

Economic Droop Scheme for Decentralized Power Management in DC Microgrids

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Abstract: This paper proposes an autonomous and economic droop control scheme for DC microgrid application. In this method, a cost-effective power sharing technique among various types of DG units is properly adopted. The droop settings are determined based on an algorithm to individually manage the power management without any complicated optimization methods commonly applied in the centralized control method. In the proposed scheme, the system retains all the advantages of the traditional droop method while minimizes the generation costs of the DC microgrid. In the proposed method, all DGs are classified in a sorting rule based on their total generation cost and the reference voltage of their droop equations is then determined. The proposed scheme is applied to a typical DC microgrid consisting of four different types of DGs and a controllable load. The simulation results are presented to verify the effectiveness of the proposed method using MATLAB/SIMULINK software.

Keywords: Cost-Based Droop Control, Generation Cost, DC Microgrids, Optimal Power Management.

1. Introduction

The concept of microgrid is recently becoming a promising approach to coordinate different types of Distribution Generators (DG) operating both in grid-connected and islanded modes. In both configurations, a global research on power managements and voltage/current control of AC and DC microgrid is being investigated [1]. Real and reactive power managements are the important challenges to be addressed by the control system of the microgrids. In this regards, the overall performance of the microgrid, including generation cost, source capacity and market price should be considered. Although, inverter based AC microgrid has been prevalently utilized in the literature, DC microgrids are more interesting concept. Nowadays, DC loads are responsible for more than 35% of the electricity consumption in residential and commercial applications [2]. Besides, the major kinds of emerging renewable energy sources and storage units have DC output and can efficiently connect to a DC network without any extra converter stage [3]. Moreover, reactive power control as one of the most prominent issues in AC microgrid, is not considered in the DC system.

The control structures for microgrids are generally achieved using either centralized or decentralized control schemes that can be composed of different hierarchical levels [6]. In the centralized control structure, the main target is to realize the optimal economic operation or to improve the power quality of microgrids. Accordingly, Microgrid Central Controller (MGCC) plays the most prominent role in the power management strategy [10], [25]. Several works have been issued to minimize the total cost of power generated by DGs [5]-[8], [26]-[27]. Among them, some articles have focused on the economic operation of DC microgrids [5], [6]. The basis of the central control methods generally includes some objective functions and the constraints associated with the generation units. Therefore, the optimization problems can be solved with various mathematical rules to specify one day-ahead forecast of generation.

Although, the centralized scheme has the advantage of accurate power dispatch from sources with a predetermined schedule, the optimization is strongly dependent to the stochastic power output of intermittent renewable sources and the accuracy of load forecast. In addition, this strategy needs to transmit data between DGs and central control system through fast and reliable communication systems which are expensive and vulnerable especially for long distances [9]. Hence, the tendency is towards the decentralized control schemes to achieve redundancy and to avoid the complexity of the system.

Decentralized scheme is mostly realized with the popular droop control method that ensures the plug-and-play feature of power sources. On the other hand, some DGs

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can be seamlessly connected to or disconnected from the microgrid when and where they are needed [11]. With the droop method, no communication or just low-frequency communication is required, which is much easier to be accomplished and then higher system reliability can be derived [3]. In the droop-based methods, the total power demand is proportionally assigned among the participating converters-based DG units based on their rated capacity. To achieve this, the output voltage reference of each converter is modified by imposing virtual output impedance to its voltage control loop.

Despite the above mentioned advantages, the traditional droop control suffers from some main concerns such as inaccurate power sharing and voltage deviation, especially in microgrids with noticeable line impedances [12]. The concerns will be raised in AC microgrid where the active and reactive power dispatch is strongly affected by the line impedance [9]. Thus, a great deal of research has been conducted to enhance the accuracy of power dispatch in microgrid [4], [13]-[19].

Nevertheless, in all researches which have been mentioned so far, the settings of the droop schemes based on the rated capacity fail to satisfy optimal operation of the microgrids. None of them employs the generation cost of DGs which has been mostly realized in centralized schemes to minimize the total cost of the microgrid. Consequently, some methods have been presented to optimally handle the droop coefficients of DG units to overcome the aforementioned drawbacks [17]. However, in all these works, the existence of MGCC and communication links are fully required to economically update the droop characteristics of the DG units.

Recently, some authors have tried to bring the cost function into the droop control structure [20]-[22]. In [20] and [21], a nonlinear droop curve is utilized to lower the total cost of the microgrid based on the nonlinear cost function of DGs. In these works, the droop coefficients are determined based on the rated capacity as well as the normalized generation cost of the sources. Although the methods utilized in these papers reduce the generation cost, the result is far from the optimization target which can be adopted from the centralized scheme. Moreover, in these papers, all DGs have a single reference voltage that causes them to simultaneously contribute in power dispatch regardless of the load condition. The microgrid thus never aims to achieve a proper cost-effective solution. An improved power sharing technique by considering different reference voltage for each DG has been issued in [22]. This method can reduce the total cost of the whole microgrid compared to the strategies mentioned earlier [20]-[21]. Though, power sharing in this method is not still tracking the feasible solution compared to the mathematical solving rules. The condition is more crucial in light load conditions of microgrid where the whole load must be supplied by the least costly DG.

To overcome the aforementioned drawbacks, an optimal power management strategy for the autonomous DC microgrids with a novel cost-based droop control method is proposed. The key feature of the proposed method is that the objective of the total cost ever tracks the minimum solution point in a smart manner and is more economical in comparison with the recent works. In this regard, a new sorting technique based on the cost curve of the involved DGs is used to determine the parameters of their droop lines. In a cost-based priority rule, less costly DGs will hence remain off in light loads and participate in power dispatch based on their predetermined ranking orders. With the new policy, the proposed strategy will still retain the advantages of the traditional droop control scheme.

The rest of this paper is outlined as follows. Section II discusses the framework of the conventional droop controller in DC microgrid. In Section III, the cost function of DG sources is presented. The proposed cost-based droop control scheme is described in section IV. Section V describes the microgrid used for validation of the proposed method in MATLAB/SIMULINK environment, and presenting and discussing the results. Finally, the main features of the presented work are highlighted in Section VI.

2. Conventional Droop Controller

The conventional droop characteristics in DC microgrids can be written as (1) [23]. In general, the output power or current of each DG is measured to control the voltage deviation of the respective DC bus [24]. The target is to enforce DGs to share the proportional power or current based on the capacity of each DG by introducing the internal virtual resistance (R_d) as a control parameter. The value of R_d for each DG is inversely relevant to its capacity and defined in (2).

$$V_{o,i} = V_{max} - R_{d,i} I_{o,i} \quad (1)$$

$$R_{d,i} = \frac{\Delta V}{I_{i,max}} \quad (2)$$

where i is the index representing each DG, $V_{o,i}$, $I_{o,i}$ and $I_{i,max}$ are, respectively, the output voltage, the output current and the current capacity of the source. V_{max} and ΔV refer to the highest permissible voltage (reference voltage) and voltage deviation of the system respectively.

A simple DC microgrid with two DGs operating with the droop control scheme is shown in Fig. 1. The droop controller characteristics curves of DGs with different virtual resistance (R_d) are depicted in Fig. 2. It is noted that the reference voltage of all DGs is generally identical, whereas the virtual impedances are certainly different for DGs of various capacities. Taking Fig. 2 as an example,

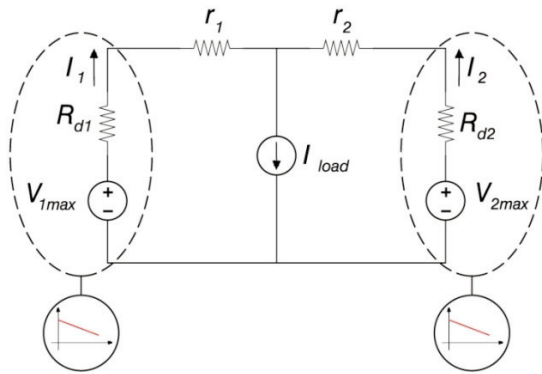


Fig. 1. A simple DC microgrid with two DGs

it is evident that for a common output voltage, the power injected from DG1 is proportional to the output power of DG2 with (3). Meanwhile, in the presence of the load, both DGs are always involved in power sharing.

However, in order to intentionally employ some DGs in a specific load condition, the reference voltage ($V_{i,max}$) and voltage variation range (ΔV_i) of each DG will be different. An example of this method in a microgrid with two DGs is shown in Fig. 3. From this figure, it is obvious that in the voltage range of $[V_{2,max} V_{1,max}]$, DG1 is the only source which supplies the load as long as the load current is less than I_{tr} .

$$R_{d,1}I_{o,1} = R_{d,2}I_{o,2} \quad (3)$$

$$V_{o,i} = V_{i,max} - R_{d,i}I_{o,i} \quad (4)$$

$$R_{d,i} = \frac{\Delta V_i}{I_{i,max}} \quad (5)$$

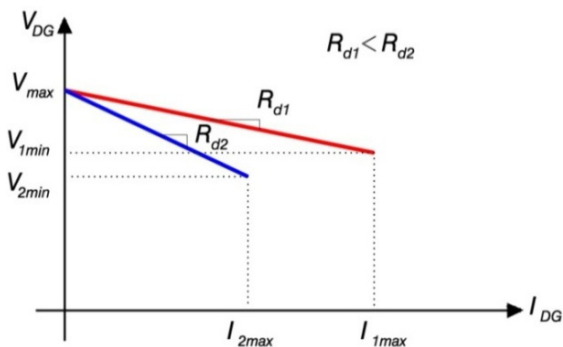


Fig. 2. A conventional droop control for two DGs

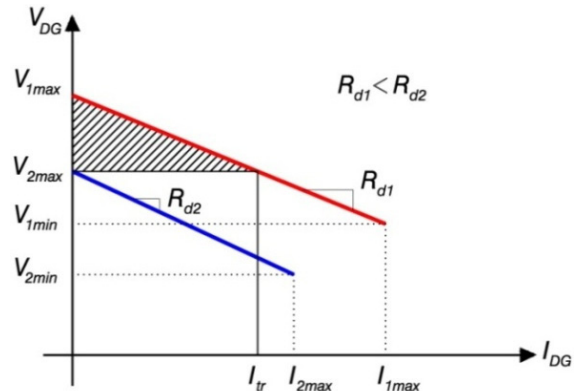


Fig. 3. Droop control curves for two DGs of different reference voltage in DC microgrid

3. Description of the Proposed Method

3.1. Cost Function of DGs

The generation cost of different types of DGs is generally related to their operating cost (consisting of fuel and maintenance costs) and emission cost. The fuel cost of traditional DGs such as diesel generator and micro-turbine and the emission cost of green sources such as fuel cell, wind and photovoltaic sources can be represented by second-order quadratic equations; whereas the maintenance cost of all types of DGs is linearly related to the power output. Then, the total generation cost function of a generic DG consisting of a dispatchable source such as diesel generator, fuel cell and micro-turbine or non-dispatchable source such as wind and PV with energy storage can be comprehensively obtained in (6) [22].

$$C(P) = a + bP + cP^2 \quad (6)$$

where a , b and c are cost coefficients. P and $C(P)$ refer to the instant power and generation cost of DG respectively.

3.2. Proposed Cost-Based Droop Control Scheme

As discussed in section II, to intentionally involve a DG in load sharing based on its respective generation cost, the reference voltage of its droop equation should be determined. In order to apply the proposed method, below procedure is employed for determining the droop parameters. The proposed algorithm is shortly depicted in a flowchart shown in Fig. 4.

1. The cost function of all DGs based on the earlier quadratic function as mentioned in (6) are applied to draw the generation cost curves. As an example, the cost curves of four DGs employed in the typical DC microgrid utilized in this paper are shown in Fig. 5. In this figure, DG1 and DG4 are diesel gen-

erators and DG2 and DG3 are renewable-based DGs. Note that for standardization, all curves need to be plotted as $C_i^{p.u.}(P_i^{p.u.})$ versus $P_i^{p.u.}$. These parameters are defined as follows:

$$P_i^{p.u.} = P_i/P_{i,max} \quad (7)$$

$$C_i^{p.u.}(P_i^{p.u.}) = C_i/P_{i,max} \quad (8)$$

where, P_i , C_i and $P_{i,max}$ are respectively the instant power, cost and power capacity of i th DG.

- DGs are classified in an ascent sorting rule based on their generation cost. Taking Fig. 5 as an example, four DGs utilized in the typical microgrid are sorted in Fig. 6. As it can be seen from this figure, DG1 and DG2 are respectively the least and the most costly DGs participating in the generation. For better realization of the cost effect of each DG on the power sharing, a new parameter, namely

“cost energy” (CE) can be described based on the cost curves. The parameter can be accurately determined by calculating the surrounded area under the cost curve of each DG. On the other hand, the new parameter can be obtained by integrating the cost function from 0 to 1 as given by (9). However, with a good approximation, it can be linearly derived as (10).

$$CE_i = \int_0^1 C_i^{p.u.}(P_i^{p.u.}) dP_i^{p.u.} \quad (9)$$

$$CE_i = \frac{C_i^{p.u.}(0) + C_i^{p.u.}(1)}{2} \quad (10)$$

In the above formulas, $C_i^{p.u.}(0)$ and $C_i^{p.u.}(1)$ are, respectively, the cost values of i th DG at the minimum and maximum value of $P_i^{p.u.}$. CE_i refers to the cost energy of the respective DG.

The cost energy defined in the proposed method directly implies the cost weight of each DG in the power sharing with no error. If there is a non-linear cost function during the interval of $[0, 1]$, then the exact formula given in (10) can be used.

- The permissible voltage drop of each DG is then related to the CE factor as follows:
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$$\Delta V_i = \Delta V_{grid} \times \frac{CE_i}{\sum_{j=1}^n CE_j}, i = 1, \dots, n \quad (11)$$

where, ΔV_i is the maximum voltage drop on i th DG and ΔV_{grid} is the safe operating voltage deviation of microgrid. The reference (maximum) voltage of each DG is then obtained from (12):

$$\begin{cases} V_{k,max} = V_{max}^{grid}, & \text{for } k = 1 \\ V_{k,max} = V_{k-1,max} - \Delta V_k, & \text{for } k = 2, \dots, n \end{cases} \quad (12)$$

where, index k refers to the sorted DGs rearranged in step 2, V_{nom}^{grid} is the maximum voltage of grid and $V_{k,max}$ is the maximum (reference) voltage of k th DG.

- The internal virtual resistance R_d is determined according to the conventional method as introduced in (2). Moreover, this parameter is indirectly dependent to the cost function.

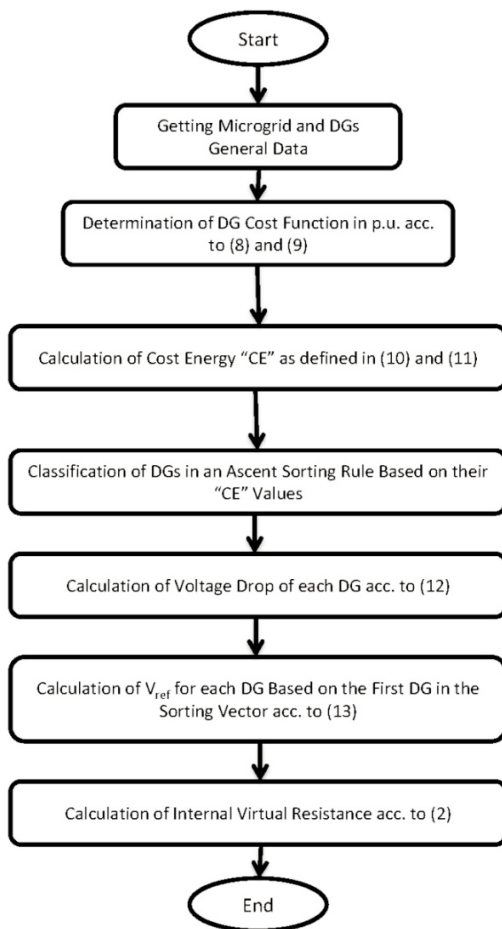


Fig. 4. Flowchart of the proposed algorithm.

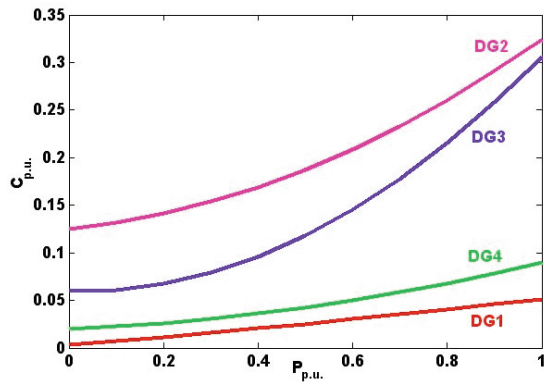


Fig. 5. Cost curves of four DGs used in the typical microgrid.

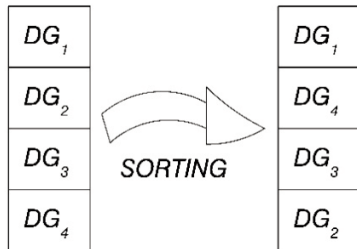


Fig. 6. Illustration of rearranged sorted DGs.

4. Microgrid Architecture and Simulation Result

In order to verify the proposed method, an autonomous DC microgrid formed with four DGs and a variable load is shown in Fig. 7. The control block of the proposed droop scheme with an inner current loop and two PI compensators is illustrated in Fig. 8.

It is assumed that the applied DGs comprise two dispatchable sources (DG2 and DG3) and two non-dispatchable sources supported by energy storage (DG1 and DG4). Table I lists the general specification of the proposed microgrid, DGs and the load.

The voltage range chosen for the microgrid is defined as $0.95 \text{ p.u.} \leq V_{nom}^{grid} \leq 1.05 \text{ p.u.}$ with the nominal voltage of 48V. Then the reference voltage of the least costly DG is set to 1.05p.u. the maximum grid voltage. Meanwhile, according to equations (12) - (13), the voltage drop of each DG and then the reference voltage of the other DGs will be obtained. Accordingly, the droop lines of the four DGs are plotted in Fig. 9.

Based on these droop control schemes, the power dispatch priorities are identified as follows:

1. As long as I_{load} is less than $I_{(1,max)}$, DG1 is the

Table 1. General specification of the microgrid.

GENERAL DATA		
Description	Value	
Nominal Voltage	48 V	
Voltage Range	45.6 V-50.4 V	
Max. Capacity	6 kW	
DISTRIBUTED GENERATORS		
DG No.	Type	Capacity
DG1	Diesel	2.5kW
DG2	Diesel	1.25kW
DG3	PV with Battery	1kW
DG4	PV with Battery	1.25kW
LOAD		
Description	Type	Value
Controllable Load	DC	0 to 6 kW

2. only DG which supplies the load.
2. When $I_{(1,max)} < I_{load} \leq I_{(1,max)} + I_{(4,max)}$, then DG4 is the second DG to generate.
3. When the load increases further, DG3 has the priority number 3 to supply the increased load.
4. In full load condition, DG2 participates in power sharing while superior DGs operate at their full capacity.

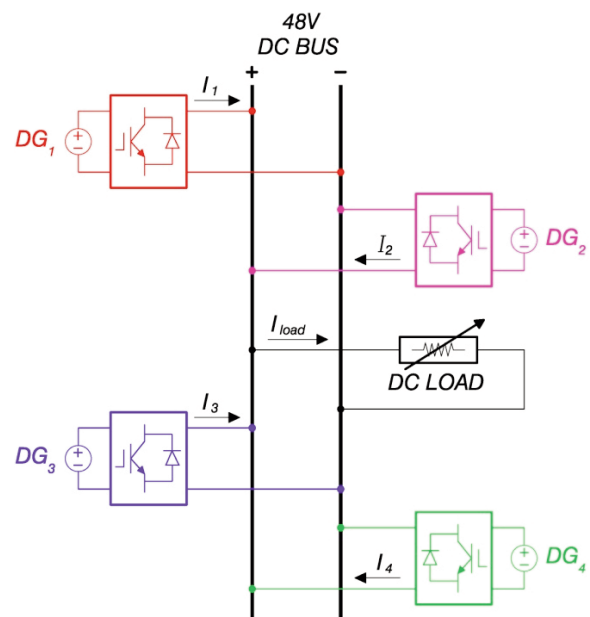


Fig. 7. Typical DC microgrid with four DGs.

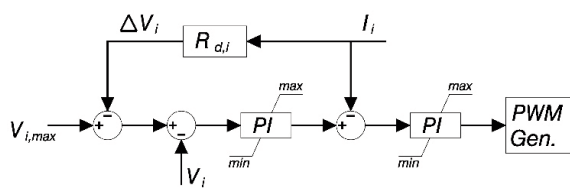


Fig. 8. Control block of the proposed droop scheme.

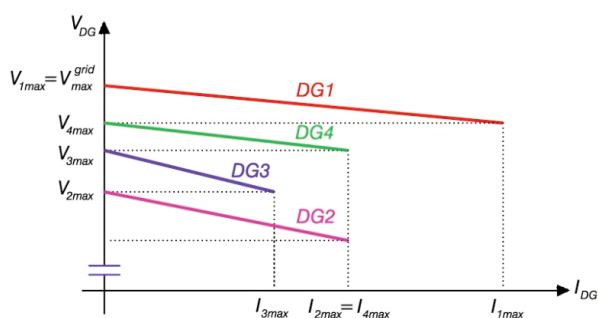


Fig. 9. Droop curves of four DGs utilized in the typical DC microgrid.

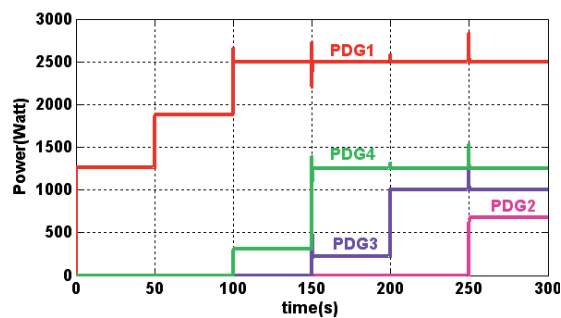
Simulation is then performed for six different load conditions which set at 20%, 30%, 45%, 55%, 70% and 85% of the total generation capacity of the microgrid. The results, including generation power dispatch, voltage and the respective costs of the microgrid were compared to the method utilized in [22] and shown in Fig. 10, 11 and 12. Based on these figures, the discussion for each interval is provided as follows:

Interval $t=0$ to 50 s, while load sets at 20% of the total generation capacity:

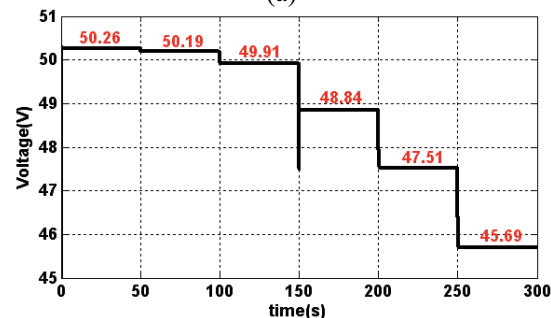
During this interval, only the least costly DG1 with the minimum “cost energy” coefficient operates to supply the light loads as depicted in Fig. 10.a; whereas, according to Fig. 11.a, the power sharing of the method utilized in [22] does not track the economic power management as the second prioritized generator has undesirably interfered in power sharing. Resulting cost derived from Fig. 12 confirms that the generation cost of the whole microgrid in the proposed method is about 46% less than that in the method of [22]. Fig. 10.b shows the microgrid voltage as 50.26V which is within the intended range and higher than the reference voltage of the other droop lines.

Interval $t=50$ to 100 s, while load sets at 30% of the total generation capacity:

Fig. 10.a shows that DG1 as the only involved generator increases its generation again to supply the load. The cost curves of the former method show that at the same



(a)



(b)

Fig. 10. (a) Power sharing, and (b) Voltage variations for the microgrid in the proposed method.

interval, DG4 and DG3 as the second and third prioritized generators cooperate with DG1 in supplying the load. Therefore, the proposed method leads to a significant cost saving of 200% of that incurred by [22]. Fig. 10.b shows the voltage of 50.19V which is still within the defined range.

Interval $t=100$ to 150 s, while load sets at 45% of the total generation capacity:

As from Fig. 10.a, the least costly DG1 increases its generation to the maximum capacity, but since the load requests further demand, then DG1 is not the only generator to operate. The second prioritized generator, i.e. DG4, starts to generate, which pushes down the voltage to 49.91V. The voltage is surely within the intended range and higher than the reference voltage of the less prioritized DGs. In this load demand, the total cost of the microgrid in the proposed method is less than of that in [22] by about 47%.

Interval $t=150$ to 200 s, while load sets at 55% of the total generation capacity:

By increasing the load to 55%, the second prioritized generator of DG4 achieves its full capacity as illustrated in Fig. 10.a and then DG3 begins to generate based on its third priority. The voltage of 48.84V read from Fig. 10.b is still within the defined range and higher than the reference voltage of the lower prioritized DGs. The microgrid in the proposed method is now saving 5% more than of that incurred in [22].

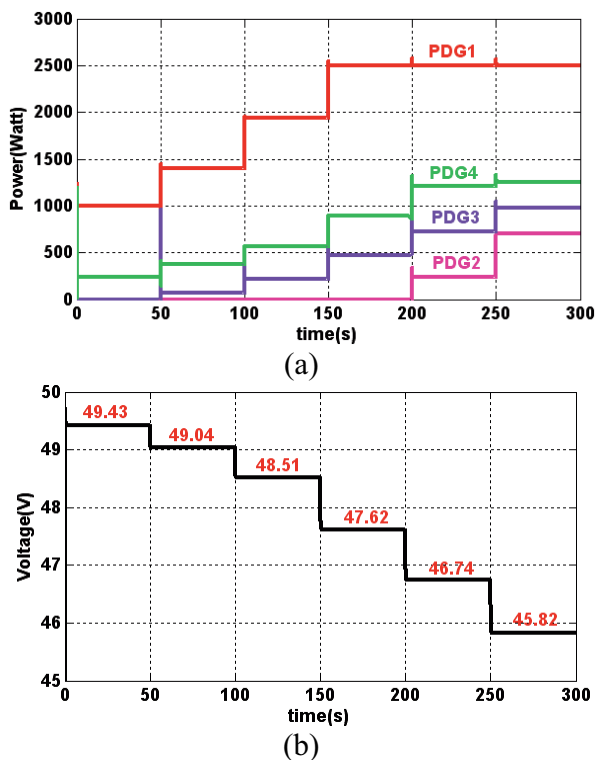


Fig. 11. (a) Power sharing, and (b) Voltage variations for the microgrid in [22].

Interval $t=200$ to 250 s, while load sets at 70% of the total generation capacity:

The same expected procedure is followed in this interval to minimize the total generation cost. Therefore, the third highest rank DG3 only increase its power output. In comparison with [22], it is evident that the proposed optimization method makes a slight cost saving of about 4%. The voltage drops to 47.51V as read from Fig. 10.b.

Interval $t=250$ to 300 s, while load sets at 85% of the total generation capacity:

Fig. 10.a shows that the most costly source, i.e. DG2,

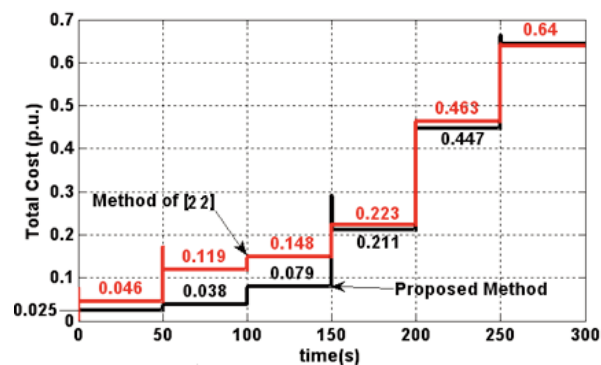


Fig. 12. Generation cost of DGs in the proposed method comparing with [22].

participates in power sharing while the other higher prioritized DGs are still operating at their full capacity. The total cost in this interval is evidently the same as that incurred in [22]. Fig. 10.b shows the voltage of 45.69V which is still within the defined range.

To better identify the predominant features of the proposed method comparing to the recent method utilized in [22], the cost saving at different load conditions is summarized in Table. II. The considerable cost saving is due to the droop schemes utilized in [22] which is based on the rated capacity as well as the normalized generation cost of the sources. In this paper, all DGs have a single reference voltage that causes them to simultaneously contribute in power dispatch regardless of the load condition. The microgrid thus never aims to achieve a proper cost-effective solution.

In real condition where the total generation of a microgrids is about two times the full load demand, the operational cost saving is more considerable.

5. Conclusions

A novel cost-effective droop control for autonomous

Table 2. Cost Saving of the Proposed Method Comparing with [22].

Load Condition (% of Total Generation)	Proposed Cost-Based Method	Cost-Based Scheme in [22]	Cost Saving Compared to [22]
	DGs in Operation	DGs in Operation	
20%	1	1 and 4	46%
30%	1	1, 4 and 3	200%
45%	1 and 4	1, 4 and 3	47%
55%	1, 4 and 3	1, 4 and 3	5%
70%	1, 4 and 3	1, 4, 3 and 2	4%
85%-100%	1, 4, 3 and 2	1, 4, 3 and 2	0

DC microgrid has been proposed to reach an optimal power sharing scheme without any centralized optimization technique. In a priority rule, DGs with the lower priority will hence remain off in light loads and will begin to generate based on a predetermined sorting procedure. The cost saving of the proposed method has been compared with the recently introduced scheme and the results have been summarized. It is shown that the new cost based droop controller causes the microgrid to operate in a most optimized cost manner. The performance of the proposed economic power sharing was performed on a typical DC microgrid with four DGs of different cost function and verified using MATLAB/SIMULINK software.

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