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Stabilization of DC NanoGrids Based on Non-Integer General Type-II Fuzzy System

Mahdi Mosayebi, Seyed Mohammad Sadeghzadeh, Josep M. Guerrero, *Fellow, IEEE*, and Mohammad Hassan Khooban, *Senior Member, IEEE*

***Abstract*—This paper proposes a dynamic consensus algorithm-based nonlinear I-V droop control for the balancing state of charge of energy storage systems (ESSs) in DC Nanogrids (DCNGs). The dynamic consensus algorithm (DCA) provides a coordinated secondary control with sharing information between Distributed Generation (DG) units to regulate the output power of each DG based on the capacity and state of charge (SoC) of the ESSs. Furthermore, a novel high bandwidth fractional order general type-2 fuzzy logic proportional-integral-derivative (FOGT2FPID) controller is applied in the secondary control level to ensure fast and accurate voltage regulation, and SoC balancing in the DCNG. In the primary control level, a nonlinear I-V droop control approach provides fast dynamic and accurate power-sharing among DGs. Moreover, the proposed control method can provide reliability, modularity, and flexibility. Compared with conventional methods, over-current failures and abruptly disconnection of DGs are prevented with the proposed controller. Also, it can provide voltage regulation by means of the balancing of the SoC in the DCNG. Experimental results are shown to verify the effectiveness of the proposed control scheme under different scenarios using facilities at the Microgrid Laboratory, Aalborg University.**

***Index Terms*— droop control, consensus Algorithm, distributed control, DC nanogrid.**

I. Introduction

The concept of microgrids is identified as a promising solution to generation and distribution energy by integrating renewable energy sources (RESs), energy storage systems (ESSs) and loads [1]. Recently, due to the advantages of the DC microgrids such as high efficiency, simple control, and no harmonic and reactive power issues, the DC microgrids (DCMGs) and DC Nanogrids (DCNGs) have gained more attention in the power industry applications [2]. In an islanded DCNG, ESSs should be installed in distributed generation (DG) units to overcome the intermittency of the RESs and deliver power to the load in various situations such as energy-shortage and load changes. Moreover, to provide voltage support and to guarantee the stability of the system, several ESSs should be connected to the common bus through paralleled bidirectional converters.

The lifecycle of the ESS units such as lithium-ion batteries in the DCNGs is affected by several factors such as charging and discharging current and temperature [3]. To prevent decreasing the lifecycle of the ESSs in DGs, the control of the state-of-charge should be considered to avoid the depth of discharge as well as restrict the charging/discharging current [4]. In the conventional power-sharing

M. Mosayebi and S. M. Sadeghzadeh are with the Faculty of Engineering, Shahed University, Tehran, Iran (e-mail: mmahdimosayebi@gmail.com, Sadeghzadeh@shahed.ac.ir).
J. M. Guerrero is with the Department of Energy Technology, Aalborg University, 9200 Aalborg, Denmark (e mail: joz@et.aau.dk).
M. H. Khooban is with the Department of Engineering, Aarhus University, 8200 N Aarhus, Denmark. (e-mail: khooban@ieee.org).

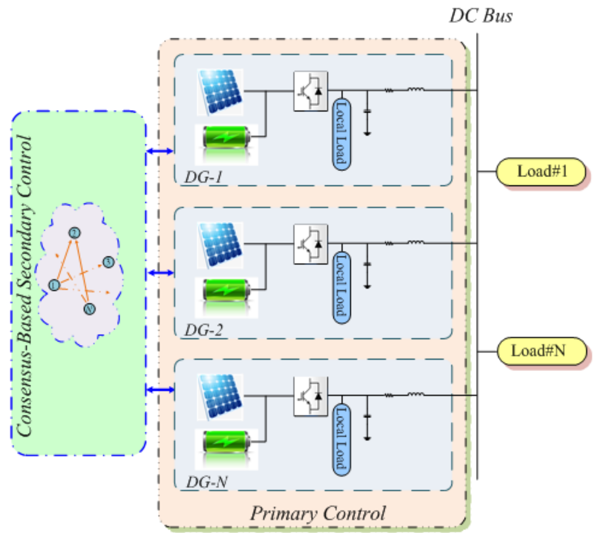

Fig. 1. PV/ESS-based DC Nanogrid.

control method for paralleled converters, all DGs contribute to common load with equal output power. Since the SoC and capacity of the ESSs in a DCNG are different, the ESSs have different discharge rates. It means that in conventional control strategies with equal power sharing, the ESS unit with fewer SoC and capacity have a faster discharge rate and will be shut down when its SoC reaches the predefined threshold level. In this situation, other DGs should participate in power-sharing with higher current and it is caused overcurrent discharge for the ESSs, which is degraded the efficiency of the ESSs units. Moreover, the voltage stability will be affected as well as the reliability of the system. To avoid this problems, all factors such as SoC and capacities of the ESSs should be considered in the coordinated output power control of the DGs in the DCNGs.

To have a proper SoC balancing in the DCNGs, several coordinated control strategies have been proposed based on the hierarchical control structure [5]. In the primary control level, V-I droop control has been proposed to provide power sharing among DGs. In [4], adaptive droop control is proposed to adjust the virtual resistance based on the SoC, which the DG with higher SoC injects more power to the common load. However, due to the voltage deviation of the droop control, a secondary controller needs to be implemented to restore the voltage of the DCNG. In [6], a centralized coordinated control method with communication links is proposed to achieve energy balancing in paralleled DGs. In these control strategies, the power-sharing among DGs is achieved by proper adjusting virtual resistance of the droop control method in the primary control level. However, to overcome the disadvantages of the centralized control method such as single point of failure (SPOF), distributed coordinated control methods have received more attention in the DCNGs [7]. In distributed coordinated control methods, the information is shared between neighboring units to improve the stability and reliability of the system with respect to the variation of the electrical parameters and configuration of the DCNGs. Dynamic Consensus Algorithm (DCA) is one of the most promising distributed communication-based algorithms [8]. In the DCA, the

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information of neighboring units is only needed, which decreases the communication cost. Generally, secondary control has a slower speed in comparison to the primary control. Therefore, the secondary control level suffers from low bandwidth and slow dynamic response, which is degraded the performance of the system in transient conditions.

On the other hand, the aforementioned control methods based on the droop control in the primary control level have a slow transient response due to the V-I droop control. Wang *et al.* in [9] shows that the I-V droop control has faster dynamics in comparaison to the V-I droop control. Also, the conventional PI controller is not fast enough to compensate the voltage during a fast transient [10].

In this paper, a distributed coordinated control strategy based on the DCA is proposed for balancing the SoC of the ESSs in the DCNG with different SoC and capacity. To improve power-sharing among DGs in a DCNG according to the SoC and capacity of the ESSs, a novel nonlinear I-V droop control is implemented at the primary level, which provides fast response and accurate power sharing. The DCA in the secondary control level is applied to adjusting the virtual resistance of the proposed nonlinear droop control. Additionally, a high bandwidth fractional order general type-2 fuzzy logic proportional-integral-derivative (FOGT2FPID) controller is presented to provide fast response as well as regulate the voltage of the DCNG. Moreover, the proposed control method can protect ESSs against over-current discharging and improve the stability and reliability of the DCNG.

II. DC Nanogrids (DCNGs) Structure

Fig. 1 shows a PV/Battery-based DCNG consists of several paralleled DGs. Generally, PV works in MPPT to inject power to the local and common loads. To increase the redundancy of the system, ESSs are installed beside the PV to work in charging and discharging mode according to the power generation and consumption. PVs and ESSs are connected to the DC bus through the DC/DC converters. Each DG has a primary control loop based nonlinear I-V droop control to control the output power and voltage. Moreover, a DCA-based secondary control level is implemented to adjust the virtual resistance of the droop control according to the average value of the SoC in a DCNG. Due to the different values of the SoC and various capacities of ESS units in the DCNG, each DG should participate in power sharing according to its capacity and SoC. It means that the DG with the highest SoC and capacity should inject more power to the common load. In order to improve the reliability of the system and to avoid over-current discharging for the ESSs and to prevent failure in the DCNG due to the unexpected disconnection of DGs, a coordinated control strategy should be considered to adjust the output power of the DGs with respect to their SoCs and capacities.

III. Proposed Control Method

A. I-V Droop Control in primary level

By proper optimization of the droop resistance trajectory, the desired current sharing and good voltage regulation in the droop control methods can be achieved. Several droop curves can be considered for a specified voltage deviation, from no-load to full load operation of the converters in the islanded DCNG. The droop control method can be presented by the following equation:

$$V_i = V^* - R_{di} \cdot \left(I_i^n\right), n \in R \tag{1}$$

where V_i is the output voltage of the DC-DC converter, R_{di} is the virtual resistance, and V^* is the reference voltage. I_i is the output current of the i^{th} converters.

Fig. 2 (a) shows the droop gains based on the output current of the converters for different values of n. It is evident that high droop gains yield better current sharing among paralleled converters in the DCNG. As shown in Fig. 2 (a), it is clear that the linear droop method (i.e. n=1) has small droop gain in the heavy-load condition, which

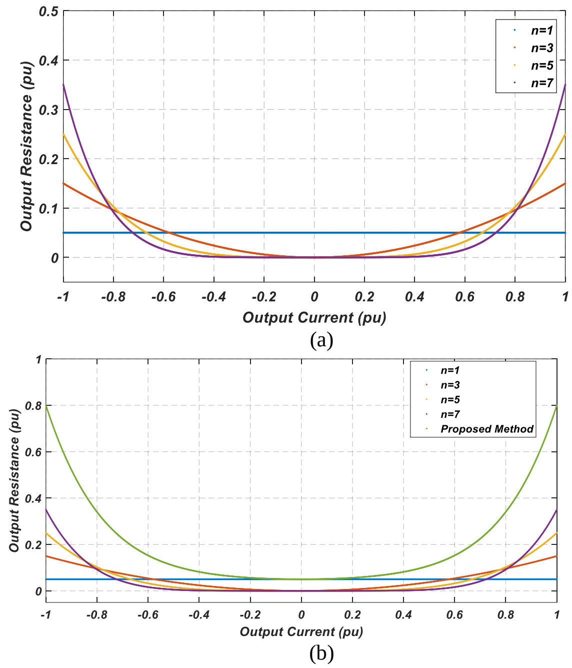

Fig. 2. (a) Droop gains based on the output current for different values of n. (b) Different droop gain based on the proposed method for n=1,3,5,7.

degrades the current sharing. Also, the nonlinear droop methods suffer from poor current sharing in the light-load conditions. To overcome the limitation of the conventional linear and nonlinear methods, and to satisfy good performance in the current sharing and voltage restoration, a novel nonlinear I-V droop-based control is proposed.

As depicted in Fig.3, in the primary control level, an I-V droop control method is implemented to achieve proper current sharing. In this technique, a single control loop is replaced with dual outer voltage and inner current control loops, which provide a faster response. The reference current in reverse droop control can be expressed as follows:

$$I_{ref} = \frac{V^* - V_{Ci}}{R_{di}} \tag{2}$$

where V_{Ci} is the output voltage of the converter, R_{di} is the virtual resistance, and V^* is the reference voltage.

By expanding Eq. (1), with respect to the linear droop gain, the general equation of the droop curve can be achieved as follows:

$$V_i = V^* - R_{di,1} \cdot I_i - R_{di,n} \cdot I_i^n \tag{3}$$

The selection of n (i.e., $n = 3,5,7,...$), is depending on the amount of voltage deviation and the maximum current value in i^{th} converter in the DCNG [11]. It should be noted that it is preferred to select the droop curves with odd values to have a symmetrical characteristic for the bidirectional DC-DC converter. Therefore, Eq. (3) can be rewritten as:

$$R_{di,1} \cdot I_i = V^* - V_i - R_{di,n} \cdot I_i^n \tag{4}$$

And finally, Eq. (4) can be expressed as:

$$I_{ref,i} = \frac{V^* - V_i}{R_{di,1}} - \left(\frac{R_{di,n}}{R_{di,1}} \cdot I_i^n\right) \tag{5}$$

where $R_{di,1}$ is the linear droop gain and R_{di} is defined as follows:

$$R_{di} = \frac{\Delta V}{\left(I_{i,\max}\right)^n} \tag{6}$$

where ΔV is the desired voltage deviation from the reference voltage. Moreover, $I_{\max}$ is the maximum output current of each DG.

As illustrated in Fig. 2 (b), it can be concluded that the proposed droop method has both good features of linear and nonlinear droop methods. To put it another way, throughout all loading conditions

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from no-load to full-load for the converters in the DCNG, the proposed method has maximum available droop gain, which is provided good current sharing among DGs.

Moreover, for N-paralleled converters in a DCNG, the relationships of the output current and the virtual resistance can be represented as [12]:

$$I_{o1}R_{d1} = I_{o2}R_{d2} = \cdots = I_{oN}R_{dN} \tag{7}$$

where I_{oi} is the output current of the i^{th} converters. Therefore, the output current of each converter can be regulated by adjusting the virtual resistance based on the power rating of each unit.

B. SoC Estimation

The SoC of the battery in the DG is approximated as follows:

$$SoC_i(t) = SoC_i(0) + \frac{1}{C_i}\int_0^T P_i \cdot dt \tag{8}$$

where $SoC_i(0)$ is the initial state-of-charge for the i^{th} DG, P_i is the output power and C_i is the capacity of the battery. From Eq. (8), it can be concluded that the discharging rate of the ESSs in the DCNG is influenced by the output power and the rated capacity of the ESSs. Therefore, from Eq. (7) and Eq. (8), by adjusting the virtual resistance in the primary control loop, the power-sharing among DGs in the DCNG is achieved based on the SoC and capacity of the ESSs.

C. Dynamic Consensus Algorithm (DCA) in secondary level

A centralized control system suffers from low reliability due to the single point of failure (SPOF) i.e. any failure in the central controller degrades the operation of the entire system. Moreover, in centralized secondary control the two-way communication link between the master agent and all units is required, which increases the cost of the system. To increase the reliability and flexibility of the system and to decrease the number of communication links between agents, and to eliminate the effect of the SPOF, a distributed secondary control based-DCA is proposed. In this method, by exchanging information through communication network between neighboring agents, each unit only communicates the SoC of the ESS. Therefore, each unit updates its SoC reference by providing an equation of its own SoC and neighbors' SoCs. Finally, the SoC of all units can converge to the desired average value of the SoC.

In a connected graph for N-paralleled DGs in a DCNG, each DG is considered as a node and the communication links between two DGs are represented the edges, which can be denoted as $G_{DCMG} = (N, E)$. To ensure the accurate convergence in dynamically changing in communication networks, a DCA can be described as [8]:

$$x_i(k+1) = x_i(0) + \varepsilon \cdot \sum_{j \in N_i} \delta_{ij}(k+1) \tag{9}$$

$$\delta_{ij}(k+1) = \delta_{ij}(k) + a_{ij}.\left(x_j(k) - x_i(k)\right) \tag{10}$$

where x_i and x_j are the states in the nodes i and j, respectively, which $i, j = 1, 2, ..., N, \{i, j\} \in E$. a_{ij} denotes the connection status between node i and node j, $a_{ij} = 0$ if there is no connection between node i and node j. N_i is the number of the agents that can be connected to node i and ε is a constant edge weight, which can be defined to minimize the convergence time for a given network communication as follows:

$$\varepsilon = \frac{2}{\lambda_1(L) + \lambda_{n-1}(L)} \tag{11}$$

where $\lambda_1(L)$ and $\lambda_{n-1}(L)$ are the first and second largest eigenvalue of the Laplacian matrix ($\mathbf{L}$) of the network communication. Additionally, $\mathbf{L}$ can be defined as:

$$L = \begin{bmatrix} \sum_{j \in N_1} a_{1j} & \cdots & -a_{1N_T} \\ \vdots & \vdots & \vdots \\ -a_{1N_T} & \cdots & \sum_{j \in N_T} a_{N_T j} \end{bmatrix} \tag{12}$$

Besides, in Eq. (10), $\delta_{ij}(k)$ stores the accumulative difference between two agents, and $\delta_{ij}(0) = 0$. The final consensus is $x_{ave} = \frac{1}{N}\sum_{i=1}^{N} x_i(0)$ and regardless of any changes to $x_i(0)$, the algorithm will converge to a proper average value [8]. In the proposed

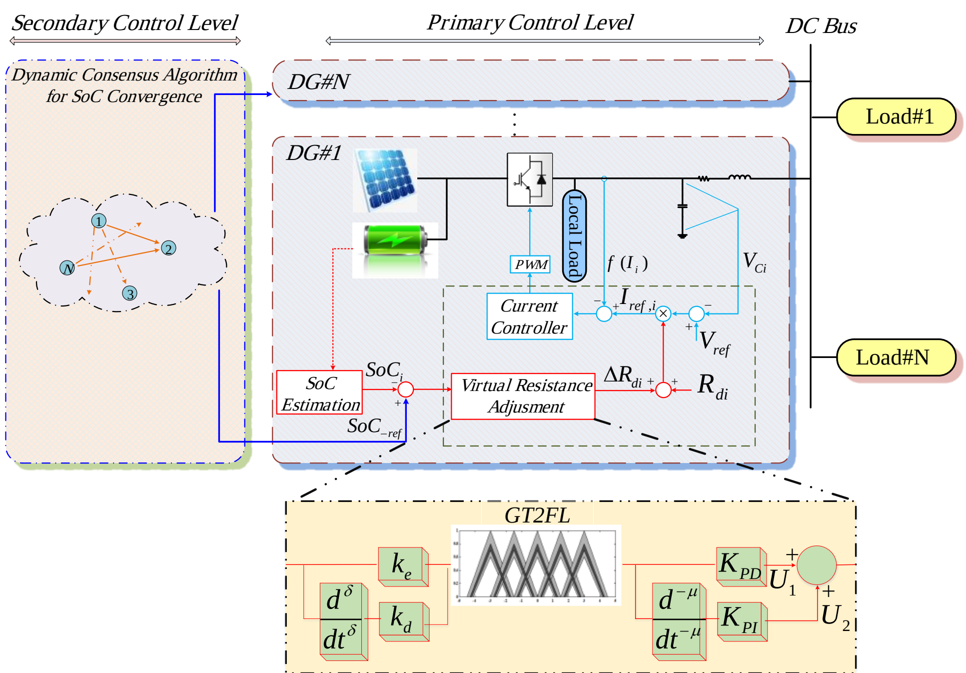

Fig. 3. Proposed DCA-Based distributed control.

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TABLE I
THE MOFOFPID CONTROLLER RULES SET

$\dot{e}$ \ e	NL	NM	NS	PS	PM	PL
S	NL	NM	NS	PS	PS	PM
M	NL	NL	NM	PS	PM	PM
L	NL	NL	NL	PM	PM	PM

method, only the SoC of the units is exchanged between units and therefore recalling Eq. (10) it can be rewritten as:

$$SoC_{ref,i}\left(k+1\right) = SoC_i\left(0\right) + \varepsilon \cdot \sum_{j\in N_i} \delta_{ij}\left(k+1\right) \tag{13}$$

$$\delta_{ij}\left(k+1\right) = \delta_{ij}\left(k\right) + a_{ij}.\left(SoC_j\left(k\right) - SoC_i\left(k\right)\right) \tag{14}$$

where $SoC_{ref,i}$ is the SoC reference of DG-*i*.

The proposed distributed secondary control is depicted in Fig. 3. The DCA is implemented in the secondary control level to find the desired average value of the SoC by exchanging the SoC of units through a communication network. Since the discharge rate of the ESSs according to the capacities of the ESSs in the DCNG are different, the proposed method can balance the discharging rate based on the average value of the SoC. In the proposed control method, the reference of the SoC is calculated by the DCA and the difference between the reference value and the SoC of each DG is sent to a FOGT2FPID controller. The output of the proposed controller is added to the virtual resistance in the nonlinear I-V droop control loop to control the discharging current of the ESS. Thus, the final virtual resistance of the nonlinear I-V droop control can be described as:

$$R_{di,new} = R_{di} + \Delta R_{di} \tag{15}$$

where R_{di} is the initial virtual resistance of the nonlinear I-V droop control for i^{th} converter. Therefore, with respect to the SoC values and different energy storage system capacities of the DGs in a DCNG, by tuning the virtual resistance of the nonlinear I-V droop control, the output current of parallel-connected units can be adjusted properly.

D. Proposed FOGT2FPID Controller

Model-free controllers such as the general type-2 fuzzy logic (GT2FL) controller are very suitable for controlling power systems when finding and deriving the mathematical model of these systems are very difficult [13], [14]. As presented in [15], the GT2FL can consist of several interval type-2 fuzzy logic (IT2FL) sets. Here, a novel fractional order general type-2 fuzzy logic proportional-integral-derivative (FOGT2FPID) controller is proposed, which has the advantages of the GT2FLC and classic PID controller. As shown in Fig.3, the inputs of the GT2FLC are presented by K_d and K_e such that the order of these variables is non-integer. Additionally, K_{PI} and K_{PD} are indicated the outputs of the proposed novel model-free controller, which have non-integer powers. The superiorities of non-integer controllers in comparison to other integer controllers like conventional PIDs are introduced briefly in [16].

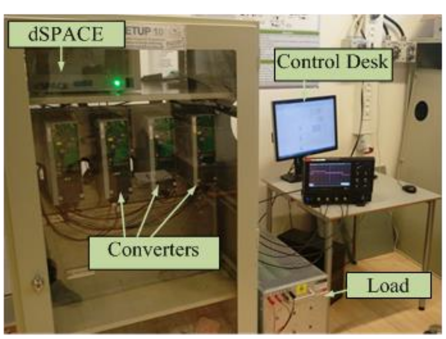

Fig. 4. Experimental setup.

In the proposed method, the powers of the integral (μ) and derivative (δ) are non-integer while in the classic fuzzy logic PID controller these variables are an integer. The architecture of the novel FOGT2FPID is demonstrated in Fig.3.According to Fig.3, the virtual resistance compensation term can be expressed as follows:

$$\Delta R_{di} = U_1 + U_2 \tag{16}$$

It should be noted that if the orders of the inputs and outputs of the proposed method (i.e λ and δ) are selected as one, the suggested controller turns to a conventional controller. The FOGT2FPID rule sets are displayed in Table I. In this table, the fuzzy linguistic variables, which are similar to the input and output variables are classified as (NS), (NM), (NL), (ZR), (PS), (PM), and (PL), referring correspondingly to "Negative Small," "Negative Medium," "Negative Large," "Zero," "Positive Small," "Positive Medium," and "Positive Large." The categorization is based on triangular Membership Functions (MFs) [15].

IV. EXPERIMENTAL RESULTS

To verify the effectiveness of the proposed FOGT2FPID controller and nonlinear I-V droop control method, an experimental setup including three DGs is developed as shown in Fig. 4. The experimental parameters are listed in Table II. The communication links are emulated in SIMULINK and dSPACE. The initial SoC of three DGs is assumed 100% and the minimum threshold of the SoC is equal to 30%. The capacities of the ESSs in DGs are different as $C_1 = 30Wh$, $C_2 = 60Wh$, and $C_3 = 90Wh$. The discharged current rate of each DG is assumed to be 10A.

The experimental results of the conventional control method with equal power sharing are illustrated in Figs. 5(a)-(c). In this scenario, at $t = 100$s , a $400W$ step-up common load is applied in the DC bus and based on the conventional control method for equal power sharing, the discharge rate of the ESSs in DGs are different. In this condition, at $t = 140$s , DG1 with the smallest capacity reaches the minimum threshold of the SoC and shuts down. Therefore, two other DGs participate in common load and at $t = 200$s , the second DG goes off as SoC_2 reaches the minimum threshold. Since DG3 solely provide the required power of the common load, it experiences over-current discharging and a voltage drop below the acceptable range (i.e. $\pm 5\%$ of the reference value) in DC bus is observed.

Additionally, the performance of the proposed DCA-based FOGT2FPID controller is depicted in Figs. 6(a)-(c). In this case, the DCA starts to find the average value of the SoC in the DCNG. Fig. 6(a) indicates that adjusting the virtual resistance in the nonlinear I-V droop control based on the DCA decreases the SoC of three DGs with the same rate from the original value. Furthermore, the output currents of the DGs are different according to the SoC and capacity of the ESSs. All three units reach the minimum threshold of the SoC and shut down simultaneously. Therefore, the over-current discharging is eliminated with the proposed method and the DC bus voltage is stabilized in an acceptable range.

V. CONCLUSION

In this paper, a distributed secondary control based-dynamic consensus algorithm was proposed for the SoC balancing in a DC Nanogrid. In the primary control level, a new nonlinear droop control

TABLE II
PARAMETERS FOR EXPERIMENTAL TESTS

	Description	**Value**
Electrical Parameters	Reference voltage	$48V$
	Input voltage	$24V$
	Converter Inductance	$1000\mu H$
	Converter Capacitance	$2200\mu F$

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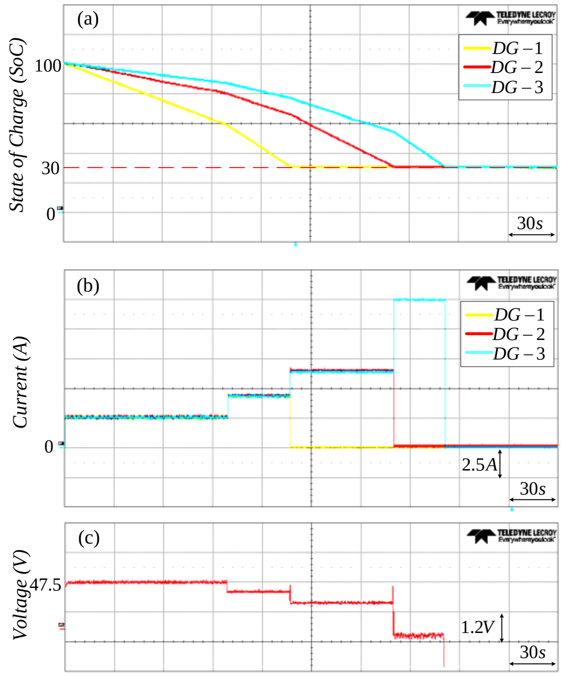

Fig. 5. Experimental results with the conventional droop control method (equal power sharing). (a) SoC of the ESSs, (b) Output current of the DGs, (c) DC bus voltage.

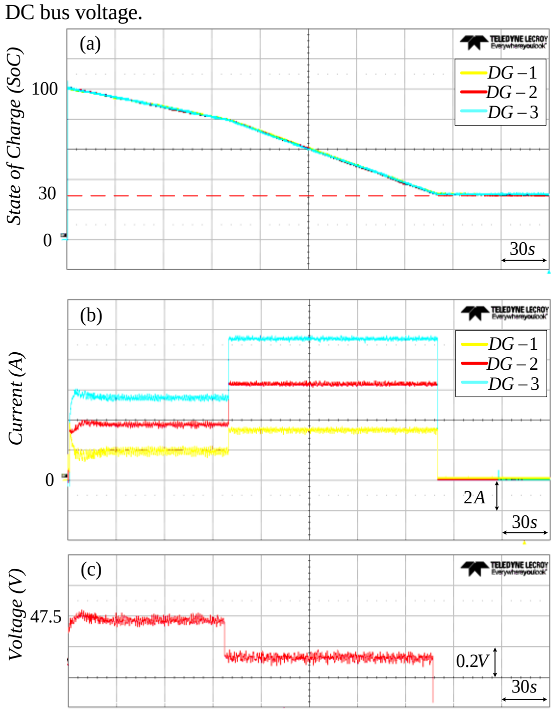

Fig. 6. Experimental results with the proposed controller. (a) SoC of the ESSs, (b) Output current of the DGs, (c) DC bus voltage.

approach was implemented to achieve fast an accurate power-sharing among DGs. In the DCA-based secondary control level, the DGs share the SoC of the ESSs with communication links to adjust the virtual resistance according to their SoCs and capacities. Additionally, a novel high bandwidth fractional order general type-2 fuzzy logic proportional-integral-derivative (FOGT2FPID) controller was presented in the secondary control level to achieve fast and accurate voltage regulation and SoC balancing in the DCNG. The proposed method successfully eliminated the over-current discharge for the ESSs and protected the DCNG against the unexpected disconnection of the DGs. Finally, the effectiveness of the proposed method was validated with experimental results. For the future works, the researchers can investigate the performance of the proposed method on the other loading conditions in the DCNGs such as constant power loads (CPLs). Moreover, the effects of time-delay and cyber-physical attack in the communication network can be studied. The proposed novel model-free controller can be applied for power electronic converters to achieve high-performance and less switch losses.

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