Distributed Secondary Control of Energy Storage Units for SoC balancing in AC Microgrid

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***Abstract*— This paper introduces a new distributed secondary control (DSC) method for distributed energy storage units (DESUs) in an islanded alternative current (AC) microgrid (MG). Dynamics of distributed storages for the extended time duration are not taken into account in the traditional hierarchical control of MG. Thus, it is challenging to control the DESUs with various levels of stored energy represented by the state of charge (SoC). The storage units can utilise their full power capacity after converging to a common SoC to mitigate the generation and demand variations in the MG. SoC depletion of DESUs with lower initial SoC occurs faster than those with higher initial SoC by using the traditional P-*f* droop control and then their capacities are no longer accessible. Furthermore, applying the droop control to match the SoC of DESUs causes the deviation of frequency and voltage from their reference values. However, restoration of the MG frequency using the conventional DSCs disrupts the SoC-balancing. The designed DSC can achieve simultaneous frequency/voltage regulation, power sharing and SoC-balancing as well as removing the centralized communication. The proposed method is evaluated in the established Matlab/Simulink model and the results validate the effectiveness of the proposed method.**

***Index Terms*—Distributed Control, Secondary Control, SoC Balancing, Power Sharing, Multi-Agent System.**

I. INTRODUCTION

Microgrids (MGs) are becoming one of the most significant research topics as the electricity network is transitioning from the conventional generation, transmission and distribution networks to multi-directional, more dynamic action with distributed energy resources (DERs). The MG can offer a suitable solution for the power system stability problem introduced by the high penetration of the DERs [1]. They are also being used in the improvement of power system reliability and resilience, by managing the DERs like wind and solar photovoltaic (PV) generation to provide the sustainable energy solution to rural areas where the centralised electrical networks are unable to serve.

Due to the intermittent nature of DERs and less inertia of power electronic converters, distributed energy storage units (DESUs) are a crucial part of MG for balancing the electricity generation and consumption especially in the islanded mode of operation. Likewise, more than one group of DESUs are demanded to enhance the grid reliability. However, the control system design of an autonomous MG with DESU is one of the critical technologies which must be done accurately as the lack of controllability impacts negatively on the MG performance and efficiency. Recently, the control strategies of MG with DESUs, which also assist as stabilising energy buffers, have been studied by many researchers [2]. The complexity of control structure is even more for the islanded mode in order to confirm the stable and reliable performance of MGs. In general, the main control objectives of DESUs can be summarised as: (i) to preserve the balance condition between generation and load demand, (ii) to regulate the system frequency and voltage, (iii) to balance the state of charge (SoC) of DESUs specially when DESUs with different initial SoC, and (iv) to give the protection of DESUs from power surplus as well as rapid discharging or overcharging.

The operational functionality of standard MG systems with DESUs follow the hierarchical control structure which comprises of the primary, secondary, and tertiary control levels. The power sharing among the DESUs, proportional to their power capacities, can be achieved by the familiar primary droop control technique. However, using the traditional droop control to assist the power sharing among DESUs has some drawbacks. The main limitation is the DESU with lower initial SoC is depleted sooner than the DESU with higher initial SoC, and thus cannot contribute to the power sharing any longer. Besides, operating the DESUs at a low SoC reduces the facility lifetime and efficiency of the DESUs [3]. The SoC of a DESU is also affected by the remaining end period, temperature of the atmosphere, operational competences for the charging and discharging of the DESU.

On the other hand, the deviance of the MG voltage and frequency inversely proportional to the SoC level of the DESU. A droop control of DESU was offered in [4] for active utilisation of the existing stored energy and capacity of the DESU which accomplishes the SoC balancing by applying the SoC-based *P-f* droop control scheme locally in order to extend the service lifespan of DESUs but the constraints of dissimilar capacities in power sharing still exits. Another SoC-based droop control for SoC balancing is presented in [5] to exclude the effect of capacity on SoC balancing and preserve a satisfactory power quality but the dynamic characteristics (plug-and-play) of DESUs are not considered. Authors in [6] emphasised on discharging rates of DESUs for SoC balancing by proposing a coordinated secondary control method based on an independent current-sharing control approach for the islanded alternative current (AC) MGs, but the SoC preserves balancing at the cost of necessitating a centralised communication structure and the control system will be inactive when the centralised communication stops working. Apart from this, the centralised structure limits the scalability, network extension, and the redundancy of the MG. The stability of MG with centralised control is extremely reliant on the communication restrictions and breakdown of the control centre. Moreover, the centralised SoC balancing techniques [6] cannot support the MGs with high penetration of DESUs, due to the restraints in scalability and communication costs.

Distributed controls based on consensus algorithm have recently attracted much attention [7, 8] for attaining the global coordination among DGs. A dynamic consensus algorithm based distributed secondary control (DSC) with the current sharing control approach is suggested in [9] for balancing the discharge rate of DESUs in an islanded AC MG. A distributed multi-agent cooperative control scheme for dynamic energy level balancing among DESUs as a technique to advance frequency regulation and reliability in the droop controlled MGs is recommended in [3]. Authors of [10] introduced a coordinated control scheme to control the charging or discharging of DESUs utilising an arrangement of the local droop-based control strategy and a DSC which guarantees the voltages of feeder persist within an acceptable limit as well as balance the SoC of DESUs, but the shortcomings of different capacities are not resolved. The above reviews show that less research has been considered for the regulation of voltage and frequency along with the SoC balance of DESUs, which becomes a vital issue to be further researched.

This paper proposes a novel DSC scheme utilising the distributed consensus control algorithm to recover the MG frequency and voltage as well as to get the accurate power sharing for SoC balancing through a distributed control architecture, by using the local communications between the neighbouring DESUs of an islanded MG considering the limitations mentioned above. Thus, the cyber resilience of the MG can be enhanced by the proposed controller. The rest of the paper is organised as the following. The MG configuration which includes the preliminaries is represented in Section II. Afterward, Section III describes the proposed DSC for DESUs and Section IV discusses the time-domain simulation results of the proposed DSEUs with case studies. Finally, Section V draws the conclusions and suggests the possible future work.

II. AC MICROGRID CONFIGURATION

A. MG Arrangement with DESUs

Fig.1 illustrates a simple AC MG architecture with three DESUs, which can be considered as a multi-agent system (MAS), and the communication network shown by the blue dashed lines. As shown, three DESUs are connected by the AC bus, where DESU1 and DESU3 are associated with load1 and load2, respectively. Generally, in an MG structure, each inverter interfaced DG or DESUs includes a primary DC power source, a voltage source inverter (VSI), an LCL filter (combining the LC filter with a coupling inductor) and the output filter known as the coupling inductor, as shown in Fig.2. As shown, the power controller allows the DESUs to share the active and reactive power, permitting the maximum ratings based on the droop gain. The dynamic droop characteristic for the i^{th} DESU can be represented as follows:

$$\omega_i = \omega_{ref} - m_{pi} P_i \tag{1}$$
$$v_i = v_{ref} - n_{qi} Q_i \tag{2}$$

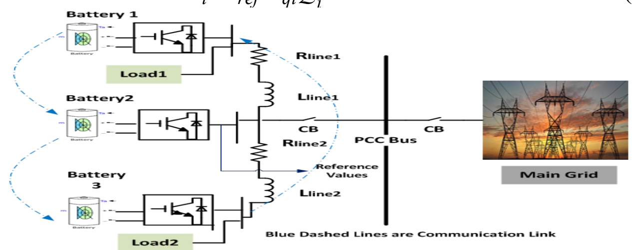

Figure 1. Simple configuration of test MG model

where ω_i and v_i are the angular frequency and voltage amplitude references of the i^{th} DESUs, P_i and Q_i the measured active and reactive power at the output of the i^{th} DESUs, m_{pi} and n_{qi} the droop coefficient for frequency and voltage control of the i^{th} DG units, ω_{ref} and v_{ref} the nominal angular frequency and nominal voltage, respectively.

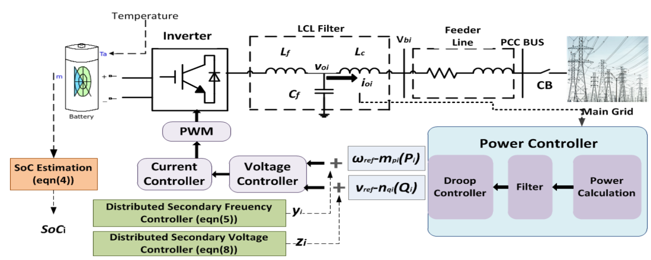

Figure 2. Block diagram of inverter interfaced individual energy storage unit

B. Preliminaries of Graph Theory

A directed graph (digraph) $G = (N_G, E_G)$ with a set of N nodes, $N_G = \{1,2,3,4 \dots \dots N\}$, a set of edges $E_G \subset N_G \times N_G$ and an adjacency matrix $A_G = (a_{ij} \geq 0) \in R^{N \times N}$ is considered, where $a_{ij} = 1$ if there is a path from the i^{th} node to the j^{th} node and otherwise $a_{ij} = 0$. An agent is represented by each node, and each edge (i, j) (pointing from j to i) indicates that the information flows from j to i related with a_{ij}. The neighbors of node i is represented as $N_i = \{j \in N_G: (i,j) \in E_G\}$. According to this, an agent/node i only has access to the data from its neighbors in N_i. If every agent (node) can be represented as a single-state system defined by $\dot{x}_i = u_i$, where u_i is the input as a function of the i^{th} agent's neighboring state $x_j, j \in N_i$, the common form of consensus protocol can be expressed as follows:

$$\dot{x}_i = u_i = -\sum_{j \in N_i} a_{ij}(x_i - x_j)$$

C. SoC Estimation of DESUs

In this paper, estimation of the SoCs of the DESUs is done by using the basic coulomb counting method, and expressed as

$$SoC = SoC_0 - \frac{1}{C}\int \eta i_{dc} dt \tag{3}$$

where SoC_0 is the initial value of the SoC, C symbolises the capacity of the DESU, i_{dc} is the output DC current of the battery, and η the charging/discharging efficiency of the DESU. Let P and v_{dc} denote the DC output power and voltage of the DESU and assuming the power loss of the interfacing VSI is negligible. Then, according to the conservation of energy in the output and input of the VSI, we have $P \approx P_{dc} = v_{dc} i_{dc}$, where P is the active power of VSIs, and the DESU operates with unity efficiency (i.e. η = 1). By the above assumption, the SoC with respect to the DESU output power and the initial SoC value can be represented by

$$SoC = SoC_0 - \frac{1}{C}\int \frac{P}{v_{dc}} dt \tag{4}$$

Therefore, the control of the output active power of the DESUs can deliver the SoC-balancing strategy. However, the power output is primarily affected by the droop coefficient in the traditional droop control methods, which cannot balance the SoCs with different $SoC_0{}'$s. Therefore, the SoC based DSC is needed to overcome the limitations of the primary droop control for DESUs. In the proposed technique, the droop constant of the DESU with higher SoC is virtually reduced in the control loop, which simultaneously increases the output active power of the DESUs and vice versa; and thus the proposed DSC gradually balances the SoCs of DESUs. In addition, energy storage devices are expensive, and their operation needs further attention, especially the SoC level of the battery unit. Thus, the SoC balancing among the multiple DESUs in the MG can help fully utilize the maximum energy capacities of DESUs.

III. DSC FOR SOC BALANCING AND POWER SHARING

According to the primary control introduced in the prior section, the main contribution of secondary control can be achieved by varying the frequency and voltage set points. The goal of frequency and voltage restorations is to control the frequency and voltage of individual DESU back to the reference values, ω_{ref} and v_{ref}, respectively, maintain the MG stability in a balanced operating point at the steady-state, balance the power demand with respect to the SoC_0 initially and balance the SoCs of the DESUs. A second-order system model is formulated and controlled in this section. Each DESU in the MG will be charged or discharged slowly according to its SoC level during the operation. The suggested DSC of DESUs is described in the following subsections in detail.

A. Proposed DSC of DSES for Frequency Restoration, SOC Balancing and Active Power Sharing

The DSC is completed by choosing the angular frequency, ω_i, to the reference frequency, ω_{ref}, synchronously with all the agents performing as a group. Hence, the consensus-based DSC signal for the i^{th} DESU can be written as follows:

$$\begin{aligned} y_i = -G_\omega \int\left[\sum_{j\in N_i} a_{ij}(\omega_i - \omega_j) + b_i(\omega_i - \omega_{ref})\right] - \\ G_{SOC}\int\left[\sum_{j\in N_i} a_{ij}(SoC_i - SoC_j) * sign(P_i)\right] - \\ G_p\left(\sum_{j\in N_i} a_{ij}\big(m_{pi}(P_i) - m_{pj}(P_j)\big) * sign(P_i)\right) \end{aligned} \tag{5}$$

where y_i is the secondary control signal for frequency restoration, SoC balancing and active power sharing. G_ω, G_{SoC} and G_p are the DSC gains. It should be noted that, in (5), b_i=1 if the i^{th} DESU is directly connected with the point of common coupling and otherwise $b_i = 0$. Adding the control signals in (5) to (1), we can express the resultant inverter reference frequency as:

$$\omega_i = \omega_{ref} - m_{pi}(P_i) + y_i \tag{6}$$

Proposition 1: The proposed DSC (6) restores the drooped frequency of the MG to the nominal value, shares the active power among the DESUs (i.e. $\forall i$, j: $m_{pi}P_i = m_{pj}P_j$), and balances the SoC of the DESUs (i.e. $\forall i, j$: $SoC_i = SoC_j$), in a distributed manner based on the leader–follower system.

B. Proposed DSC of DSES for Voltage Restoration

The DSC for voltage restoration is completed by adding the control input z_i to the primary control in order to restore the voltage to the reference value v_{ref} synchronously with all the agents performing as a group. Hence, the consensus-based DSC signal for the i^{th} DESU can be written as follows, where G_v is the DSC gain for voltage restoration:

$$v_i = v_{ref} - n_{qi}Q_i + z_i \tag{7}$$

$$z_i = -G_v \int\left[\sum_{j\in N_i} a_{ij}(v_i - v_j) + b_i(v_i - v_{ref})\right] \tag{8}$$

IV. TIME-DOMAIN SIMULATIONS

To validate the recommended control, the simulation of test MG is performed based on MATLAB/Simulink platform as in Fig. 1. The simulations have been performed considering that the MG runs in the islanded mode. The AEMO power quality obligations are used as the working standards for the control arrangements, which includes a frequency range of 49.5Hz to 50.5Hz [11] and a voltage magnitude range of -6% to +10% [3]. The test MG parameters are given in Table I and the parameters of filter, voltage and current controllers are same as those in [8]. The DSC parameters are listed in Table II. The initial SoCs of DESUs 1-3 are chosen with different values from each other intentionally as [90%, 80%, 70%] while the capacities are the same (except in case 5). It is needed that during the discharging mode, the DESU with higher SoC will deliver more power than the others and. The proposed DSC is active from the beginning. Several scenarios are considered through different case studies as the follows:

Case 1: Frequency and voltage restoration with SOC balancing by the proposed DSC

The performances of the primary droop control (1) and (2) are shown in Figs. 3(a)-3(d). As shown, with only the primary control, the frequencies deviate to 49.38 Hz and the voltages of 3 DGs deviate to different values from the reference value (311V). Fig. 3(c) shows that the active power sharing is based on their capacities and Fig. 3(d) the SoCs of DESUs, which are unbalanced when DESUs use the conventional *P-f* droop control. Figs. 4(a) and 4(b) show that the proposed DSC can give fast response to restore the deviated frequencies and voltages to the nominal values. Moreover, Fig. 4(c) shows that the active powers converge to the same value after the SOCs are balanced at *t*=50s and Fig. 4(d) indicates that the SoCs of all DESUs tend to be balanced.

Case 2: Performance of the proposed DSC with the step load change

The suggested DSC is tested with the step load change.

TABLE I. SPECIFICATIONS OF TEST MG

Description	Parameter	Value	Unit
DC bus Voltage	V_{dc}	700	V
Nominal Voltage	v_{ref}	311	V
Nominal Frequency	f_{ref}	50	Hz
Capacities of DESUs	$C_1 = C_2 = C_3$	200	Ah
Active Power Droop Gain	$m_{p1} = m_{p2} = m_{p3}$	$4e^{-5}$	rad/W
Reactive Power Droop Gain	$n_{q1} = n_{q2} = n_{q3}$	$2.6e^{-5}$	V/Var
Impedance of Line1	R_{line1}, L_{line1}	0.23, 318	Ω, μH
Impedance of Line2	R_{line2}, L_{line2}	0.12, 312	Ω, μH
Impedance of Load1	R_{load1}, L_{load1}	18, 10	Ω, mH
Impedance of Load2	R_{load2}, L_{load2}	22, 12	Ω, mH

TABLE II. SECONDARY CONTROLLER PARAMETERS

Controller Parameters	Values
Frequency Gain, G_ω	25
Voltage Gain, G_v	25
Active Power Gain, G_P	15
SoC balancing Gain, G_{SoC}	5

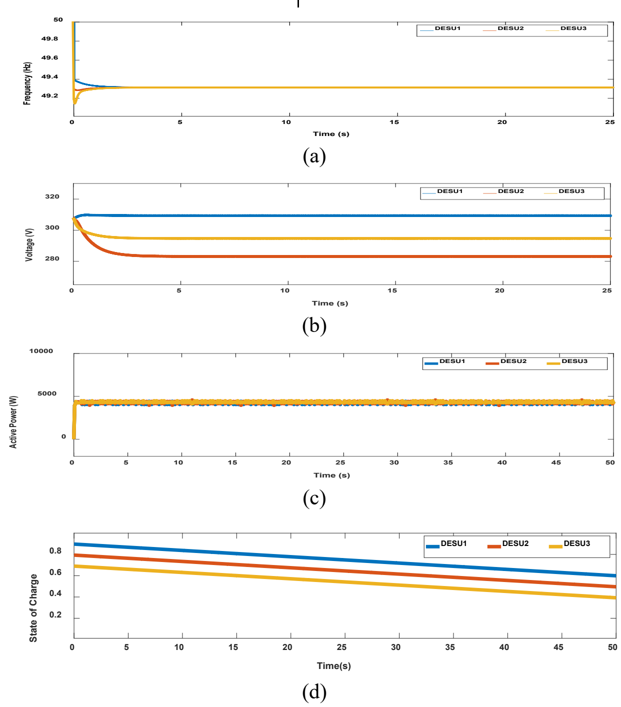

Figure 3. Output of DESUs under only primary control (Droop Control) (a) Frequencies (b) Voltages (c) Active Powers and (d) State of Charge

Initially, loads 1 and 2 are connected to the system. After reaching the steady state, load 3 ($R_{load3} = 10\Omega, L_{load3} = 6mH$) is added with load 2 at t=55s and is disconnected at t=65s. Simulation results in Figs. 5(a) and 5(b) indicate that the proposed control technique can accomplish power sharing and SoC control (SoC decreases faster during the increase in load) under the step load change.

Case 3: Plug-and-play operation of the proposed DSSC.

Plug-and-play ability of the suggested distributed control method is presented in Fig. 6, where DESU 1 is disconnected at t = 70s. The frequency is controlled after a fast transient. The load is then shared between the remaining DESUs (batteries 2 and 3), and the SoC levels are still balanced for the remaining DESUs.

Case 4: Effect of measurement noise

The effect of measurement noise on the performance of the control system is displayed in Figs. 7(a)-7(b). Here, we assume that the output active power, reactive power, voltage, and frequency measurements of every DESUs are disturbed by distinct band-limited white noises with the power spectrum of 10, 2 and 0.1 respectively. The simulation results in Fig. 7 show that the proposed DSC can operate with measurement noises, restore the voltage and frequency to the reference values, and maintain the stability at steady-state.

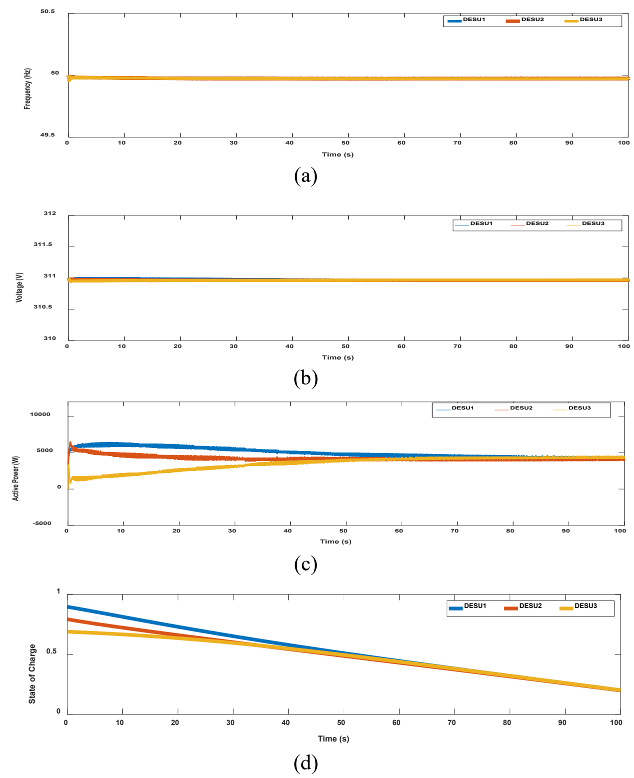

Figure 4. Output of DESUs after applying proposed DSC in DESUs (a) Frequencies (b) Voltages (c) Active Powers and (d) State of Charge

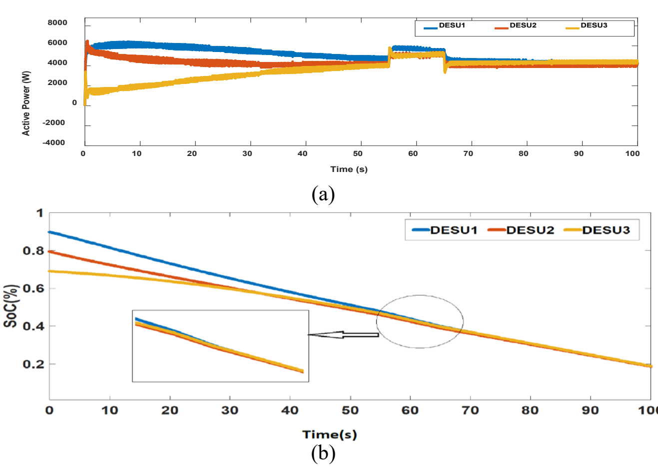

Figure 5. Output of DESUs after applying proposed DSC in DESUs with step load change (a) Active Powers and (b) State of Charge

Case 5: SoC balancing of DESUs with different capacities

The performance of the proposed control scheme for DESUs with different capacities are shown in Fig. 8. Fig. 8(a) illustrates that the DESUs share the active power in accordance with their capacities (ratios are $DESU_1:DESU_2:DESU_3$=2:2:1) after SoC balancing at t=50s. The SoC balancing can also be achieved when the DESUs with different capacities are controlled by the proposed scheme.

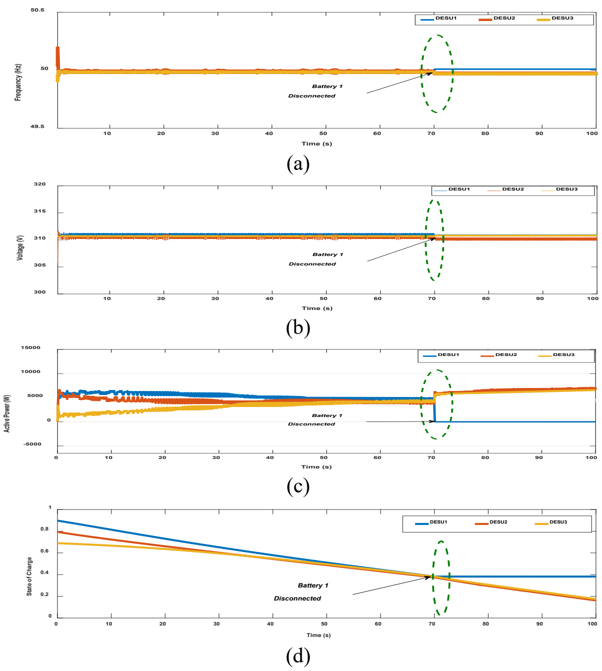

Figure 6. Output of DESUs with proposed DSC in DESUs with plug-and play (a) Frequencies (b) Voltages (c) Active Powers and (d) State of Charge

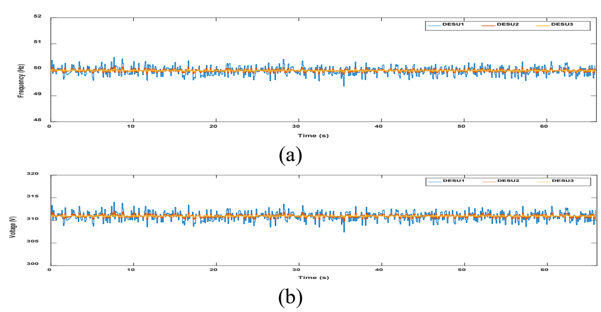

Figure 7. Output of DESUs after applying proposed DSC in DESUs with measurement noise (a) Frequencies and (b) Voltages

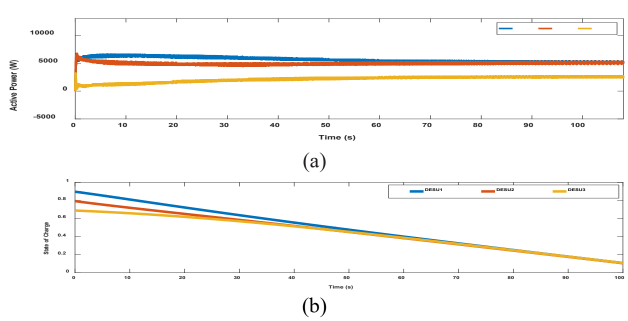

Figure 8. Output of DESUs with different capacities after applying the proposed DSC (a) Active Powers and (b) State of Charge

V. Conclusion

In this paper, a novel DSC is established for mitigating the frequency and voltage deviations and SoC balancing for the DESUs in the islanded MG as well as active power sharing mismatch caused by the droop-based primary control. The performance of the proposed DSC of DESUs are verified by several numerical case studies considering the dynamic behaviour of MG like step-load change, plug-and-play capability, act with random measurement noises as well as different capacities of batteries for SoC balancing of DESUs. The proposed DSC exhibits smooth transient response in restoring the voltage and frequency of the MG, sharing the active power, and balancing the SoCs of DESUs. Protection of DESUs from rapid discharging or overcharging in accordance with the power demand or surplus would be the extended work of this research. Also the detailed stability analysis considering the DSC and effects of controller gains is considered as the promising work for future.

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