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Adaptive droop controller design for energy management system in DC microgrid architectures

DC mikro şebeke mimarilerinde enerji yönetim sistemi için uyarlanabilir düşüş denetleyici tasarımı

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Abstract

In this study, the hierarchical two-level energy management system with an adaptive droop control approach is proposed for the microgrid system consisting of distributed generation units. The primary control layer controls the converters to transfer power from the distributed generation units as part of the hierarchical two-level control structure. The secondary control layer is used to improve current sharing accuracy and to provide DC bus voltage restoration. The DC microgrid system is analyzed using Thévenin's equivalent model and Kirchhoff's laws. The distribution generation units' current sharing parameters are obtained depending on the analysis results. The proposed adaptive droop control method is compared to the conventional droop control method. In the proposed system, the performance of the adaptive droop controller at 2250 W, where the demand is highest, is 9.65% better than the conventional method. Similarly, the proposed method performed 6.67% better in voltage regulation of the DC bus. The simulation results show that the designed control strategy increases the voltage restoration for the DC microgrid under variable operating conditions and provides better power sharing between the sources. Thus, the constraints of the conventional droop control method are improved by using the adaptive method.

Keywords: Hierarchical energy management strategy, Microgrid, Adaptive droop control.

Öz

Bu çalışmada, dağıtık üretim birimlerinden oluşan mikro şebeke sistemi için uyarlamalı düşüş kontrolü yaklaşımına sahip hiyerarşik iki seviyeli bir enerji yönetim sistemi önerilmiştir. Hiyerarşik iki seviyeli kontrol yapısında dağıtık üretim birimlerinden aktarılacak güç, birincil kontrol katmanında dönüştürücülerin kontrol edilmesiyle sağlanmaktadır. İkincil kontrol katmanı, DC bara gerilim restorasyonunun sağlanması ve akım paylaşım doğruluğunun eşzamanlı olarak iyileştirilmesi amacıyla kullanılır. DC mikro şebeke sistemi Thévenin eşdeğer modeli ve Kirchhoff yasalarından faydalanılarak analiz edilmiştir. Dağıtık üretim birimlerinin akım paylaşım parametreleri, analiz sonuçlarına bağlı olarak elde edilmiştir. Önerilen uyarlanabilir düşüş kontrol yöntemi, geleneksel düşüş kontrol yöntemi ile karşılaştırılmıştır. Önerilen sistemde, talebin en yüksek olduğu 2250 W'lık güçte uyarlanabilir düşüş kontrolörün güç aktarımındaki performansı geleneksel yönteme göre 9.65% daha iyidir. Benzer şekilde önerilen yöntem, DC baranın gerilim regülasyonunda 6.67% daha iyi bir performans sergilemiştir. Sonuçlar göstermiştir ki tasarlanan kontrol stratejisinin değişken çalışma koşulları altında DC mikro şebeke için gerilim restorasyonunu arttırdığı ve kaynaklar arasında daha iyi bir güç paylaşımı sağladığını göstermektedir. Böylece geleneksel düşüş kontrol yöntemindeki kısıtlar uyarlanabilir yöntemin kullanılmasıyla iyileştirilmiştir.

Anahtar kelimeler: Hiyerarşik enerji yönetim stratejisi, Mikro şebeke, Uyarlanabilir düşüş kontrolü.

1 Introduction

With the developing technology, the need for electrical energy is increasing daily. At the same time, power plants largely produce electrical energy based on fossil fuels. However, the adverse effects of fossil energy sources on the environment are quite worrying [1],[2]. Generally, in today's power systems, electrical energy is produced centrally, and the energy produced is transferred to distant consumption centres. In this case, it causes an increase in transmission losses and control problems. Distributed energy resources (DER) consisting of renewable energy sources (RES) are one of the most effective ways to overcome these problems. The significant trends in energy management applications are using RESs together, ensuring the continuity of energy and reducing energy costs. Solutions to these specified problems are sought with microgrids (MG). [3].

Among the advantages of MG structures, the use of DERs with renewable resources, their ability to operate independently of the grid and their easy integration with energy storage systems can be demonstrated. The electrical grids are in a significant transition phase from passive distribution grids, which can transmit unidirectional energy, to active distribution grids that transmit bi-directional energy [4]. The MGs use power electronic equipment to perform control, measurement and protection functions during island or grid-connected operating modes. Grid-connected mode allows connecting the MG to the main grid either fully or partially and exchanging power. It is possible for the MG to switch to island

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mode in the event of any disturbance in the grid in order to continue transmitting power to priority loads [5],[6].

Control of MG structures is carried out in two main categories: centralized and distributed [7]. The control capability of the MG is the most distinctive feature that distinguishes it from conventional power systems. Thus, the system offers an upward coordination and control structure in the grid. In MG, an energy management system (EMS) is required to realize the optimum load sharing of DERs in an intelligent, reliable and coordinated manner. EMS in MG ensures that the bus voltage and frequency remain within specific operating limits for transient voltage stability and steady-state events [8]. With the help of EMS, many benefits, such as energy saving in production, reactive power support, frequency regulation, and reduction of greenhouse gas emissions, are provided. An EMS decide the amount of power produced by DERs [9], obtains the maximum usable power output from energy sources [10], and ensures environmental and economic benefit by minimizing operating costs [11],[12]. Also, it performs various functions, such as determining the most appropriate strategy for the charge/discharge processes of battery groups in energy storage systems [13],[14].

Many researchers have recently been interested in the hierarchical control of DC MGs. In this context, various operational control methods have been proposed to be applied to converters, such as master-slave [15], distributed-centralized autonomous [16],[17] and multi-agent [18]. The cascade structure of hierarchical control architecture is widely used in MGs because it allows the operation of multiple variables independently. Generally, two-level control layers are used in hierarchical control architecture [19]. In the primary control layer, power sharing is carried out evenly. In the secondary layer, current and voltage are restored. In addition, a tertiary control layer can be added in case of the need for dynamic optimization in the MG system [20],[21]. Han et al. [22] proposed the dynamic droop coefficient correction control method to eliminate conventional droop control's negative effects when the DC MGs with different line impedances are connected to the grid. Experimental results showed that dynamic droop control stably maintains voltage and current restoration under various disturbances. Also, Babaiahgari et al. [23] introduced the DC MG structure using renewable resources in their study. An adaptive voltage droop control has been implemented to ensure optimum load sharing in the primary layer of the MG. The proposed method showed a successful performance in simulation and experimental studies.

The aim of this study is to present a hierarchical two-level control structure for DC MG structures based on an EMS. An adaptive method is used in the system to regulate DERs effectively, flexibly, and securely. Power flow between the DERs is controlled by the primary layer in the hierarchical control system, whereas current restoration and voltage restoration are controlled by the secondary control layer. The DC MG structure has been simulated using the MATLAB/Simulink environment simulation platform. It has been compared with the conventional method to demonstrate the advantages of the adaptive method.

2 Hierarchical control in DC microgrid architectures

MG structures operating in grid-connected and island modes have increased the importance of hierarchical control and energy management. In MG, power sharing is controlled through consensus-based, adaptive virtual-impedance, programming algorithms, and agent-based control methods. Among these approaches, the droop-based method is the most commonly used method due to its high level of reliability and ease of use [24].

The MG structure with a two-level hierarchical control architecture consisting of DERs is shown in Figure 1. Figure 1(a) represents the DER units that supply the system. Figure 1(b) is the lowest primary control level of the hierarchical structure and realizes the power-sharing among DERs. This process is carried out by generating a control signal to DC/DC converters depending on the current and voltage of the associated resource. Thus, it is ensured that each DER transfers energy to the DC bus. Figure 1(c) shows the secondary control level at the top of the hierarchical architecture. At the secondary control level, voltage differences and voltage deviations due to line impedances at the converter output are restored. In addition, a communication network is used to provide the flow of information between the layers in the MG.

2.1 Adaptive droop control method

The droop control is one of the fundamental control techniques for load current sharing in DC MG. In conventional methods, linear reduction of the DC output voltage is achieved as the output current of the converter increases. Thus, it is aimed to keep the DC bus voltage constant. However, this method has two main limitations. When the line resistance is considered in the DC MG, each converter's output voltage cannot be exactly the same, thus reducing the accuracy of output current sharing. It also causes voltage deviation between DERs connected to the DC bus due to the droop effect. Unlike non-hierarchical control approaches, the secondary controller exchanges information between the primary controller and converters using communication networks. In order to improve current-sharing accuracy and restore DC bus voltage, all converters in the system use the resulting average voltage and current data simultaneously. Communication systems are used only to transfer DC voltage and current values. All control operations are performed locally using a distributed control system. The simplified two-node circuit model is given in Figure 2.

The node voltage equation of the equivalent circuit based on Kirchhoff's Current Law is given in Equation (1).

$$\begin{aligned} v_{bus} &= v_{ref} - i_{o1} \cdot \frac{R_{d1}}{k_1} - i_{o1} \cdot R_{l1} \\ &= v_{ref} - i_{o2} \cdot \frac{R_{d2}}{k_2} - i_{o2} \cdot R_{l2} \end{aligned} \tag{1}$$

Here v_{bus} (V) is the DC bus voltage, v_{ref} (V) is the reference value of DC bus voltage, i_{o1} (A) is the output current of the first converter, and i_{o2} (A) is the output current of the second converter. R_{d1} (Ω) and R_{d2} (Ω) represent the droop coefficients of the DC/DC converters and R_{l1} (Ω) and R_{l2} (Ω) are line resistors, respectively. k_1 is the current sharing ratio of the first converter and k_2 is the current sharing ratio of the second converter.

It is generally assumed that the line resistors have a small value because the transmission lines are short in DC MGs [25]. Accordingly, since R_{d1}"R_{l1} and R_{d2}"R_{l2} , it can be accepted as $R_{d1} = R_{d2}$. Thus, Equation (1) can be simplified as in Equation (2).

$$\frac{i_{o1}}{i_{o2}} = \frac{k_1}{k_2} \tag{2}$$

The current ratio is associated with the current data received from the DC/DC converter output. PWM signals are generated by proportional-integral (PI) controllers in DC/DC converters. Every voltage PI controller has a reference value equal to v_{ref}, and the output voltage of the converters is restored to the reference value. For each of the current PI controllers, the reference value is equal to i_{oi}/k_i. The local voltage loop equation (3) is expressed at the primary layer of the hierarchical architecture shown in Figure 1(b).

$$G_{vc} = \frac{G_v G_c}{1 + G_v G_c} \tag{3}$$

Here G_c represents the local current controller transfer function, G_v represents the local voltage controller and G_{vc} represents the voltage loop. A secondary control block is also equipped with current and voltage proportional-integral (PI) controllers in addition to the conventional droop control. It is important to note that when using the average voltage PI controller, the converter's output voltage is restored to the reference voltage for the DC MG.

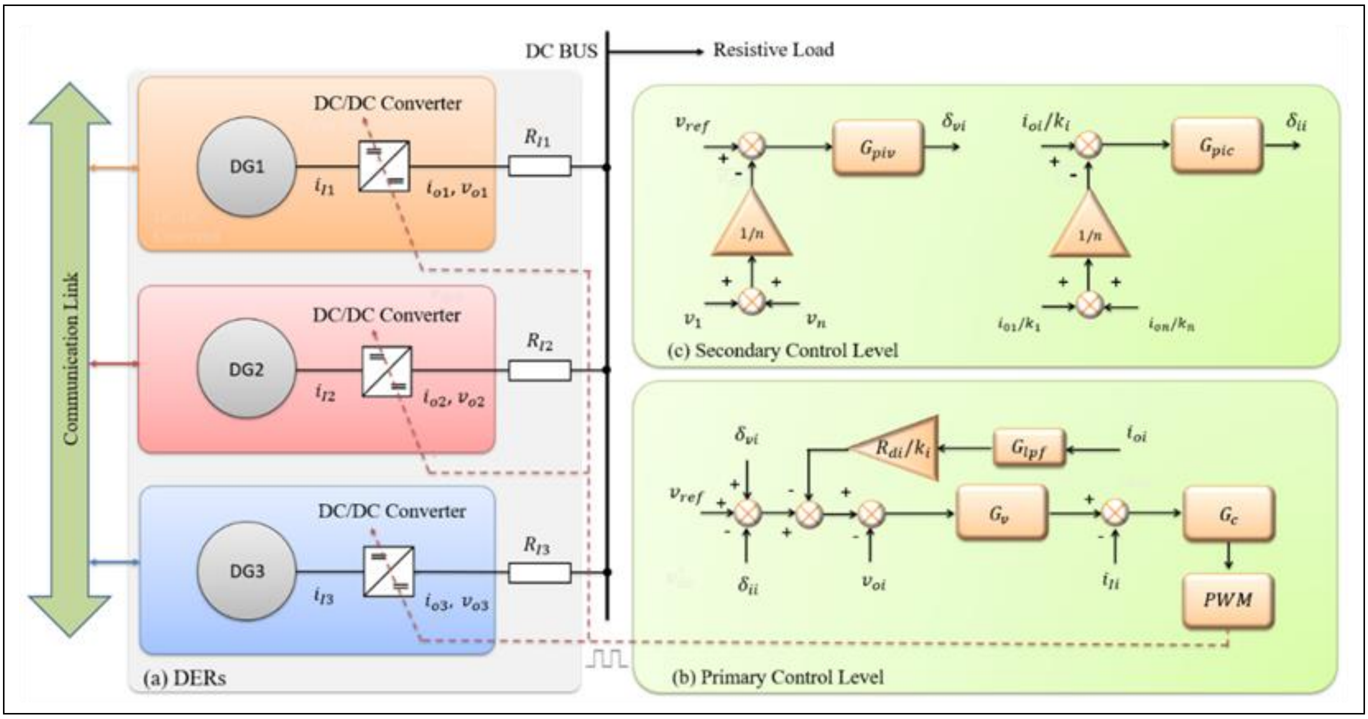

Figure 1. Block diagram of proposed DC MG. (a): DERs, (b): Primary and (c): Secondary control.

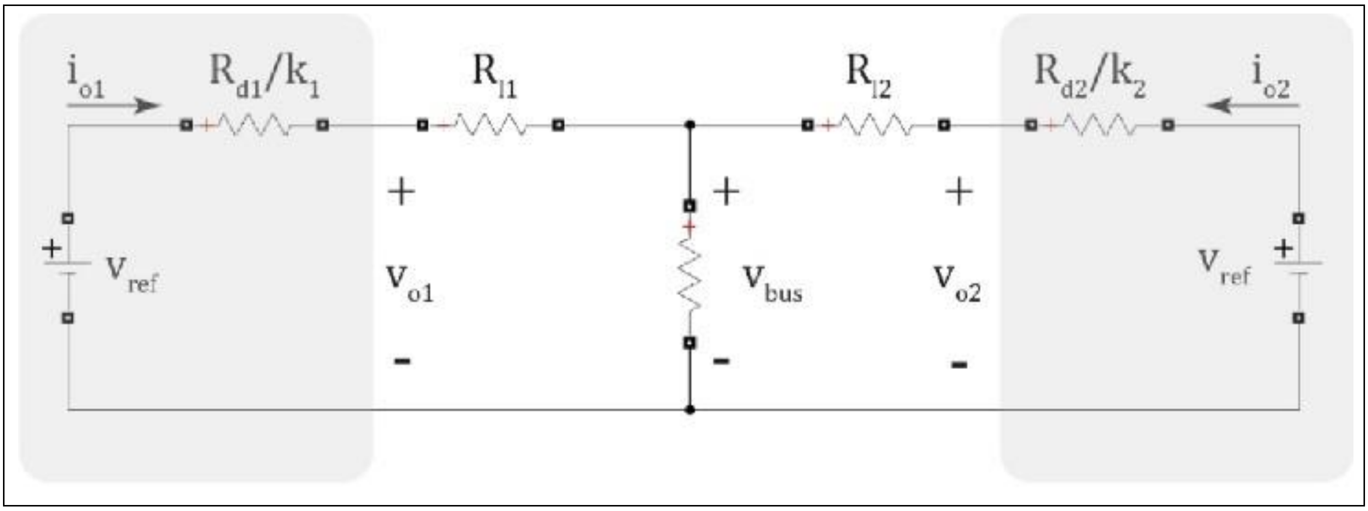

Figure 2. Equivalent circuit model of two-node DC MG structure

Similarly, when using the average current PI controller, the i_{oi}/k_i current ratio is employed to ensure a proportional sharing of output current among the converters. In Equation (4) and Equation (5), average voltage and average current are defined, respectively.

$$\delta_{v_i} = \left(v_{ref} - \frac{v_1 + \cdots + v_n}{n}\right) \cdot (G_{piv}) \tag{4}$$

$$\delta_{i_i} = \left(\frac{i_{o_i}}{k_i} - \frac{i_{o_1}/k_1 + \cdots + i_{o_n}/k_n}{n}\right) \cdot (G_{pic}) \tag{5}$$

Here, n represents the amount of DER units that constitute the MG. δ_{v_i} (V) and δ_{i_i} (V) represent the drop voltage on the droop coefficient depending on voltage and current, respectively. G_{piv} and G_{pic} represent the average voltage and average current PI controller transfer function, respectively. According to Equation (6), the output voltage of each converter is expressed by v_{oi}.

$$v_{oi} = [v_{ref} + \delta_{v_i} - \delta_{i_i} - R_{di}/k_i \cdot G_{lpf} i_{oi}] \cdot G_{vc} \tag{6}$$

Here the value G_{lpf} represents the low-pass filter transfer function used in the secondary controller of the system.

3 Simulation results and discussion

In the simulated DC MG, it is assumed that there are three identical DER units in the supply of the grid. Each DG unit's nominal input voltage level is determined as DC 48 V, and the output power is 1 kW. The created DC bus has a voltage level of 96 V. DC/DC converters are used to adapt the voltage levels between the DC bus and each DG unit. In the proposed DC MG, hierarchical two-level EMS has a droop control approach. The primary layer provides power sharing, while the secondary layer provides voltage restoration in the hierarchical EMS. In the secondary layer, the reference voltage is compared with the average voltage and applied to the input of the PI controller. From here, the average voltage variable parameter is calculated. Likewise, the error between the average of the i_{on}/k_n and the reference value i_{oi}/k_i is applied to the PI controller input. Thus, the average current parameter is calculated. The PI parameters of these controllers are computed as $k_p = 0.5, k_i = 10$ for average voltage and $k_p = 0.035, k_i = 10$ for average current. The coefficients of the PI controller used in the calculation of the current reference in the primary control layer are $k_p = 0.5, k_i = 10$. The reference current and converter current are compared and applied to the other PI controller. The coefficients of the PI controller are $k_p = 0.025, k_i = 10$. The PWM duty rates applied to the converters are determined by the value obtained at this controller output.

In this study for the DC MG;

- Conventional droop control,
- Adaptive droop control,
- Power allocation according to different current sharing rates in adaptive droop control,

simulation studies have been carried out, respectively. Finally, a comparison of controllers and interpretation of results is evaluated.

3.1 Conventional droop controller results

The conventional method has been used in the DC MG. In DC MGs, mostly line resistors may be neglected because DERs are close to the consumption centre. However, in this method, simulation studies have been carried out on whether line resistors are included to observe the effect of line resistors on DERs. In the system powered by three different DERs, the current sharing ratios are chosen as 1, and the system's performance is examined for variable load groups. Firstly, where line impedance is not included, the output current, voltage and power graphs for the conventional method are given in Figure 3.

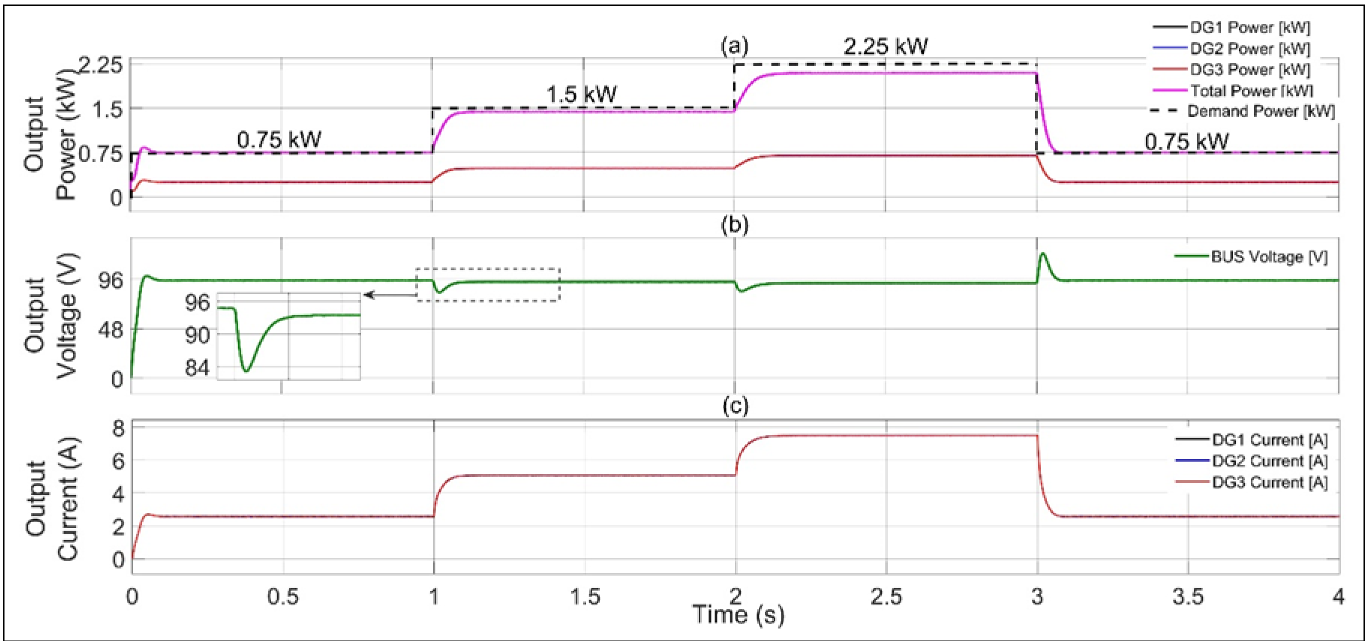

Figure 3. Analysis results without using line resistors in the conventional method. (a): Power. (b): Output voltage and (c): Output current graphs.

Initially, the system, which is 0-1 s range, is loaded with 750 W. The system is supplied with 249 W power by each DER source; in this case, the total power transferred is 747 W. A resistive load, which is a capacity of 750 W, is added to the DC MG system in 1 second of the simulation. Although the output currents of the DGs are evenly distributed, a voltage drop of approximately 2.5 V occurs in the DC bus (see Figure 3(b)).

When an additional resistive load, a capacity of 750 W, is activated at 2 s, the total demanded power is 2250 W. Depending on the load increase, the DC bus voltage and the power transferred to the load decline. Although the demanded power has been 2250 W, the power transferred to the load has been limited to 2091 W. When the power of 1500 W is removed at 3 s, the total demanded power is 750 W. The graph of the simulation performed with the conventional method, in which the line impedances are neglected, is given in Figure 3, and the results are shown in Table 1. When the line resistors are not included in the system, the total power that can be transferred to the system is shared equally among identical DER sources. However, the DC bus has a voltage drop, and the demanded power cannot be fully met.

Under the same conditions, a similar simulation study is performed to include line resistances. The values of the line resistances have been determined as 0.2 Ω, 0.4 Ω, and 0.6 Ω for DG1, DG2, and DG3, respectively. The output current, voltage and power graphs for the simulation are presented in Figure 4. It is seen that there is an unbalanced current sharing among the converters by adding different line resistances to each DG. Although the droop coefficients are the same, the current sharing among the sources differs. This situation is a constraint of the conventional method. Also, as expected, there has been some decline in DC bus voltage with the inclusion of line resistors. In meeting the power demanded by the system, DERs could not be loaded equally, and the demand power could not be fully met. The results regarding this situation are given in Table 1. For example, it is clearly seen that there is a voltage drop of 4.3 V in the simulation's 1-2 s interval. The highest demanded power, the 2250 W, has been met by DERs as 829 W, 659 W and 544 W, respectively, in 2-3 s time intervals. In this case, the total power transferred to the load has been realized as 2032 W.

3.2 Adaptive droop controller results

The adaptive method is used in the proposed DC MG. Similarly, the simulation studies of the system are examined separately for the case of not including the line resistance and including it. The simulation results in DC MG controlled by the adaptive method are given in Figure 5, where line resistors are not considered. When the simulation results are examined, the bus voltage stability of the adaptive method is better than the conventional method. For example, while the bus voltage in the 1-2 s time interval is 93.5 V in conventional droop control, it is restored to approximately 96 V by adaptive droop control. A similar performance increase is seen in the ability to meet demand power. For example, the demand is the highest in the 2-3 s time interval, in which each DERs produce approximately 750 W. This generated total power fully meets demand power as 2250 W.

The DERs in DC MG, where the adaptive droop control method is applied, are operated by adding line resistors. The output current, voltage and power graphics are given in Figure 6. As in previous simulation studies, the same scenario is applied when line resistance is considered in the system. Contrary to what is observed in Figure 4(c), the output currents of the converters are shared equally among DERs. Thus, the accuracy of current sharing has been increased. The output voltages of the converters have been restored to the reference voltage.

3.3 Power allocation according to different current sharing rates in adaptive droop control

In this subsection, the power-sharing performance of the proposed adaptive droop controller at different current-sharing ratios has been examined. In the analyses made for the proposed DC MG, the current sharing ratio of k_i is chosen as 1. Thus, it is aimed to share the demand load equally among all converters. The current sharing ratios chosen for DERs determine the power each source will transfer to the load. The power distribution has been simulated according to different current sharing ratios for 1500 W demand load. While the output currents of the converters are $i_{o1}: i_{o2}: i_{o3} = 2: 3: 4$ in the 0-1.5 s time interval; these ratios are determined as $i_{o1}: i_{o2}: i_{o3} = 6: 3: 4$ in the 1.5-3 s time interval. Analysis results of DC MG operated according to different current sharing ratios are given in Figure 7. The power-sharing values between DER units in the 0-1.5 s range are 330 W, 490 W and 680 W, respectively. Depending on the change in the current sharing ratios, the power values in the 1.5-3 s range are 650 W, 330 W and 520 W, respectively. The results show that the proposed system shared power according to the current sharing ratios and supplied the resistive load stably. At the same time, as seen in Figure 7(b), a stable bus voltage has been obtained by keeping the DC bus voltage constant at 96 V, which is the reference voltage. These results show that the proposed adaptive droop controller supplies the resistive load stably by sharing power according to the current sharing ratios.

Table 1. Performance comparison of controllers at different load conditions.

		Conventional droop control							Adaptive droop control					
	Time (s)	Demand power (W)	Total power (W)	DG1 power (W)	DG2 power (W)	DG3 power (W)	BUS voltage (V)	Power demand coverage ratio(%)	Total power (W)	DG1 power (W)	DG2 power (W)	DG3 power (W)	BUS voltage (V)	Power demand coverage ratio(%)
Without line res.	0-1	750	747	249	249	249	94.7	99.60	749	250	249	250	96	99.87
	1-2	1500	1435	478.3	478.5	478.2	93.5	95.47	1495	498	500	497	95.9	99.67
	2-3	2250	2091	697.1	696.9	697	92.2	92.40	2247	752	748	747	95.9	99.87
	3-4	750	744	248	248	248	94.7	99.19	749	250	250	249	95.9	99.87
With line res.	0-1	750	742	302	240	200	93.8	98.92	750	252	252	254	96	100
	1-2	1500	1406	576	456	376	91.7	93.13	1499	501	512	518	96	99.93
	2-3	2250	2032	829	659	544	89.6	89.27	2249	770	769	782	96	99.96
	3-4	750	737	310	238	189	93.8	98.24	750	251	255	254	96.1	100

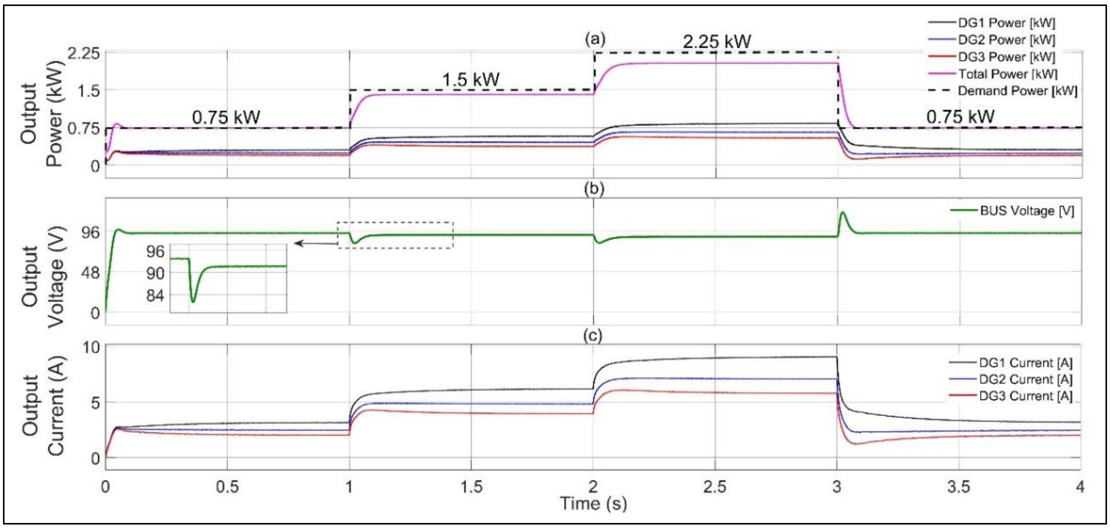

Figure 4. Analysis results by using line resistors in the conventional method. (a): Power. (b): Output voltage and (c): Output current graphs.

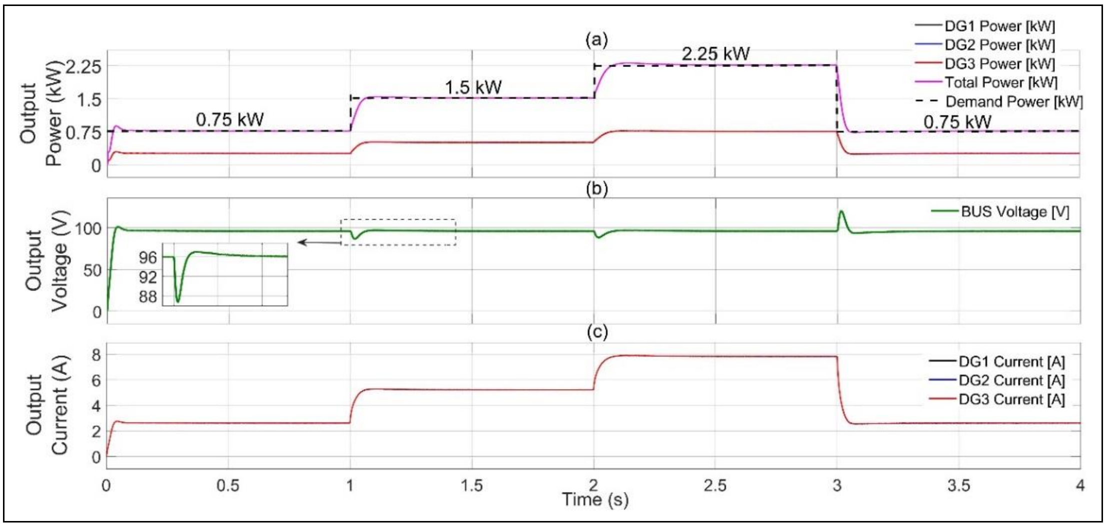

Figure 5. Analysis results without line resistances in the adaptive droop control method. (a): Power. (b): Output voltage and (c): Output current graphs.

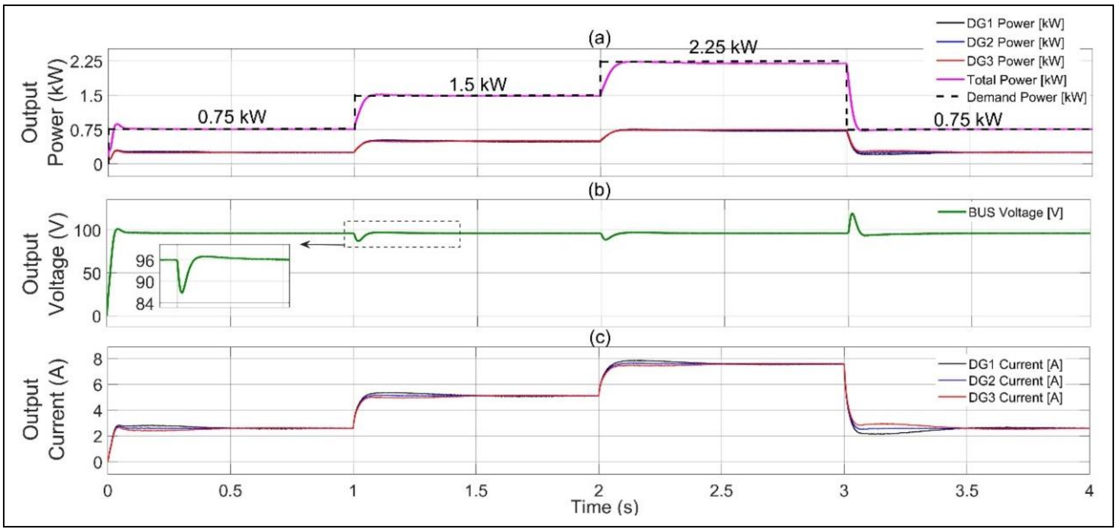

Figure 6. Analysis results with line resistances in the adaptive droop control method. (a): Power. (b): Output voltage and (c): Output current graphs.

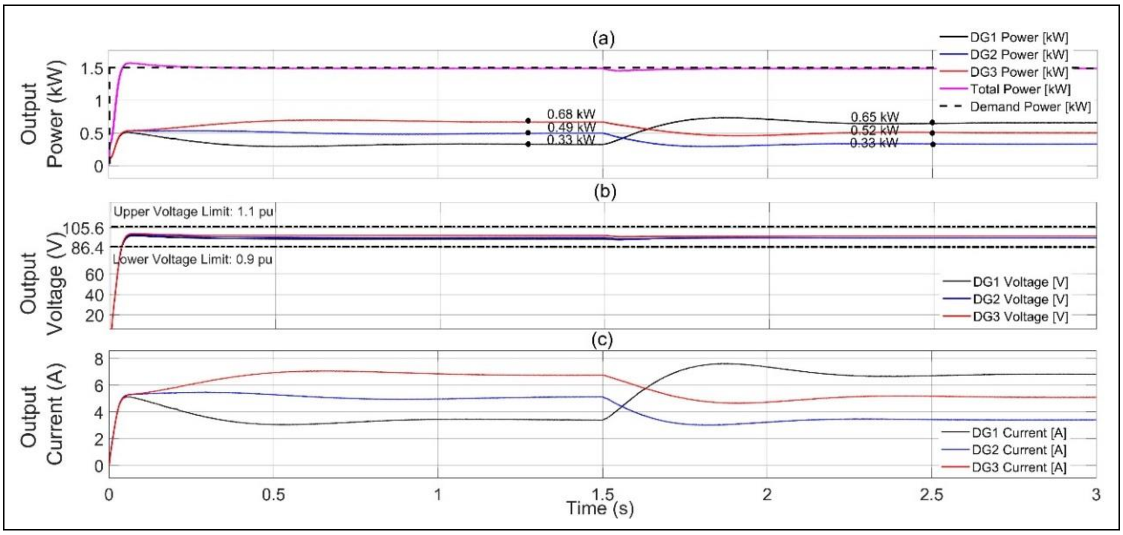

Figure 7. Analysis results according to different current sharing ratios between converters. (a): Power. (b): Output voltage and (c): Output current graphs.

3.4 Comparison of controllers and interpretation of results

In this study, conventional and adaptive droop controllers are used in the proposed DC MG energy management. The performance of the controllers is analyzed according to variable load demand and whether or not line resistors are included. The simulation results are presented in Table 1. In this case, where line resistors are not included, and current sharing ratios are chosen equally, both methods share demand power equally. However, in conventional droop control, the DC bus voltage is lower than the reference voltage and hasn't fully met the total demand power.

On the other hand, the proposed adaptive droop control reaches the reference bus voltage and fully meets the demand power. In similar conditions, analyses have been performed for the inclusion case of the line resistance. The DC bus voltage drops slightly depending on the line resistance in conventional droop control. At the same time, the demanded power is not fully met, and power sharing among DERs is unequal. These situations are significant disadvantages of the conventional droop controller. The adaptive droop controller overcomes these disadvantages by stabilizing the DC bus voltage and realizing equal power sharing among the DERs. Comparative performance of conventional and adaptive droop control is given in Figure 8 for the worst-case scenario, including line resistors. As can be seen clearly from Figure 8, adaptive droop control provides better DC bus voltage stability. Accordingly, its performance in meeting the demand power is higher than the conventional method. The conventional method in the DC MG structure has been measured as 89.6 V in the 2-3 s time interval when the demand power is highest (2250 W). In adaptive droop control, the bus voltage is equal to 96 V, which is the reference voltage. In this case, where line resistors are included, the conventional droop controller provides 2032 W, while the adaptive droop controller provides 2249 W. According to these results, the performance of the adaptive droop controller in power transfer is 9.65% better.

In this study, an adaptive droop control approach and a hierarchical two-level energy management system are proposed to coordinate the DG units' operation. According to the proposed adaptive droop controller, the primary layer provides load sharing among the DERs, while the secondary layer provides current and voltage restoration. Thus, power sharing among DG units has been realized stably. The conventional droop controller could not restore the bus voltage to the reference voltage and could not provide equal load sharing among the DERs. The adaptive droop control method uses a secondary control level to maintain the DC bus voltage around the voltage reference. At the same time, it provides balanced load sharing among DERs, and its performance in meeting power demand is higher than the conventional method. By using the proposed adaptive method, the functions and constraints of conventional droop control are eliminated. The proposed adaptive droop controller, operated by the highest power demand at 2250 W, improved the DC bus's power transfer performance and voltage regulation by 9.65% and 6.67%, respectively, compared to the conventional method. As a result, the adaptive droop controller restores the DC bus voltage and stably manages the power flow. Additionally, DC MG provides plug-and-play flexibility and can be integrated into rural and industrial applications.

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5 Author contribution statements

In this study, Ahmet KAYSAL contributed to the literature review, design and writing of the paper, Selim KÖROĞLU contributed to the evaluation of the results and review, and Yüksel OĞUZ contributed to the spelling and checking of the paper's content and review.

6 Ethics committee approval and conflict of interest statement

The ethics committee is not required to grant permission for the article to be written.

There is no conflict of interest between the author and any person or organization contributing to the article.

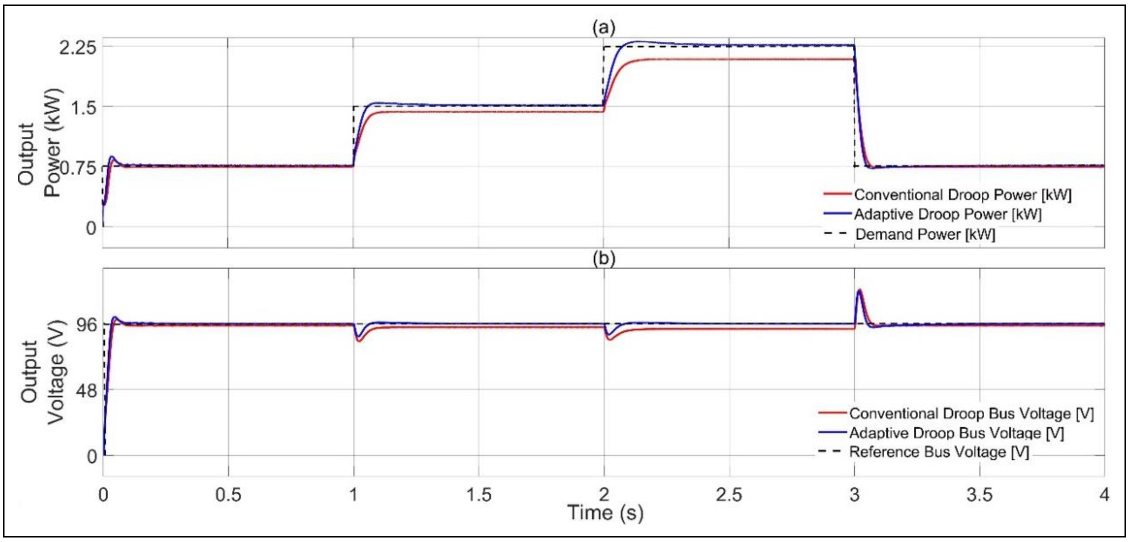

Figure 8. Performance comparison of conventional and adaptive droop controllers. (a): Output power (W). (b): DC bus voltage (V).

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