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An optimal adaptive control of DC-Microgrid with the aim of accurate, current sharing and voltage regulation according to the load variation and gray-wolf optimization

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Highlights

- A novel adaptive control method enhances management of energy storage, generation sources, and consumers in DC microgrids.
- Overcomes a common challenge by enabling current sharing and voltage adjustment simultaneously based on load conditions.
- Utilizes a gray-wolf algorithm to optimize droop gains for improved accuracy in managing current and voltage.
- Demonstrates the effectiveness of the proposed method for DC microgrid management through comprehensive simulation results.

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Abstract

Today, DC microgrids provide the possibility to provide proper management and control for energy storage systems, generation sources, consumers, and other power components. The droop control method is one of the most common methods used in DC microgrids. One of the main challenges in the droop control method is that it is not possible to share the current and regulate the voltage simultaneously in this method. To overcome the weaknesses of the voltage drop control method, the paper presents an adaptive control method that can be used to share the current and adjust the voltage accordingly based on the load condition. When the load in the microgrid is low, the output current is lower than the maximum limit, so current sharing is not a difficult challenge. When the load increases to the point where the output current exceeds the maximum limit, then current sharing becomes very important. This method solves this problem by increasing the total gain decrease. For more accuracy, a gray-wolf algorithm has been used to optimize the droop gains. The performance of the proposed method has been verified through a set of simulations, and the results confirm the effectiveness of the proposed plan for the DC microgrid.

1. Introduction

A. Motivation

Because of the concerns related to weather conditions, climate warming, expensive fossil fuels, etc., scattered production sources and new energies have been highly welcomed by researchers. Various equipment such as DGs, ESSs, consumers, and other devices are integrated into a microgrid. The microgrid must be flexible enough to have high efficiency and reliability, which depends on the design and implementation of a suitable control strategy. Microgrids can be divided into two main categories [1], [2]. AC microgrids and DC microgrids. Both can work in two

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modes: connected to the network or island mode. In recent years, DC microgrids have been intensively studied by researchers. Because these microgrids have many advantages compared to AC microgrids, these benefits include more accessible control systems because of the lack of reactive power, frequency, higher quality of power, and lower costs. However, all these benefits depend on designing and implementing a suitable control system. Also, microgrids are widely used in smaller applications such as electric ships and data centers [3], [4]. Since DC voltage changes are used to determine the power share among DC sources, controllers utilizing the level of DC voltage changes have been widely used to establish a connection between different DC units. For example, a control method based on dc-bus signaling (DBS) for a hybrid renewable microgrid is presented in [5]–[7].

B. Literature review

In [8], voltage support while power sharing is done through decentralized control methods is discussed. Power converters at grid frequency provide active power to local loads and inject reactive power into the grid to support the voltage. It is shown in [9]–[11] that it performs better than network tracking for power adjustment. In reference [12], the problem of load loading accuracy has been investigated while maintaining network stability, and a control strategy has also been proposed to improve the accuracy of power-sharing in the independent microgrid. In this control strategy, two droop gain coefficients are defined, showing the voltage angle's droop value against the active output power and the drop of the voltage size against the reactive output power, respectively. Increasing the droop gain improves the accuracy of power-sharing. However, it hurts the overall stability of the system. In reference [13], among the different control methods used to control the interface converter in distributed generation sources, the sequential output and drop controller are used, which shows more suitable work in the conditions of operation connected to the grid and separated from the grid. In reference [14]–[16], the methods of designing and optimizing a controller for integrating multiple DGs with an inverter interface and robust control of the inverter interface against voltage and frequency disturbances are presented.

In reference [17], a DBS-based control method for a microgrid considering PV sources and ESSs is provided. The authority [18] has provided an enhanced controller for DC microgrids to provide power to consumers in a completely reliable way. Reference [19] presents a voltage controller according to DC-microgrids' frequency, considering terminals with multiple slacks. A new 3-level controller is also shown in contact [20] for a microgrid where sources and loads change frequently. As mentioned, Droop control methods have also attracted much attention from researchers. They are used in many applications, such as power distribution among distributed generation sources in DC and AC microgrids [21]. Reference [22] presents two methods of decentralized power distribution for distributed generation units, in which the effects of internal connection cables are not considered. Also, in reference [23], a small signal AC injection method is presented, using which a precise current division is obtained. On the other hand, the strategies presented in references [24]–[27] have used complex control methods that result in higher costs and lower reliability.

C. Contributions

To complement the past research in the field of DC microgrids, this paper presents an adaptive method based on droop control for DC microgrids. In other words, in the proposed form, high-precision current sharing and voltage regulation based on droop control for microgrids are presented, in which the droop gains are changed adaptively so that the load current is considered in its changes, and no link Communication among DGs is not used. This article presents an adaptive control method that can share the draft and regulate the voltage according to the load conditions to address the weakness in the droop control methods. When the load in the microgrid is low, the output current is lower than the maximum limit, and therefore, sharing the wind is not a difficult challenge. When the load increases so that the output current exceeds the maximum limit, the current sharing becomes very important. This method solves this problem through the increasing total droop gains. For more accuracy, a gray-wolf algorithm has been used to optimize the droop gains.

D. Paper organization

The remaining sections of the paper can be organized as follows. The conventional droop controller is presented in Section 2. The proposed optimal adaptive droop controller is described in Section 3; Section 4 shows the adaptive method’s stability. Also, the simulations discussion is performed in Section 5, and the conclusion is presented in Section 6.

2. The droop-control method

To check the adequate performance of the desired method, its implementation should be compared with the primary Droop control method. Therefore, in this part, the primary droop control method is introduced. The characteristics of the DC microgrid considered in this article are specified in Table 1 and Figure 1. Since both distributed generation sources are similar, the drupe gains are chosen similarly for them in this baseline method. The cable is also modeled as a resistance for the steady-state analysis. The line is modeled using a series resistance connected to an inductance to check the microgrid stability.

Table. 1. Parameters of the DG units

Parameter	Value
Vn	60
IL	25
rated current	15
R1	0.15
R2	0.25
L1	0.25
L2	0.42

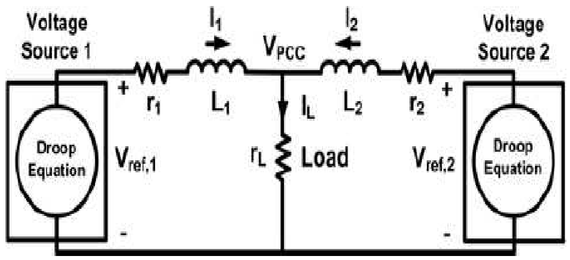


Fig. 1. DC microgrid

The primary Droop control method can be formulated as follows:

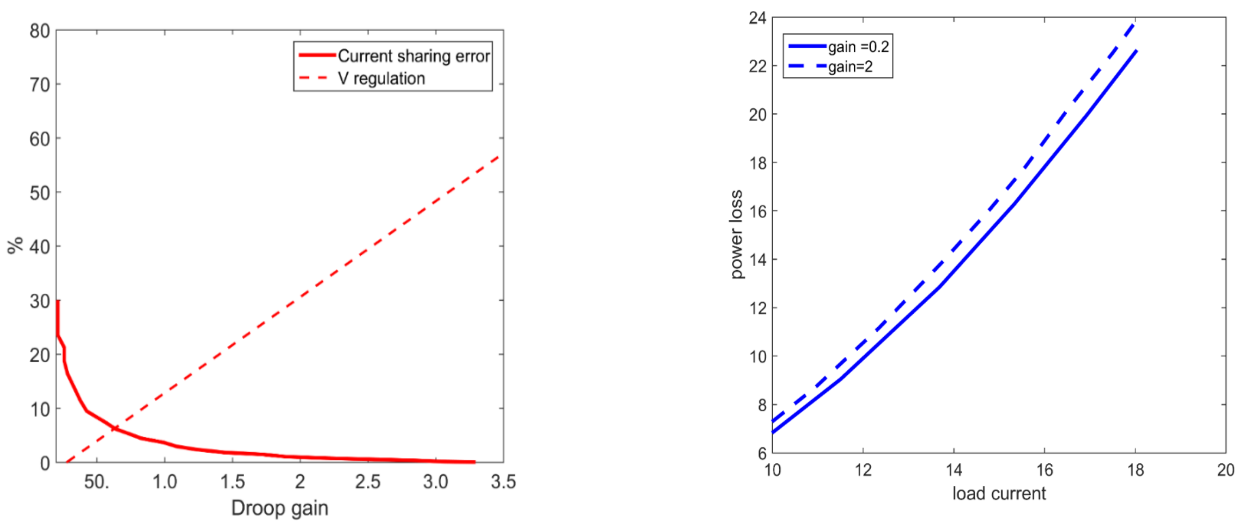
$$V_{r,k} = V_n - n_k I_k \quad (1)$$

In which V_n is nominal voltage yjoyous$subscriptions$e voltage, $I_k$is output current, and $n_k$is droop gain in the k^{th} source.

As mentioned earlier, the increase in consumer load increases the output current of the DC microgrid and causes the droop gains to increase. The voltage regulation in the DC microgrid will deteriorate with the increase of droop gains. In other words, the voltage regulation will not be at the desired level in heavy load currents. This fact can be seen in Figure 2a. According to this figure, the voltage regulation in the microgrid becomes worse with the increase of changes in droop gain.

On the other hand, if the load current increases and, as a result, the droop gains increase, the present sharing error will decrease significantly. In other words, the changes in droop gains directly affect the accuracy of the current sharing. As the droop gains increase, the present sharing error decreases. This issue can also be seen in Figure 2a.

As mentioned in the previous section, proper current sharing among distributed generation units and power sharing between them becomes possible by increasing droop gains. The result of this will be that the power losses will increase. Therefore, it can be concluded that an increase in droop gains causes increased power losses. This can be seen in Figure 2b. In this figure, two (low and high) profits are considered for droop, and as it is clear from it, in lower droop gains, the power loss will be less, resulting in higher system efficiency.



A **B**

Fig. 2. The performance of the primary droop method (a. error of the current-sharing or the voltage-regulation. b Power losses)

3. The proposed method

3.1.Proposed adaptive method

As mentioned in the previous sections, an adaptive control method is presented in this section. Since consumers' demand is low in low load flows, the output flow of distributed generation resources will be less than the maximum. Therefore, the issue of power-sharing will not be challenging. On the other hand, since power dissipation and voltage regulation are other concerns, droop gains are set at a low value, which makes good voltage regulation happen in the microgrid and increases the overall efficiency of the microgrid.

On the other hand, when the amount of consumer demand increases and the load flow increases, the microgrid may go towards lower reliability. In addition, with increasing power, fluctuations may occur in the DC link voltage. Therefore, at this stage, the droop gains should be increased so that the current can be divided more accurately, and as a result, overload conditions can be avoided. In addition, since droop gains mimic a resistive state, increasing the growth will further dampen voltage fluctuations. As a result, increasing droop gains creates a compromise between voltage regulation and current division. To achieve an optimal voltage setting, the droop characteristics should shift upwards to solve the issue of dropping voltage.

Therefore, gains of droop must have a small or significant value at low or high loads, respectively. To achieve this, the droop characteristic curve must be changed accordingly. Therefore, the equations for determining the drupe characteristic are defined as follows.

$$V_{r,k} = V_n - m_k I_k^{\beta} \quad (2)$$

$$m_k = \frac{V_n - V_{min}}{I_k^{\beta,max}} \quad (3)$$

$Cap I_k^{\beta,max}$ is the maximum output current of the k^{Cap}. V_{min} is the minimum voltage. β and m_k are curve coefficient and constant, respectively. The point here is the value oofsubscriptf m_k must be that the voltage does not exceed its acceptable level at any load current value.

As can be seen from the characteristic curve of the desired droop, which is presented in Figure 3, the final gain of the droop, which is the tangent line' slope to the indicated curve, increases with the load current increase. On the other hand, to reach an acceptable voltage regulation, we must find a voltage shift by increasing the power of consumers. This causes the intersection between the voltage and droop axes to increase. Therefore, we have:

$$equalyouqual R_k = \frac{\partial V_{r,k}}{\partial I_k} = \frac{-\beta(V_n - V_{min}) I_k^{\beta-1}}{I_k^{\beta,max}} \quad (4)$$

In which R_k is the total droop gain. The equivalent value of the voltage shifting on the voltage axis is:

$$\Delta V_k = \frac{(\beta - 1)(V_n - V_{min}) I_k^{\beta}}{I_k^{\beta,max}} \quad (5)$$

The graph of changes in total droop gain and the amount of voltage shift is shown in Figure 4. As it is clear from this figure, when the load current increases, the total droop gain also increases. In addition, the amount of voltage shift is also related to the load's current as it is clear from Figure 4b, when the draft of the load increases, the amount of voltage shift also increases to the extent that the voltage does not always go out of the allowed limits. The droop curve coefficient should also be determined based on the line impedance and the desired precision in the current sharing. In the system considered in this article, the maximum amount of droop gain is extracted based on the acceptable accuracy for sharing the present. After that, the coefficient of the droop curve is calculated by removing the voltage shift amount at the maximum load current.

$$\beta \frac{R_k^{max} I_k^{max}}{V_n - V_{min}} \quad (6)$$

To compare the performance of the proposed adaptive method with other droop-based methods in which the droop gains have small or large fixed values. Figure 5 compares the system voltage regulation in three different cases. As it is clear from Figure 5, when the droop gains have a significant discount, the voltage regulation level using basic methods is not good. On the other hand, using the desired adaptive control method, the voltage regulation has a suitable range of 9%. In addition, Figure 5b shows the current sharing accuracy using these two methods in different cases. According to this figure, Droop-based methods could not provide good accuracy for current sharing at low gains. However, using the desired adaptive form, the current sharing has a very favorable accuracy. In addition, the power loss using the chosen adaptive method is very low compared to the basic techniques.

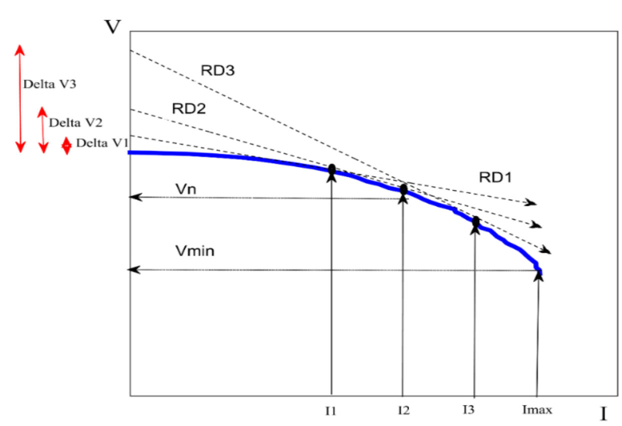
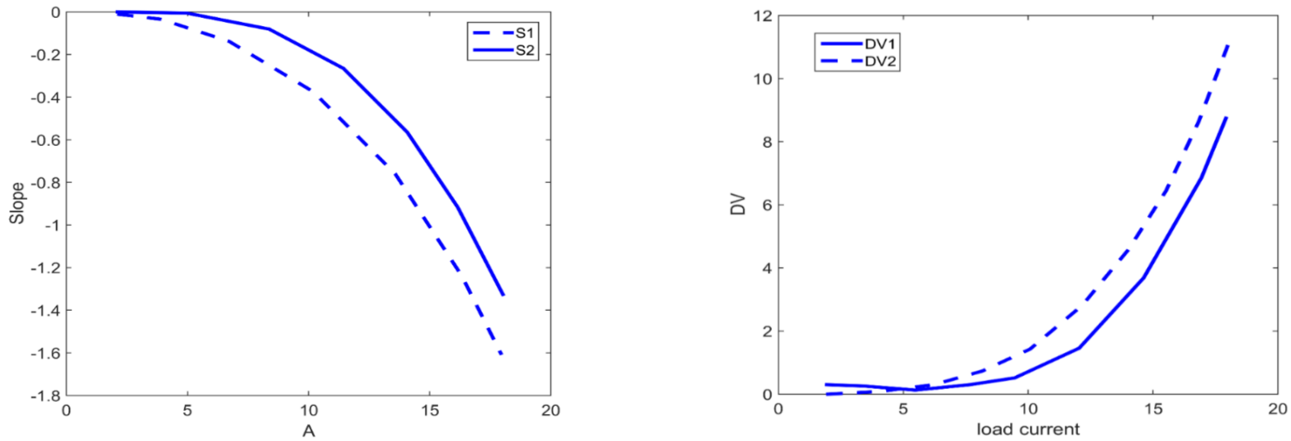


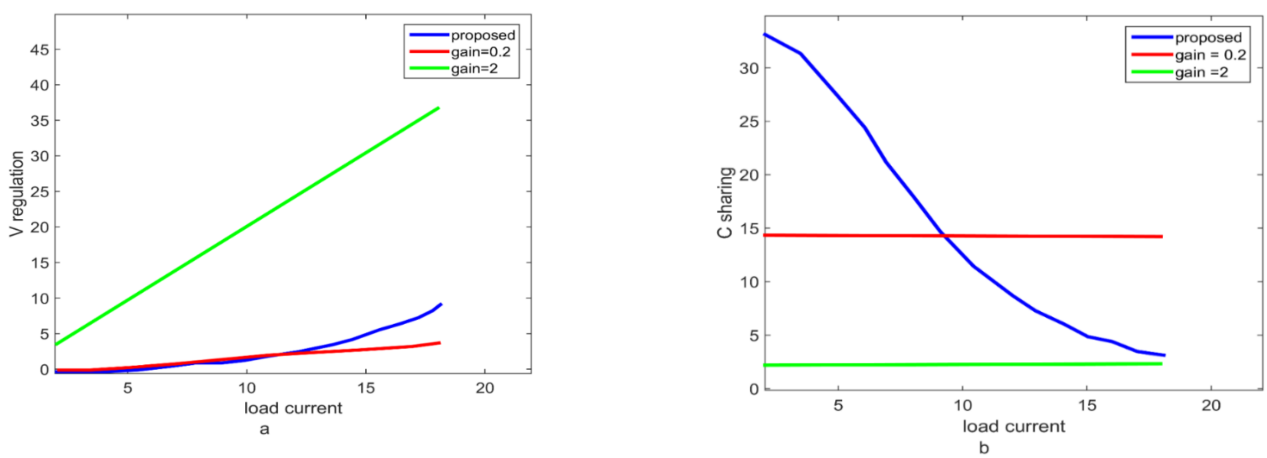
Fig. 3. Proposed droop controller's characteristics



A

B

Fig. 4. Total gain of droop and also voltage-regulation using proposed controller (a. Total droop gains b. Voltage shift)



A

B

Fig. 5. The adaptive method's performance with the primary droop method (a voltage-regulation. B. current-sharing error)

3.2. Gray-wolf optimization

We must develop a workable objective function to confirm the stability and smooth switching of the different operating modes since a microgrid can move between a grid-connected and islanded state. In this research, the objective function is defined as the integral of the deviation between the instantaneous power and the nominal power in different forms. The goal is to minimize this cost function. By minimizing this cost function, the system quickly reacts to changes in nominal power, and this power is stabilized without anything happening of overshoot at switching moments. This is because DG output power is a leading indicator of system performance. The following best describes the objective function:

$$inJ = \sum_{\mathrm{i}=1}^{M} \left\{ \int_{t=t_0^{\mathrm{i}}}^{t_f^{\mathrm{i}}} (t - t_0^{\mathrm{i}})[P(t)P^*(t))^2 \right. \\ \left. +(Q(t) - Q^*(t))^2]dt \right. \qquad (7)$$

When t_0^i, t_f^i are the start and end times for operation mode i, and M equations amber of operation modes for the microgrid.

The problem cannot be solved using conventional mathematical optimization techniques because the objective function is not differentiable. With an evolution and constraint mechanism, the improved gray wolf algorithm (IGWO) speeds convergence and enhances the accuracy of GWO optimization to achieve a balance between exploration and exploitation.

In nature, mutation, selection, and inheritance all play a role in the continual evolution of organisms from primitive to sophisticated states. The searching behavior of wolves also undergoes several alterations due to inheritance, selection, and mutation. Evolutionary techniques, including differential evolution (DE), quantum change, cooperative growth, etc., have been created based on the biological development of nature. Simple differential evolutionary strategies have received much attention since they are simple to employ, have fewer parameters, and have been extensively studied. For the evolution of GWO, the DE approach has been adopted. The fundamental tenet of the DE operator is to take the difference between people and recombine the population to produce the middle individuals, who are then used to produce the subsequent generation of individuals. Three procedures are used in this strategy: mutation, cutting, and selection.

The parental difference vector comprises two distinct people (x sub r 1 to the t,x sub r 2 to the t from the parents (generation t) and is the primary component of DE change.

$$Dd_{r12} = x_{r1}^{t} - x_{r2}^{t} \tag{8}$$

Where $r1$ a $r2are$ the index numbers of two distinct population members. The following is a description of the mutation operation:

$$V_i^{t+1} = x_{r3}^{t} + F * (x_{r1}^{t} - x_{r2}^{t}) \tag{9}$$

Various integers in the range (1, 2, . . . n) of the index of the current target vector I are designated as,$r1r2$ and $r3$, respectively. The scaling factor F manages the scaling of the differential vector. We select parents from exceptional wolves to ensure the beneficial development of wolves and to create complete diversity. Beta and Delta are chosen as parents before being coupled with alpha following many simulation tests.

$$V_i^{t+1} = x_{\alpha}^{t} + F * (x_{\beta}^{t} - x_{\delta}^{t}) \tag{10}$$

A dynamic scaling factor is utilized in the first stage of the algorithm to keep it from falling into the local optimum and in the second stage to have a strong exploitation ability and speed up convergence. As a result, the scaling factor F fluctuates in size depending on how many times the equation is repeated.

Vector cap reformed vector cap vector cap vectorV_i^{t+1}, and the test vector U_i^{t+1} is produced. IT guarantee evolution f x sub i. to the t, IIT adopts the IA random selection method. The cutting probability coefficient is used for the remaining bits of U_i^{t+1} to assign which bit of U_i^{t+1} is shown by V_i^{t+1} and which bit by x_i^{t}.

$$, U_{ij}^{t+1} = \begin{cases} V_{ij}^{t+1} & rand(j) \le CR \quad or \quad j = rand(i) \\ x_{ij} & rand(j) \ge CR \quad and \quad j \ne rand(i) \end{cases} \quad j = 1,2,\dots,D \tag{11}$$

The selection process uses the "greedy selection" method. Experimental individual A is created after a cutting and mutation operation to compete with B.

$$x_i^{t+1} = \begin{cases} & f(U_i^{t+1}) < f(x_i^{t}) \\ x_i^{t} & f(U_i^{t+1}) \ge f(x_i^{t}) \end{cases} \quad i = 1,2, \tag{12}$$

Suppose the fitness level of the wolf determines the strength of each wolf, and the size of the group is fixed. The better the answer, the higher the fit. To eliminate the R wolves with the highest fitness values, sort the fitness values of each wolf in ascending order after each algorithm iteration. Meanwhile, they produce a random number of new wolves equal to those eliminated. The number of wolves who give birth to young is high when R is significant, contributing to the variety of wolves. However, if the value of R is too high, the algorithm is more likely to engage in random search, which slows convergence. The value of R should not be too low in order to sustain population variety. As a result, R is a random integer between $\frac{n}{2\varepsilon}$ and $\frac{n}{\varepsilon}$. Fig. 5 depicts the suggested algorithm's flowchart.

4. Stability analysis

In this part, we examine the stability of the DC microgrid presented in Figure 1 and described in Table 1 based on the small signal model. Since the speed of the voltage-controller is more than the speed of the droop method, the distributed generation's voltages and its reference are given to have the same values.

$$V_k = V_{r,k}\,, k = 1, 2 \tag{13}$$

Therefore, Droop's equations are investigated in the DC microgrid stability investigation. By applying a perturbation to equation two and substituting the reference voltage from the previous equation, we have:

$$\widehat{V_k} = -\beta m_k I_k^{\beta-1} \widehat{I_k} \tag{14}$$

In these equations, the signal indicates the presence of disturbance on the variable. As it is clear from Figure 1, a series resistance with inductance has been used to model the cable. By applying the KVL law, we will have:

$$\begin{aligned} V_1 - V_3 &= R_1 I_1 - l_1(\tfrac{dI_1}{dt}) \\ V_2 - V_3 &= R_2 I_2 - l_2(\tfrac{dI_2}{dt}) \\ V_3 &= R_L(I_1 + I_2) \end{aligned} \tag{15}$$

By applying perturbation, the above equations are rewritten as follows:

$$e\widehat{V_1} - \widehat{V_3} = R_1\widehat{I_1} - l_1(\tfrac{d\widehat{I_1}}{dt})\ \widehat{V_2} - \widehat{V_3} = R_2\widehat{I_2} - l_2(\tfrac{d\widehat{I_2}}{dt})\ \widehat{V_3} = R_L(\widehat{I_1} + \widehat{I_2}) \tag{16}$$

By combining the above equations, we will have

$$\begin{bmatrix} \frac{d\hat{I_1}}{dt} \\ \frac{d\hat{I_2}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-\beta m_1 I_1^{\beta-1} - R_L - R_1}{l_1} & \frac{-R_L}{l_1} \\ \frac{-R_L}{l_2} & \frac{-\beta m_2 I_2^{\beta-1} - R_L - R_2}{l_2} \end{bmatrix} \begin{bmatrix} \hat{I_1} \\ \hat{I_2} \end{bmatrix} \quad (17)$$

In Figure 6, the root locus diagram for dominant eigenvalues is shown. Although the change in the load resistance causes a change in the location of the poles, the whole system's stability is not changed. Figures 6b and 6c show the location of the roots of the dominant eigenvalues, taking into account variable resistance for cables and variable inductance for them from 80 to 120% of the value given in Table 1. These figures confirm that the system is stable. In addition, it is clear in Figure 2 that the increase in load resistance causes the eigenvalues to shift and be located far from the imaginary axis. Therefore, the margin of stability increases. Unlikely, in Figure 6c, it is quite clear that increasing the size of the cable resistance causes the eigenvalues to be closer to the imaginary axis and reduces the stability margin.

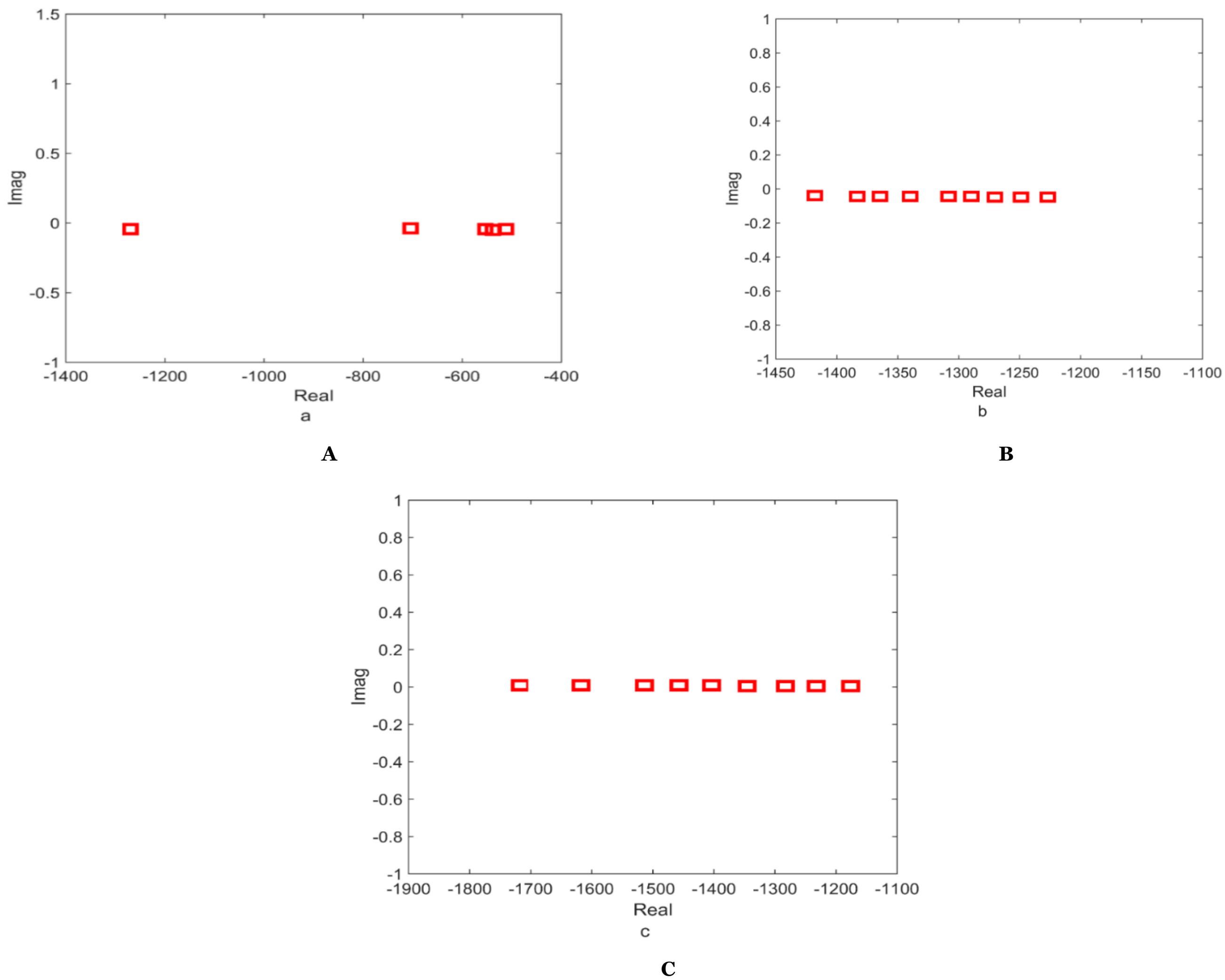


Fig. 6. Stability analysis (a. The shift of eigenvalues according to the load resistance increasing. b. The change in eigenvalues according to the line resistance increasing. c. The shift of eigenvalues according to the line inductance increasing)

5. Simulation results

To check the performance of the proposed adaptive control method, a DC microgrid shown in Figure 7 along with three distributed generation units, has been simulated in the MATLAB Simulink software environment. The nominal currents have different values of 10 10 and 5 amps for each distributed generation source. Each of these sources has a DC-to-DC buck-converter with an internal current controller and external voltage controller, whose loops are indicated in Figure 8. The desired adaptive method is applied to this DC microgrid to yield the reference value of voltage for the external voltage controller. In order to be able to apply a light load to the system, a 4 Ω resistor is used. At 0.25 seconds, another resistor of size 4 is added to the load to simulate heavier loads. To bold the effective performance of the adaptive method compared to the primary method, the droop gains are set to 0.2, 0.2, and 0.4, respectively, which are small DROP gains. Values of 2, 2, and 4 were considered for larger drupe gains. The output flow of each scattered production unit is shown in Figures 9 and 10, respectively.

This paper presents an adaptive control method that can share the current and regulate the voltage appropriately according to the load conditions. When the load in the microgrid is low, the output current is lower than the maximum limit, and therefore, sharing the current is not a difficult challenge. When the load increases so that the output current exceeds the maximum limit, the current sharing becomes very important. This method solves this problem by increasing the total droop gains. In other words, total droop gains are adaptively changed based on the load current. The results of simulations show that, in low load currents, the output currents of distributed generation units have values different from the maximum standard value. Therefore, sharing the current is not a challenging issue. When the load increases, the output-currents in distributed generation sources tend to the maximum value within the standard range. So, in loads with large currents, high-precision current sharing becomes essential. In the proposed adaptive method, with increasing load, the total gains are adaptively increased so that the current sharing can be done more accurately.

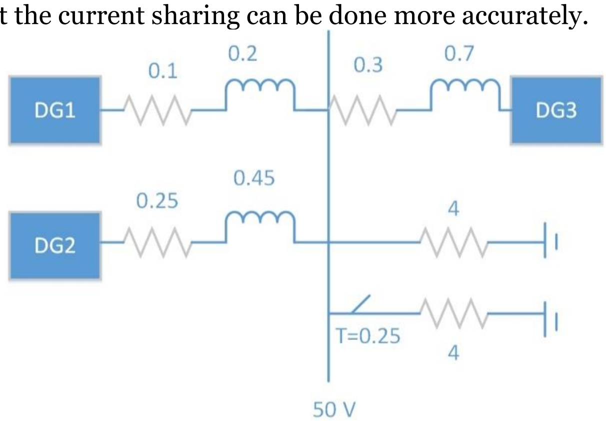


Fig. 7. Purposed DC Microgrid

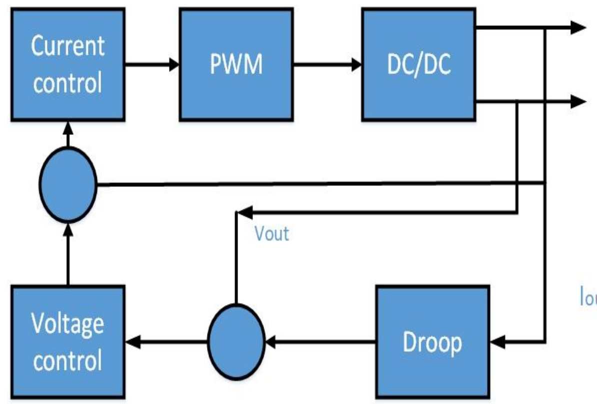
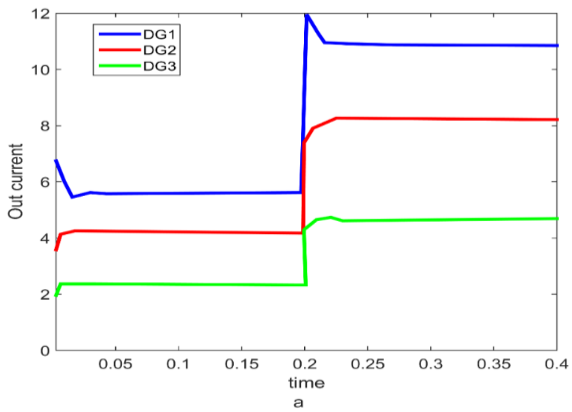


Fig. 8. Control of the converter

Figures 9-a and 10-a show the current and voltage of all distributed generation sources through the basic droop procedure, considering gains with small values. As shown in Figure 10-a, the voltage regulation is kept in an acceptable range of 10% for light and heavy loads. However, due to the error in dividing the output-current, the current of distributed production units exceeds its maximum value and is at the total value of the load current. This issue is shown in Figure 9a. Figures 9-b and 10-b also indicate the output current and voltage of all distributed generation sources utilizing the primary droop-control method and considering high gains. As shown in Figure 9-b, subject to the heavy and light loads, the accuracy of the current division is good. Still, the output voltage of distributed generation sources exceeded its standard range, as indicated in Figure 10-b.

In Figures 9-c 10-c, the output-current and output-voltage of all distributed generation sources are shown utilizing the presented adaptive method. In low load currents, the output currents of distributed generation sources have values different from the maximum standard value. Therefore, sharing the current is not a challenging issue. As the load increases, the output currents in distributed generation sources tend to the maximum value within the standard range. Therefore, in high-load currents, high-precision current sharing becomes important. In the proposed adaptive method, with increasing load, the total gains are adaptively increased so that the current sharing can be done more accurately. This issue is shown in Figure 9c. In addition, the proposed adaptive method has an acceptable voltage regulation, confirmed in Figure 10c.



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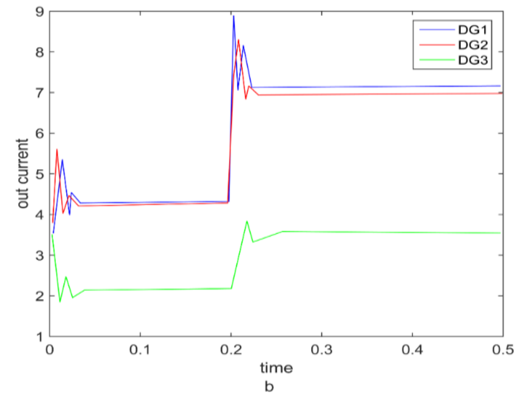

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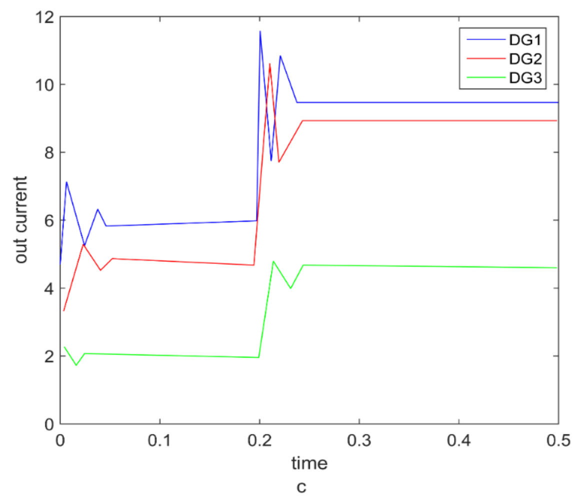
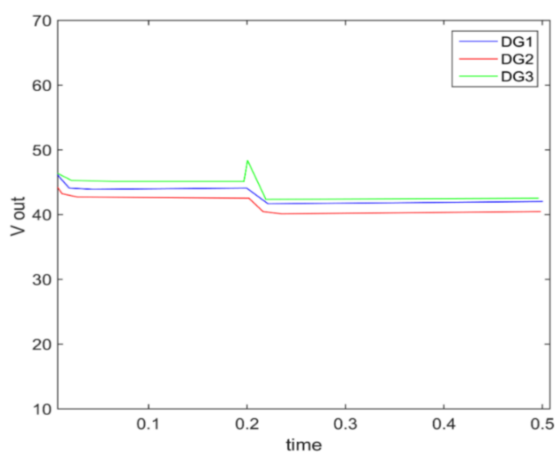


C

Fig. 9. Output currents (a basic droop control-small gains. b essential droop control method-large gain. c proposed)



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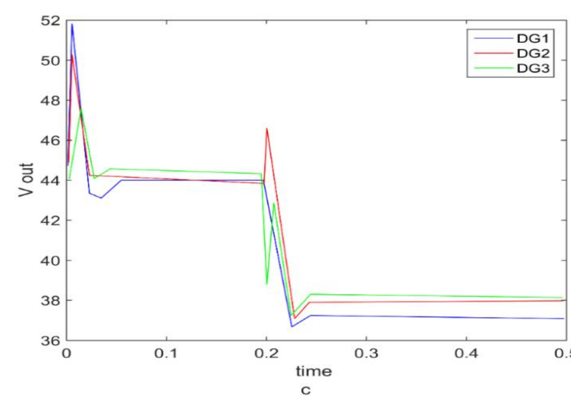

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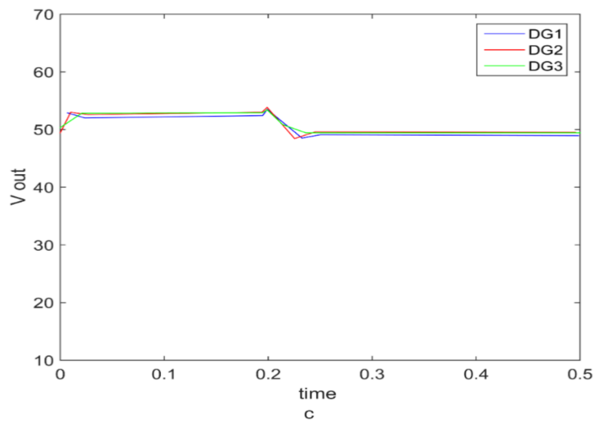

C

Fig. 10. Output voltage (a basic droop control-small gains. b essential droop control method-large gain. c proposed)

6. Conclusion

One of the main challenges in the droop control method is that it is impossible to share the current and regulate the voltage simultaneously. To solve this weakness, this paper presents an adaptive control method that can be used to share the current and regulate the voltage appropriately according to the load conditions. When the load in the microgrid is low, the output current is lower than the maximum limit, and therefore, sharing the current is not a difficult challenge. When the load increases so that the output current exceeds the maximum limit, the current sharing becomes very important. This method solves this problem by increasing the total droop gains. In other words, total droop gains are adaptively changed based on the load current. The results of simulations show that, in low load currents, the output currents of distributed generation units have values different from the maximum standard value. Therefore, sharing the current is not a challenging issue. When the load increases, the output-currents in distributed generation sources tend to the maximum value within the standard range. So, in loads with large currents, high-precision current sharing becomes important. In the proposed adaptive method, with increasing load, the total gains are adaptively increased so that the current sharing can be done with higher accuracy.

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