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by Dhafer Mayoof Dahis

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a Novel Communication-Free Control Method for Eliminating DC Microgrid Shortcoming

Dhafer Mayoof Dahis
Southern Technical University, Iraq
Eng.dafir@stu.edu.iq

Abstract. *High voltage deviation, State of charge (SOCs) divergence, and inappropriate load/power sharing are some challenges that DC microgrids face. These problems can be rectified easily if the control algorithm is designed based on the other units' data. However, utilization of communication links has some disadvantages which make them improper in many cases. Regarding that, in this paper, a novel communication-free control method is presented. In this method, the droop gain is divided into two parts. The first part of the droop gain is selected according to the line resistance in such a way, that the effect of line resistance on current sharing is omitted, while the second part is considered for balancing SOCs. Regarding that, it is defined as a function of SOC such that the higher SOC unit injects more and absorbs less current. Comparing the simulation results of the proposed method with other methods proves that the proposed method can balance SOCs and reduce the DC bus voltage deviation like the SOC-based method. Besides, it can share current properly like the virtual resistance method.*

Keywords: *Renewable energy sources (RES), DC microgrid, SOCs balancing, current sharing, Voltage recovery*

1. INTRODUCTION

Many problems such as environmental issues, increase in the need of industries for energy, enhancing fuel costs, and reduction in fossil fuel resources force countries to pay more attention to renewable energy sources (RES). Among the RESs wind and solar are more attractive because they have low maintenance costs, a wide range of capacity, fast return on investment, accessibility, etc. [1,2].

The power produced by the RESs has fluctuations as the nature of the wind speed, solar irradiance, and temperature changes. In this condition, the RES influences the grid power quality or in the worst case it may lead it to instability. Besides, during night and when the wind speed is very low, they cannot inject any power into the grid. As a result, another source of power should be considered to satisfy the loads. Regarding these matters, it is suggested to use at last an energy storage system (ESS) along with RESs to absorb power fluctuations in case of power variations and to satisfy the loads when RESs power is too low.

The set of RESs, loads, and ESS introduces a new concept called 'microgrid'. The microgrid can operate in both the grid-connected and islanded modes. In grid-connected mode, the ESS just absorbs the power fluctuation and regulates its SOC while in islanded mode it is responsible for satisfying the load demand and the microgrid power quality.

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* *Dhafer Mayoof Dahis , Eng.dafir@stu.edu.iq*

When the microgrids are far from the utility grid, they can have different frequencies. Many loads such as LEDs, motors drive, TVs, computers, and energy storage units (ESU) like batteries, capacitors, SMEs, and some RESs as PVs are more compatible with DC systems. In this condition, if the CD microgrid is designed for the system more benefits can be obtained. Generally, DC microgrids have higher reliability, more flexibility, expandability, and efficiency. Additionally, they are free from expected problems such as frequency, phase, harmonic, synchronization, and reactive power. They are the reasons why the DC microgrids are preferred more in recent years [3-6].

Along with these benefits, the DC microgrids suffer from some disadvantages, the most critical of them are [7-9]:

SOCs divergence
Imbalance ESUs loading
High DC bus voltage deviation

Many control methods are introduced in the literature to address these shortcomings. Totally, these methods are classified into three categories. They are, centralized, distributed and decentralized.

In centralized methods, all units set their current via a droop or a PI controller to prevent system instability [10-12]. After that, the central controller adjusts the ESU operation point according to the data collected from the loads, RSSs, and all ESUs. For instance, in [13] a robust control method is presented in which a central controller calculates the power of ESUs and RESs such that not only the stability is ensured but also the microgrid power quality is satisfied when the communication system faces with some delay. In [14] a central controller calculates the load power (EVs charge power) and ESUs current and regulates the voltage of DC bus according to the microgrid status, ESUs SOC, and electricity price. In [15] a central controller determines the ESUs operation point through an optimization process based on the data collected from the ESUs. In this method, If ESUs cannot satisfy the microgrid requirements, the central controller warrants the system stability by reducing the generation power and disconnecting some inessential loads. As can be seen, these methods rely on communication links and central controllers which makes them more expensive, less flexible and expandable, and more effective against cyber attacks.

Similar to the centralized methods, distributed methods use local parameters in the first layer of their control algorithm. Next, all units exchange some information with their neighbors. After that, all ESUs manipulate their operation point according to the neighbor's data and predefined aims (SOCs balancing, proper current sharing, and Voltage recovery). The more data exchanges between ESUs, the more aims can be defined for units [16-18].

For example, in [19-20] only the data of SOCs are communicated. Hence this method only can balance SOCs. As the SOCs variation is not too fast, therefore a low bandwidth communication link can be utilized which has less cost. In [21-22] the voltage and SOCs are exchanged which means that these methods can regulate the DC bus voltage drop along with balancing ESUs SOC. The authors in [23-24] suggest methods that can load ESUs properly and reduce DC bus voltage drop with a communication system that only transfers ESUs current. In [25-26] both the ESUs current and SOC are communicated therefore these methods benefits of proper current sharing and SOCs convergence. It should be noted the communication systems used in [25-26] are stronger than the system used in [19-22] as they are exchange more data. Resultantly they are more expensive and complicated.

Similar to the centralized method, distributed methods are dependent on communication systems which make them inappropriate for widespread DC microgrids where the units are far from each other. Besides they have low expandability, flexibility, reliability and lack of plug and play capability and high cost and complexity.

To get rid of the problems associated with communication-based methods, Many researchers suggest methods which are not rely on other units data. The conventional droop is one of them. In this method, the unit voltage is set according to its current, and the droop gain depends on the unit capacity and allowable DC bus voltage drop [27].

The conventional droop cannot balance SOCs as they are not involved in the ESUs power specification. A cluster of droop methods called SOC-based method are introduced to tackle this problem. In these methods, the droop gains are adaptively changed according to the SOCs such that the higher SOC units absorb less and inject more current. Exponential, inverse, and linear are some of the functions that can be defined for the droop gain [28-30].

The SOC-based methods rectify the problem of SOCs disparity and diminish the voltage deviation, but they deteriorate the current sharing when the SOCs are low and ESS is charging or SOCs are close to the upper limit and the microgrid faces power deficiency [31-32].

Many searchers refer to improper ESUs loading. Therefore, many solutions suggested in the literature can be classified into several categories.

A group of methods called DC bus voltage signaling is suggested in [33-35]. In these methods, the DC bus voltage is used as a signal and the ESUs and RESs operation mode (CCM or VCM) and their reference current are specified according to this signal. Low power quality, inappropriate reliability indices, and reducing RESs absorbed power are of these methods' drawbacks. Nonlinear and piecewise droop curves are suggested in [36-40] where the droop gains are set according to the current such that the improper current sharing and voltage deviation only improved in the high and low current respectively.

Signal injection is another technique to solve the DC microgrid shortcoming [41-43]. In this method, a sinusoidal current is injected into the DC bus. After that, all units update their operation point to enhance the microgrid performance. Deteriorating DC bus power quality, requiring lines data, affecting the method accuracy by the loads and RESs, and needing high-accuracy sensors are of these methods drawbacks.

As the improper current sharing is established by the lines resistance, it is suggested in the virtual resistance methods that the droop gain is selected based on this parameter and allowable voltage deviation [44-46]. Resultantly, this class of methods tackles the effect of the lines resistance and loads ESUs proportionally. It should be noted in these methods neither SOCs balancing nor voltage deviation reduction is considered. A summary of the advantages, disadvantages, and capabilities of each method is presented in Table 1.

Table I: A comprehensive comparison of the literature on DC microgrids

	Ref	**Proper current sharing**	**SOCs balancing**	**Voltage deviation reduction**	**Communication free**	**Main disadvantages**
Centralized		✓	✓	✓	×	High cost-low reliability, flexibility, and expandability
Distributed		✓	✓	✓	×	High cost-low reliability, flexibility, and expandability
SOC based	[28-30]	×	✓	×	✓	High current deviation in charge (discharge) mode when SOCs are low (high)
DC bus voltage signaling	[33-35]	×	×	×	✓	Non-optimal utilization of RES-Improper reliability indices, Low power quality
Non-linear droop	[36-38]	✓	×	✓	✓	Over-using ESUs are connected to the

						DC bus with low resistance
Piecewise droop	[39-40]	✓	×	✓	✓	Over-using ESUs are connected to the DC bus with low resistance
Signal injection	[41-43]	✓	×	✓	✓	Complexity-Low power quality-requiring high accuracy sensors, affected by loads
Virtual resistance	[44-46]	✓	×	×	✓	-----
Proposed method		✓	✓	✓	✓	------

As can be seen, some of these methods like SOC-based methods solve the problem of SOCs balancing but they don’t improve voltage deviation and, in some cases, they deteriorate current sharing. In the contrary, some methods like virtual resistance improve current sharing but don’t have any effect on SOCs balancing and voltage deviation reduction. Regarding these matters in this paper a method is considered that cover the shortcoming of the both the virtual resistance and SOCs balancing methods. The main achievements, including contributions of the proposed method, can be summarized as follows.

- The proposed method manipulates the current of ESUs according to their SOCs in both the charge and discharge mode to benefit SOCs balancing capability.
- A part of the droop gain is considered for rectifying the effect of the line resistance. Through this part, the proposed method is equipped by the proper current sharing.
- Compared to the other communication-less methods, the proposed method has less voltage deviation.
- The proposed method does not require other units of data (communication-free), which means that it is proper for geographically dispersed DC microgrids.

The rest of this paper is structured as follows. The system structure and the problems engaged with the DC microgrids are explained in section 2. The proposed control method is presented in section 3. Section 4 is considered to perform the performance of the proposed method. Besides some comparisons are made which involved into this section. Finally, section 5 concludes the paper.

2. System Description and Problems Explanation

DC microgrid is a set of some DGs, Loads, and ESUs connected to a common DC bus. DGs feed the loads through the DC bus and their mismatch is absorbed from or injected to the ESUs. The general structure of a wide spread DC microgrid is depicted in Fig. 1.

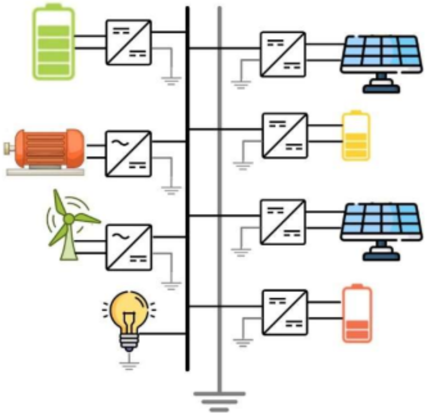

Fig. 1: A typical DC microgrid

Whether the microgrids are equipped by the communication system or not, they should be controlled by the local parameters first of all to prevent system instability in case of load or power variation. A droop controller can satisfy this requirement. Regarding that the voltage of the unit is specified by (1).

$$V_i = V_{ref} - R_i^{droop} I_i \qquad (1)$$

Where, V_i and V_{ref} are the output and nominal voltage, I_i is the injected current, and R_i^{droop} is the droop gain calculated according to allowable voltage deviation ($\Delta V_{\max}$) and the unit capacity (I_i^{nom}).

$$R_i^{droop} = \frac{\Delta V_{\max}}{I_i^{nom}} \qquad (2)$$

Fig. 2 shows a simplified electrical model of a DC microgrid composed of 2 ESUs with the same capacity. The loads power is more than that of the RESs which means that ESUs are discharging.

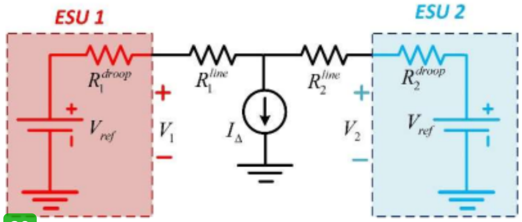

Fig. 2: Electrical model of a simplified DC microgrid

The units current share is calculated by (3).

$$I_i = \frac{I^{nom} R_j^{line} + \Delta V_{\max}}{I^{nom}(R_i^{line} + R_j^{line}) + 2\Delta V_{\max}} I_\Delta \qquad (3)$$

As can be seen, the unit connected to the DC bus via less impedance exchanges more current. Therefore, it reaches its upper and lower limit faster during charge and discharge modes, respectively (SOCs divergence).

Fig. 3 shows the DC bus voltage deviation versus units current.

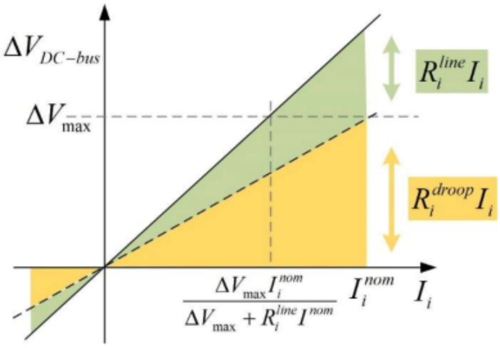

Fig .3: DC bus voltage deviation in terms of ESUs current for conventional droop

As can be seen, when the units current is high, the voltage of the DC bus leaves its allowable are. Based on Fig. 2 and equations (1) and (2), when the units current is greater than $\Delta V_{\max} / (\Delta V_{\max} + R_i^{line} I^{nom})$, the voltage of the DC bus passes its limits.

By changing the droop gain, both the proper current sharing and keeping DC bus voltage in the permissible area can be obtained. Based on figure (2) and Equation (1), if the droop gains are defined according to (4), the current will be shared properly. In this condition, the units current share is exactly half of the I_Δ. For the microgrids which have more ESUs with different capacities, the units current is calculated by (5).

$$R_i^{droop} = \frac{\Delta V_{\max}}{I_i^{nom}} - R_i^{line} \qquad (4)$$

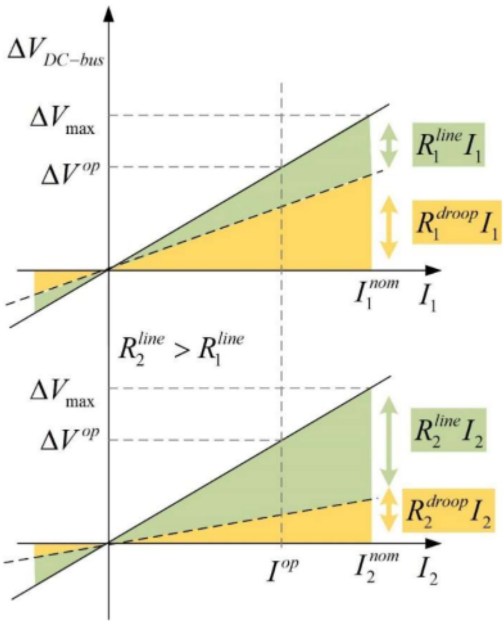

Fig. 4: DC bus voltage deviation in term of ESUs current in virtual resistance method

$$I_i = \frac{I_i^{nom}}{\sum_{j=1}^{N} I_j^{nom}} I_\Delta \qquad (5)$$

The DC bus voltage drop is expressed by (6).

$$\Delta V_{DC-bus} = \frac{I_\Delta}{\sum_{j=1}^{N} I_j^{nom}} \Delta V_{\max} \qquad (6)$$

As the DC bus voltage drop is the same for both ESUs, reducing the droop gain of a unit will increase its current portion. Therefore, to have SOCs balancing capability, the higher SOC unit should have higher droop gain during the charge period and less droop coefficient in discharge mode. Resultantly, the droop gain should be defined as a function of SOC. An equation which meets these requirements is expressed in (7).

$$R_i^{droop} = M_i \begin{cases} SOC_i^2 & \Delta V_{DC-bus} > 0 \\ DOD_i^2 & \Delta V_{DC-bus} < 0 \end{cases} \qquad (7)$$

Where DOD is depth of discharge calculated by (8)

$$DOD = 1 - SOC \qquad (8)$$

The value of M_i should be determined such that for all values of SOC, the voltage of DC bus stays in the permittable area. Hence, the value of M_i must be set based on (9):

$$M_i = \min\{\frac{\Delta V_{\max} - R_i^{line} I_i^{nom}}{I_i^{nom} SOC_{\max}^2}, \frac{\Delta V_{\max} - R_i^{line} I_i^{nom}}{I_i^{nom} DOD_{\max}^2}\} \qquad (9)$$

As $SOC_{\max}$ and $DOD_{\max}$ are 0.9 and 0.8 respectively, therefore the value of M_i is determined by (10).

$$M_i = 1.23(\frac{\Delta V_{\max}}{I_i^{nom}} - R_i^{line}) \qquad (10)$$

Figure (5) shows the operation point of unit j for different values for SOC$_j$.

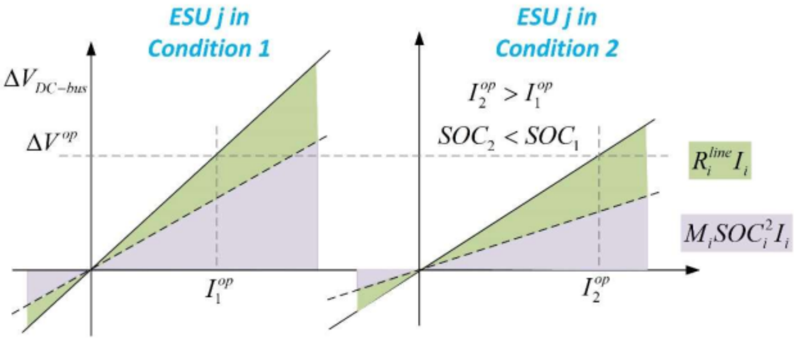

Fig. 5: The operation point of i$_{th}$ unit for different values for SOC$_i$

As can be seen in charge mode, the units current portion increases as their SOC stands lower. Substituting (10) in (7) and the result in (1) reveal that, for the microgrid presented in (1), the units relative current is determined by (11)

$$\frac{I_1}{I_2} = \begin{cases} \dfrac{1.23(\Delta V_{\max} / I_2^{nom} - R_2^{line}) SOC_2^2 + R_2^{line} I_2^{nom}}{1.23(\Delta V_{\max} / I_1^{nom} - R_1^{line}) SOC_1^2 + R_1^{line} I_1^{nom}} & \Delta V_{DC-bus} > 0 \\ \dfrac{1.23(\Delta V_{\max} / I_2^{nom} - R_2^{line}) DOD_2^2 + R_2^{line} I_2^{nom}}{1.23(\Delta V_{\max} / I_1^{nom} - R_1^{line}) DOD_1^2 + R_1^{line} I_1^{nom}} & \Delta V_{DC-bus} < 0 \end{cases}$$

(11)

Based on (11), the units have the same current when (SOC$_1$=SOC$_2$=0.9 and ESUs are charging). In other cases, the microgrid does not benefit from proper current sharing.

for the microgrid presented in Fig. 2, although the SOCs balancing are achieved and DC bus voltage deviations are controlled, but current sharing is deteriorated when SOCs are not SOC_{max}.

As can be seen, all these methods cannot bring together, SOCs balancing, current sharing, and voltage deviation improvement.

3- PROPOSED METHOD

Figure 6 shows a geographically dispersed DC microgrid composed of several ESUs controlled by the droop controller.

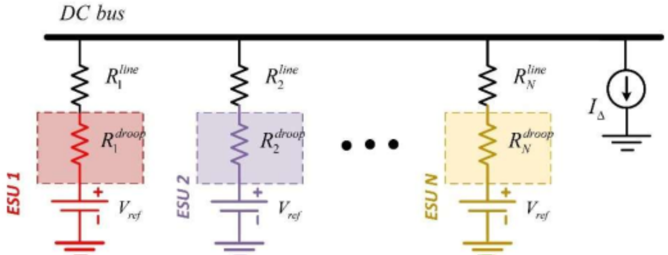

Fig. 6: A simplified geographically dispersed DC microgrid

Each ESU is connected to the DC bus through R_i^{eq}, where R_i^{eq} is:

$$R_i^{eq} = R_i^{line} + R_i^{droop} \qquad (12)$$

Where R_i^{droop} in the conventional droop, virtual resistance, and SOC-based method is calculated by (2) , (4), and (7), respectively. Figure (7) shows units R_i^{eq} for different methods.

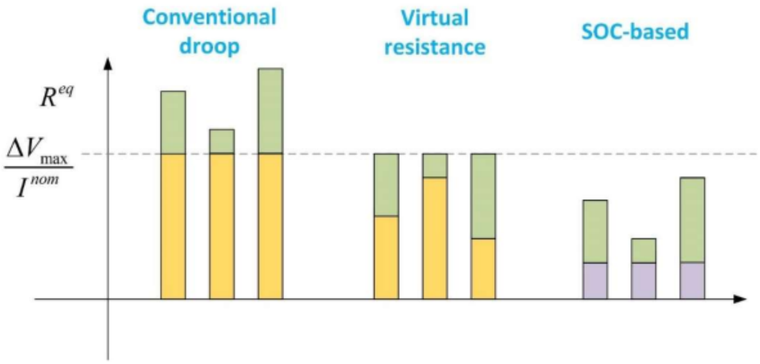

Fig. 7: R_i^{eq} for different methods

According to Fig. 7, in the conventional droop the value of R_i^{eq} is more than $\Delta V_{\max} / I^{nom}$. Thence, in some cases, especially when the units current is close to the nominal, the voltage of DC bus passes its limit. In virtual resistance the value of R_i^{eq} is $\Delta V_{\max} / I^{nom}$ which means that this method always keeps the voltage deviation less than its maximum till the current is less than its nominal. In the SOC-based method, the value of R_i^{eq} is less than $\Delta V_{\max} / I^{nom}$, therefore the DC bus voltage always experiences less voltage deviation in comparison with other methods. In other words, the SOC based method not only controls SOCs but also reduces the DC bus voltage deviation dependent on the SOCs. The more/less the ESUs SOC in discharge/charge mode is, the less the voltage deviation will be.

Another point is that only the virtual resistance has the same R_i^{eq}. Therefore, only the virtual resistance can share current properly. In other methods the proper current sharing depends on the lines resistance.

By taking a deeper look to the results, it can be concluded that virtual resistance rectifies the SOC-based method disadvantages while SOC-based method covers the virtual resistance shortcomings. To benefit of these methods capability, the units droop gain is divided into two parts. The first one is considered to rectify the effect of lines resistance like virtual resistance method while the second is defined in the function of SOC to balance SOCs. Resultantly, the value of the R_i^{eq} is:

$$R_i^{eq} = R_i^{line} + R_i^{cmp} + R_i^{b\ln} \qquad (13)$$

Where R_i^{cmp} is a part of the droop gain which compensate for the lines resistance difference while $R_i^{b\ln}$ is another part that is responsible for balancing SOCs calculated by (14). Fig. 8 shows R_i^{eq} for the proposed method.

$$R_i^{b\ln} = M_i^{'}\begin{cases} SOC^2 & \Delta V_{DC-bus} > 0 \\ DOD^2 & \Delta V_{DC-bus} < 0 \end{cases} \qquad (14)$$

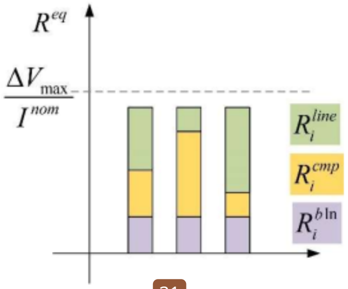

Fig. 8: R_i^{eq} in the proposed method

Selecting a high value for $R_i^{b\ln}$, increase the units current share difference when their SOC is different. As a result, the SOCs convergence speed will be enhanced. Besides, it reduces the DC bus voltage deviations. On the other side, the system stability will be improved if

$R_i^{line} + R_i^{cmp}$ is high. As can be seen, increasing the SOCs balancing speed (mimicking DC bus voltage deviation) and improving the system stability are in conflict. Therefore, a trade-off should be made to specify a proper value for each of them. Fig. 9 shows two system with different values for R_i^{cmp} and $R_i^{b\ln}$.

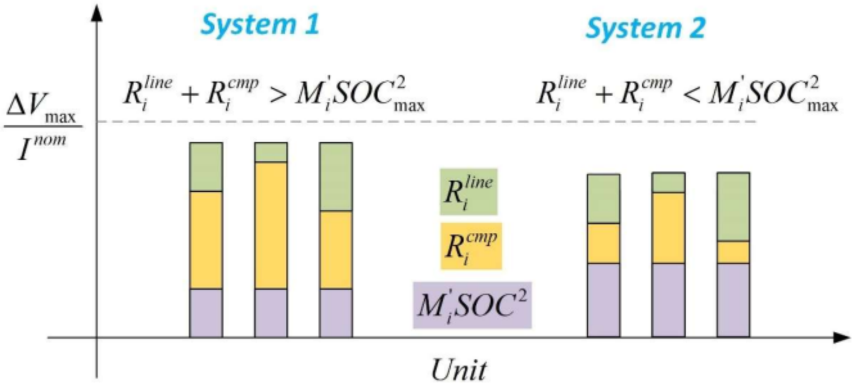

Fig. 9: R_i^{eq} for different values of $M_i^{'}$

According to the abovementioned, system 1 has more stability while system 2 has less voltage deviation and more SOCs balancing speed.

Considering half of the allowable voltage deviation for balancing SOCs and the other half for the current sharing is a reasonable choice. Regarding that, the value of the R_i^{cmp} and $M_i^{'}$ are determined by (15) and (16).

$$R_i^{cmp} = \frac{0.5\Delta V_{\max}}{I_i^{nom}} - R_i^{line} \qquad (15)$$

$$M_i^{'} = \frac{0.72\Delta V_{\max}}{I^{nom}} \qquad (16)$$

By assuming the above values for R_i^{cmp}, and $M_i^{'}$, the value of the DC bus voltage deviation is determined by (17).

$$\Delta V^{DC-bus} = \begin{cases} \frac{0.5\Delta V_{\max} I_i}{I_i^{nom}}(1+1.23SOC_i^2) & \Delta V^{DC-bus} > 0 \\ \frac{0.5\Delta V_{\max} I_i}{I_i^{nom}}(1+1.23DOD_i^2) & \Delta V^{DC-bus} < 0 \end{cases} \qquad (17)$$

By considering the nominal current for all units and different values for their SOC, the DC bus voltage deviation always change in range of 0.51 to 1 of the $\Delta V_{\max}$. The least voltage deviation belongs to the condition that all SOCs are on top and ESUs are discharging. In contrast, the DC bus voltage deviation is maximum when ESUs are charging and SOCs or on top.

4-SIMULATION RESULTS

In this section, the proposed control method is simulated. To have a proper evaluation along with the proposed method, conventional droop, SOC-based, and virtual resistance methods are simulated and some comparisons are made. Besides, another section is added to investigate the effects of the value of $R_i^{b\ln}$ and R_i^{cmp} on the system performance and the microgrid power quality.

The simulated system structure and its parameters are expressed in Fig. 10 and Table II.

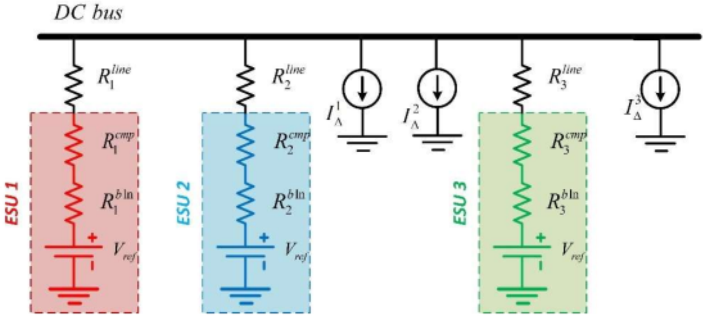

Fig. 10: the simulated system topology

Table II: the simulated system parameters

parameter	ESU1	ESU2	ESU3
Capacity (kVAh)	20	20	20
$R^{line}(\Omega)$	0.5	0.3	0.2
$R^{cmp}(\Omega)$	0.12	0.32	0.42
Initial SOC (%)	60	30	30
$R^{droop}(\Omega)$ virtual resistance	0.75	0.95	1.05
$R^{droop}(\Omega)$ conventional	1.25	1.25	1.25
M_i (Ω) SOC-based	0.92	1.17	1.29
$M_i^{'}$	0.76	0.76	0.76
SOC range (%)	20-90	Vref (Volt)	500
ΔV_{max}(Volt)	50		

Section I: Evaluating the Proposed Method Capability

Fig. 11 shows the current absorbed from or injected to the DC bus by I_{Δ}^{i}. A positive (negative) value for I_{Δ}^{i} means that a load (RES) is connected to this point. It is obvious that during the first (second) half of the simulation time, the loads power is less (more) than that of the RESs, therefore, from (0 to 30 min) ESS is charging while in (30 to 60 min) time interval it is discharging.

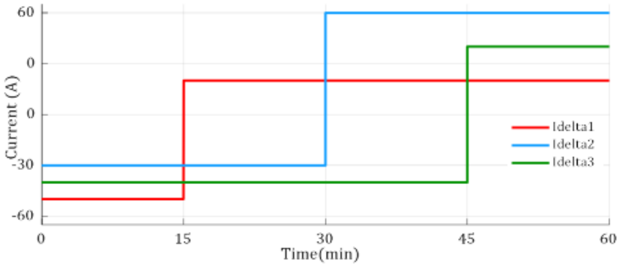

Fig. 11: the current absorbed from DC bus at different points

Sum of these currents should be compensated for the ESS. Figs. 12 and 13 show the ESUs current and SOC for the conventional droop method.

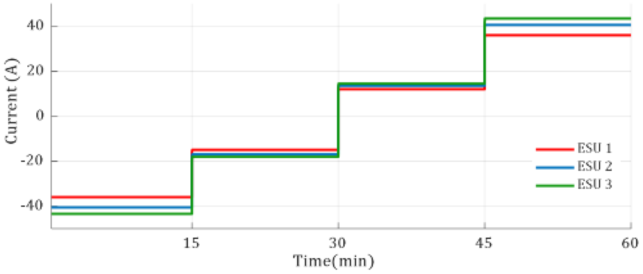

Fig. 12: the ESUs current in the conventional droop

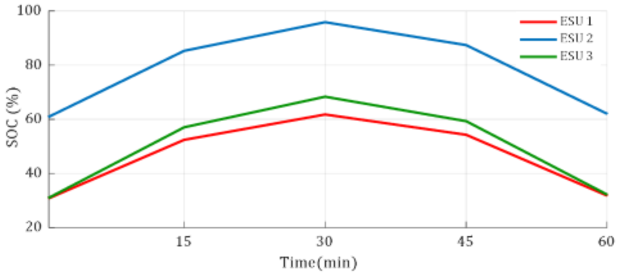

Fig. 13: the ESUs SOC in the conventional droop

The least R^{eq} belongs to unit 3. Therefore, its current portion and its SOC variation are more than others. This inequality in units current creates an SOC disparity (about 7 %) in charge mode (0 to 30 min) which compensates in discharge period (30 to 60 min).

The virtual resistance keeps the voltage deviation in the allowed area and eliminates the problem of improper current sharing. Figs. 14 and 15 display the ESUs current and their SOC when the microgrid is controlled by this method.

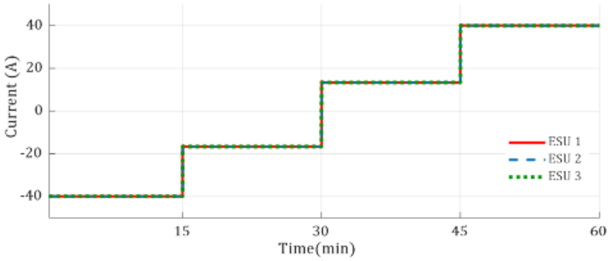

Fig. 14: the ESUs current in the virtual resistance

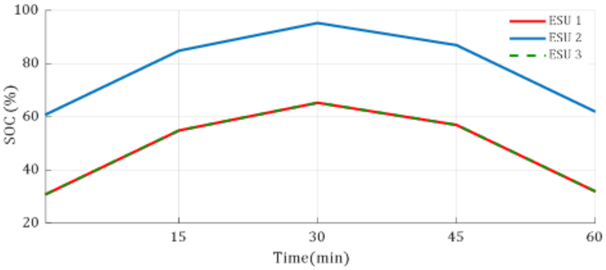

Fig. 15: the ESUs SOC in the virtual resistance

Inequality in ESUs loading is caused by the lines resistance. As the effect of this parameter is rectified by setting droop gains (equalizing the ESUs R^{eq}), it can be convinced why the ESUs current are overlapped. In other words, the droop gains are selected based on the lines resistance such that the currents are almost the same.

The result of ESUs current specification based on the lines resistance and voltage deviation without considering SOCs is that the SOCs difference remains constant. The SOCs difference at the first and end of the simulation time is 30 % which indicates this method is not able to converge SOCs although its performance in proper current sharing is admirable.

For the SOC-based method, the currents and SOCs are as below.

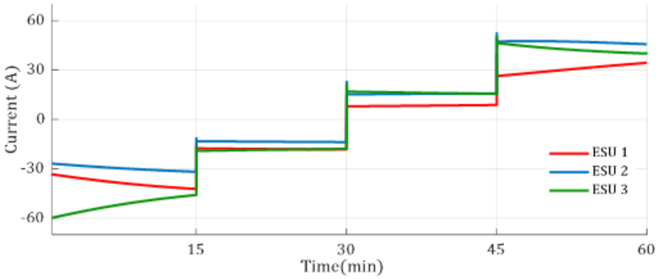

Fig. 16: the ESUs current in the SOC-based method

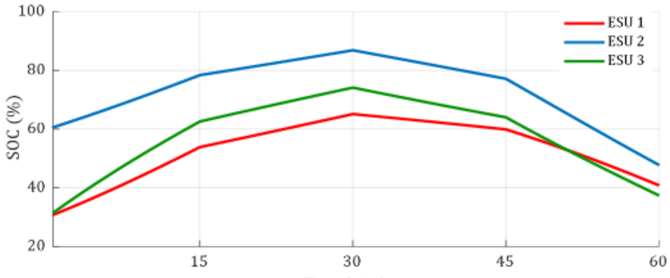

Fig. 17: SOCs in the SOC-based method

Comparing the results of ESUs 2 with 3 shows that in this method the lower SOC unit (ESU 3) absorbs more and injects less. This inequality in currents leads to a reduction in SOCs difference from 30% to 11 % after an hour.

The effect of lines resistance on improper current sharing is revealed when a comparison is made between the results of ESUs 1 and 3. Both these units have the same SOC but the current of unit 3 is more. Although the lines resistance difference diverges the SOCs but the SOC-based method holds them close together. In summary, the SOC-based method can keep SOCs close together, but it cannot overlap them. The more the lines resistance difference is, the further their SOC difference will be.

The results of the proposed method are expressed in Figs. 18 and 19. It should be noted that half of the voltage deviation is considered for the $R^{line} + R^{cmp}$ while the rest is assumed for $R^{b\ln}$

.

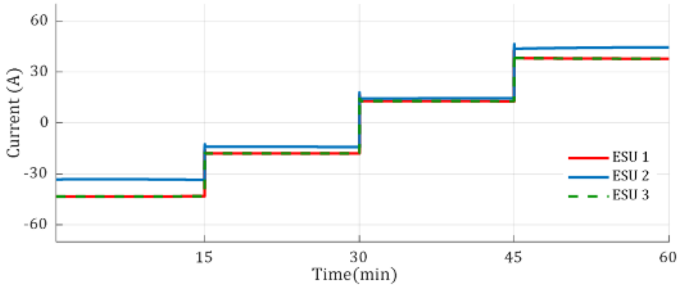

Fig. 18: the ESUs current in the proposed method

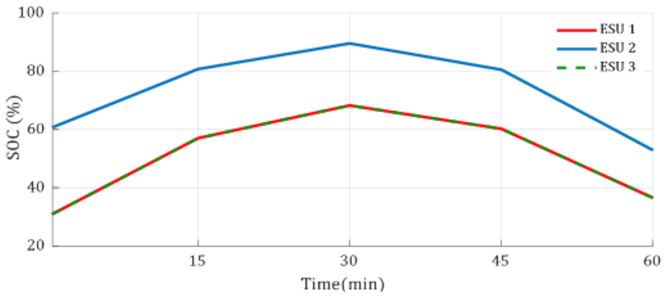

Fig. 19: the ESUs SOC in the SOC-based method

The current of ESUs 1 and 3 is overlap. As the lines resistance is different and their SOC is the same, it can be concluded the proposed method eliminates the effect of lines resistance like virtual resistance method. Both the currents and SOCs waveforms prove that the proposed method is equipped by the SOCs balancing capability. During charge interval (0 to 30 min), the current of ESUs 1 and 3 is more. Similarly, within discharge period, most of the current is absorbed from ESU 2. The result is that the SOCs difference is reduced from 30 % to 17 % after an hour.

The results of this part confirm that the proposed method benefits of proper current sharing and SOCs balancing. The DC bus voltage for all methods is depicted in Fig. 20. In the conventional droop in some cases that the units current is close to the nominal, the voltage of DC bus passes its limits. For instance, during (0 to 15 and 45 to 60 min) the DC bus voltage deviation is 23 % more than its maximum allowed. Hence, this method cannot satisfy the microgrid power quality in perspective of the voltage deviations. In the virtual resistance method, the DC bus voltage is limited to 450 to 550 volt ($V_{ref} \pm \Delta V_{\max}$) when the currents are in range of ($-I^{nom}$ to I^{nom}). It means that, by keeping the units current to less than their nominal, it can be ensured the voltage of the DC bus stays in allowed area.

In standpoint of DC bus voltage deviation, SOC-based method has a good performance. For the presented system the voltage deviation is less than 60% of its maximum where in the virtual resistance and conventional droop it is 100% and 123% respectively. Just like the SOC-based method, the proposed method reduces the DC bus voltage deviation. For the presented system, the maximum voltage deviation is 38 volt (75% of its maximum).

It should be noted, the performance of the SOC-based method in reduction of DC bus voltage deviation is better than the proposed method. The reason is that in the proposed method a part of DC bus voltage drop is occupied by R^{cmp} which increases the DC bus voltage deviation.

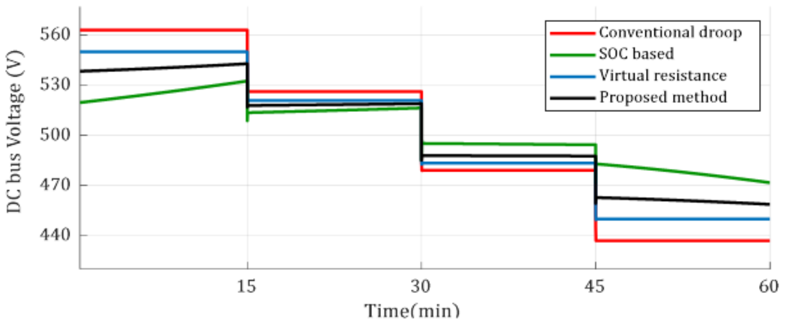

Fig. 20: The voltage of DC bus for different methods

Section II: Investigating the Effect of R^{bln} and R^{cmp}

The value of R^{cmp} (R^{bln})affects the voltage deviation and SOCs balancing speed. Regarding that, in this section different values for R^{bln} are assumed to evaluate the effects of $M_i^{'}$on the SOCs balancing speed and voltage deviation. Fig. 21 shows the SOCs when 30 and 60 percent of the maximum voltage deviation is considered for SOCs balancing.

The value of $M_i^{'}$when X percent of $\Delta V_{\max}$ is considered for SOCs balancing is calculated by (18):

$$M_i^{'} = \frac{X \Delta V_{\max}}{SOC_{\max}^2 I_i^{nom}} \qquad (18)$$

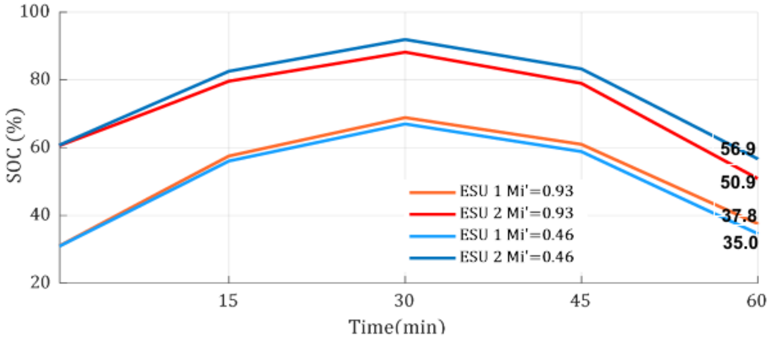

Fig. 21: SOCs variation for different values for $M_i^{'}$

The initial SOCs difference is 30 %. After an hour it is reduced to 21.9% when $M_i^{'}$ is 0.46 and 13.1% when it is 0.93. it shows that enhancing $M_i^{'}$, will reduce the SOCs convergence time.

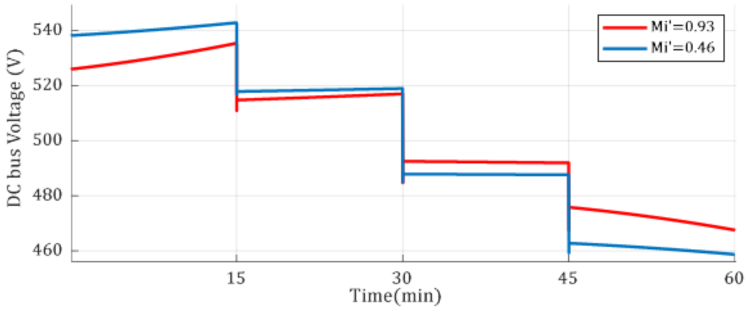

Fig. 22: DC bus voltage for different values for $M_i^{'}$

By increasing the value of $M_i^{'}$ not only the speed of SOCs balancing is improved but also the DC bus voltage deviation is reduced. Fig .22 displays the DC bus voltage.

It is obvious that the voltage of the DC bus when 60% of the ΔV_{max} is considered for SOCs balancing (Mi'=0.93) is closer to the nominal which means that increasing $M_i^{'}$ will improve the DC microgrid power quality in perspective of voltage deviation.

As can be seen the proposed method inherits the advantages of the virtual resistance (proper current sharing) and SOC-based (SOCs balancing and voltage deviation reduction) methods.

5-CONCLUSION

In this paper a novel control method for DC microgrid is introduced. First of all, an overall structure of a widespread DC microgrid is presented. After that, it was explained for the microgrids that the units are far from each other, local controllers should be designed. But microgrids under such control methods face some problems such as SOCs divergence, improper current sharing and, high voltage deviation. Next, the conventional droop, the virtual resistance, and SOC based method are explained and it was cleared that each of these methods are engaged with some of these problems. After that, a novel control method composed of virtual resistance and SOC- based method is designed to benefit of these methods advantage while eliminate their shortcoming. In this method the droop gain is divided into two parts. One of this part satisfies the proportional current sharing like virtual resistance method while the second is responsible for SOCs balancing. The simulation results confirm that the proposed method has SOCs balancing and voltage deviation reduction capability like SOC-based method while it benefits of proper current sharing like virtual resistance method.

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