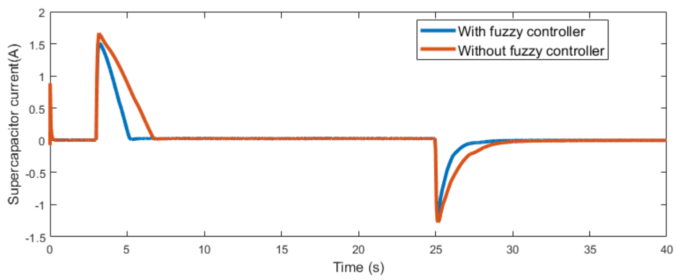

Fig. 7. Effect of fuzzy controller on SC's current

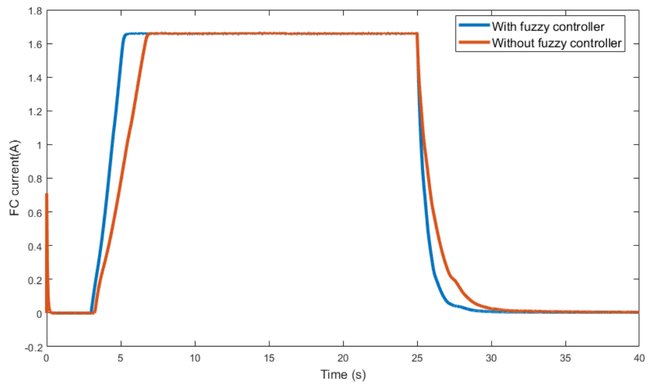

Fig. 8. Effect of fuzzy controller on FC's current

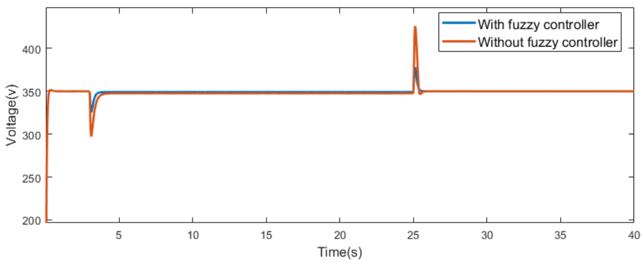

Fig. 9. Effect of fuzzy controller on DC bus voltage

system, the fuzzy controller updates the SC's value (C_{2new}= 2.5 F). The effectiveness of the fuzzy controller controlling the current and voltage fluctuation is presented in Figs. 7-9.

IV. Conclusion

In the present paper, a DC system with hybrid ESSs is proposed, and a virtual resistance-capacitance droop controller is implemented to analyse the system's dynamic response. Moreover, a fuzzy interface is introduced to the system to control the system's dynamics adaptively. The simulation results validate the proper performance of the system during both transient and steady-state modes. In future studies, the PI controllers' effect on the system dynamics should be considered to analyse the system's stability. Additionally, further research is needed to analyse the effect of the distribution system's line on the proposed system.

References

[1] W. Feng, M. Jin, X. Liu, Y. Bao, C. Marnay, C. Yao, J. Yu, A review of microgrid development in the United States – A decade of progress on policies, demonstrations, controls, and software tools, Applied Energy 228 (April) (2018) 1656–1668. doi:10.1016/j.apenergy.2018.06.096.
URL https://doi.org/10.1016/j.apenergy.2018.06.096

[2] J. Kumar, A. Agarwal, V. Agarwal, A review on overall control of DC microgrids, Journal of energy storage 21 (2019) 113–138.

[3] T. Dragičević, X. Lu, J. C. Vasquez, J. M. Guerrero, DC Microgrids - Part II: A Review of Power Architectures, Applications, and Standardization Issues, IEEE Transactions on Power Electronics 31 (5) (2016) 3528–3549. doi:10.1109/TPEL.2015.2464277.

[4] J. M. Guerrero, M. Chandorkar, T.-L. Lee, P. C. Loh, Advanced control architectures for intelligent microgrids—Part I: Decentralized and hierarchical control, IEEE Transactions on Industrial Electronics 60 (4) (2012) 1254–1262.

[5] M. Farrokhabadi, D. Lagos, R. W. Wies, M. Paolone, M. Liserre, L. Meegahapola, M. Kabalan, A. H. Hajimiragha, D. Peralta, M. A. Elizondo, K. P. Schneider, C. A. Canizares, F. K. Tuffner, J. Reilly, J. W. Simpson-Porco, E. Nasr, L. Fan, P. A. Mendoza-Araya, R. Tonkoski, U. Tamrakar, N. Hatziargyriou, Microgrid Stability Definitions, Analysis, and Examples, IEEE Transactions on Power Systems 35 (1) (2020) 13–29. doi:10.1109/TPWRS.2019.2925703.

[6] H. Bevrani, T. Ise, Y. Miura, Virtual synchronous generators: A survey and new perspectives, International Journal of Electrical Power and Energy Systems 54 (2014) 244–254. doi:10.1016/j.ijepes.2013.07.009.
URL http://dx.doi.org/10.1016/j.ijepes.2013.07.009

[7] N. Soni, S. Doolla, M. C. Chandorkar, Improvement of transient response in microgrids using virtual inertia, IEEE transactions on power delivery 28 (3) (2013) 1830–1838.

[8] E. Unamuno, J. A. Barrena, Equivalence of primary control strategies for AC and DC microgrids, Energies 10 (1) (2017) 91.

[9] Y. Gu, W. Li, X. He, Frequency-coordinating virtual impedance for autonomous power management of DC microgrid, IEEE Transactions on Power Electronics 30 (4) (2014) 2328–2337.

[10] Z. Shuai, J. Fang, F. Ning, Z. J. Shen, Hierarchical structure and bus voltage control of DC microgrid, Renewable and Sustainable Energy Reviews 82 (2018) 3670–3682. doi:10.1016/j.rser.2017.10.096.
URL https://linkinghub.elsevier.com/retrieve/pii/S1364032117314788

[11] A. S. Samosir, A. H. M. Yatim, Implementation of dynamic evolution control of bidirectional DC-DC converter for interfacing ultracapacitor energy storage to fuel-cell system, IEEE Transactions on Industrial Electronics 57 (10) (2010) 3468–3473. doi:10.1109/TIE.2009.2039458.

[12] Q. Xu, X. Hu, P. Wang, J. Xiao, L. Setyawan, C. Wen, L. M. Yeong, Design and stability analysis for an autonomous DC microgrid with constant power load, Conference Proceedings - IEEE Applied Power Electronics Conference and Exposition - APEC 2016-May (2016) 3409–3415. doi:10.1109/APEC.2016.7468357.