Decentralized Control Strategy for Optimal Energy Management in Grid-Connected and Islanded DC Microgrids

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Abstract: This paper proposes a decentralized control technique to minimize the total operation cost of a DC microgrid in both grid-connected and islanded modes. In this study, a cost-based droop control scheme based on the hourly bids of all participant distributed generators (DGs) and the hourly energy price of the utility is presented. An economic power sharing technique among various types of DG units is adopted to appropriately minimize the daily total operation cost of DC microgrid without a microgrid central controller. The DC microgrid may include non-dispatchable DG units (such as photovoltaic systems) and dispatchable generation units. Unlike other energy management techniques, the proposed method suffers neither from forecasting errors for both load demand and renewable energy power prediction modules, nor from complicated optimization techniques. In the proposed method, all DGs and the utility are classified in a sorting rule based on their hourly bids and open market price, and then the droop parameters are determined. The simulation results are presented to verify the effectiveness of the proposed method using MATLAB/SIMULINK software. The results show that the proposed strategy is able to be implemented in various operation conditions of DC microgrid with resistance to uncertainties.

1 Introduction

DISTRIBUTED generation (DG) is a promising concept to provide a reliable electric supply. DG units can be integrated into a local distribution network namely microgrid. Microgrids are defined as self-controlled distribution network, operating in either grid-connected or islanded operation modes. Based on the characteristics of the voltage supply, they are classified into alternating current (AC) and direct current (DC) types. In both configurations, a global research on power managements and voltage/current control is being investigated [1], [2].

DC microgrid is drawing attention due to provision of high-reliability and high-quality electrical power [3]. Nowadays, DC loads are responsible for more than 35% of the electricity consumption in residential and commercial applications [4]. Besides, the major kinds of emerging renewable energy sources and storage devices have DC output and efficiently connect to a DC grid without any extra converter stage [5]. Moreover, no reactive power exists in DC systems, so higher power quality and system efficiency are obtained compared to AC microgrids [6]. Thus, a great deal of research has been conducted to enhance the reliability and the operation of the DC microgrid [7]- [9].

With regard to control scheme of a microgrid, two distinctive approaches can be identified: centralized and decentralized control systems. In the centralized controller, 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 of microgrid [10], [24]. Several works have been issued to minimize the total cost of the power

generation of DG units [11]- [14], [25]- [28]. The basis of the central control method includes some objective functions and the constraints associated with the power generation. Therefore, the optimization problems can be solved by various mathematical rules to specify day-ahead forecast of the non-dispatchable DG units. Therefore, the optimal energy management of microgrids with centralized control system is based on at least two-layer procedure [3], [13] and [29]:

- Prediction layer that determines day-ahead scheduling for photovoltaic (PV) unit production and load consumption for the next day.
- Energy management layer that solve an optimization problem to determine the hourly power output of each dispatchable DG for the next day.

Although, the centralized scheme has the advantage of accurate power dispatch from sources with a predetermined schedule, the energy management layer is strongly dependent to the stochastic power of intermittent renewable sources and the accuracy of load forecast. In addition, the strategy needs to transmit data among the central control system and DG units through fast and reliable communication systems which are expensive and vulnerable [15]. Hence, the tendency is towards the decentralized control schemes to achieve redundancy and also to avoid the complexity of the system.

Decentralized scheme is mostly realized by the popular droop control method that ensures the plug-and-play feature of power sources. On the other hand, some DGs can be seamlessly connected to or disconnected from the microgrid when and where they are needed [16]. Moreover, no communication or just low-frequency communication link is required, which is much easier to be accomplished and then higher system reliability can be derived [5]. In the droop-based methods, the total power load demand is proportionally assigned among the participant DG converters based on their rated capacity. To achieve this, the voltage reference of each converter is modified by imposing virtual output impedance to its voltage control loop [31].

In all researches which have been mentioned so far, the objective function of the power sharing in the droop control strategy merely relies on the proportional power flow according to the rating power of DGs. None of them employs the generation cost of DGs which has been mostly realized in the centralized schemes to minimize the total cost of the microgrid.

Recently, some authors have tried to bring the cost function into the droop control method [19]-[21], [32]. In these papers, a nonlinear droop curve is utilized to minimize the operating cost of the microgrid based on the nonlinear cost function of each DG. Although the methods utilized in these papers reduce the total generation cost, the result is far from the optimization target which can be adopted from the centralized scheme. Moreover, the papers do not suggest a method

to involve the intermittent renewable sources and to participate in the open market.

To overcome the aforementioned drawbacks, an optimal power management has been achieved in an islanded DC microgrid using an economic droop control method [30]. In this method, the system retains all the advantages of the traditional droop method while minimizes the generation costs of the DC microgrid. The method has been only introduced for the microgrids acting in islanding mode and cannot be applied in grid connected mode. Accordingly, a new optimal power management strategy for a DC microgrid applying in both grid-connected and islanding modes is developed in this paper. The microgrid can include non-dispatchable generation units (such as PV) and dispatchable DG units. A new sorting technique based on the hourly bids of the involved DGs and the utility energy price is employed to determine the parameters of their droop controllers. In a cost-based priority rule, less costly DGs will hence remain off in light loads and will participate in power dispatch based on their predetermined ranking orders. The main contributions of this work are:

- A fully decentralized method is proposed in this paper with no communication network requirements.
- The objective of the operating cost always tracks the minimum solution point. Therefore, the total operation cost in microgrid is autonomously minimized without the need of a centralized controller.
- It requires no complicated mathematical models and it is simple enough to be implemented.
- The proposed method does not need any forecasting module for load demand and renewable energy production. Therefore, the method does not suffer from forecasting errors.
- The microgrid can exchange the power flow with the utility in open energy market to buy or sell the energy any time that needed without any change in its control system.

The rest of this paper is organized as follows. Section 2 discusses the microgrid structure utilized in this paper and the control scheme. In Section 3, the power management system is presented. The framework of the conventional droop controller in DC microgrid is reviewed in Section 3. The proposed cost-based droop control scheme is described in Section 4. Section 5 describes the microgrid used for validation of the proposed method in MATLAB/SIMULINK environment and presents the simulation results. Finally, the main features of the presented work are highlighted in Section 6.

2 DC Microgrid Structure

The understudy DC microgrid including non-controllable loads, three dispatchable sources (one micro-turbine and two fuel cells) and one non-

dispatchable unit (photovoltaic) is shown in Fig. 1. In order to connect the microgrid to the main grid, a bidirectional DC/AC converter is utilized. The converter can be employed either in rectifier or inverter mode, depending on the energy price of the electricity market. Both modes are managed with a unique control technique provided in the control system of the converters.

To precisely support the transients in load change or suddenly power drop of the photovoltaic (PV) system, the fuel cell (FC) and micro-turbine (MT) units are individually equipped with super capacitor (SC) bank. The SC bank serves as a complementary source and is connected to the FC/MT converter bus via a bidirectional DC/DC converter. The fast dynamics and high power density of the SC bank compensates for the low dynamic response of the FC/MT stack during any change on the PV generation or the load demand.

In the proposed method, the output power of the dispatchable DGs and the static converter can be hourly managed through the set points adapted from the bid coefficients and the open energy market. The control strategy of all converters except PV system is based on the droop control method. However, the converter of the non-dispatchable DG generally operates as a current source with a maximum power point tracking (MPPT) algorithm to extract the maximum possible power from the PV unit.

Thanks to the decentralized control policy, we need neither to predict the output power of the loads and non-dispatchable sources, nor to solve the optimization problem of the power sharing. Then, the forecasting error will be exactly neglected and the load power sharing among DGs is independent to the environment conditions and statistical prediction. The system operates by considering the available PV power and taking into account the grid connection. When the output power of PV instantly changes, the power balance is economically ensured thanks to the cost-based droop scheme utilized in the static converter as well as in DG converters.

The converters have to be coordinately controlled with the utility grid to provide an uninterrupted, high efficiency, and economical microgrid under variable solar irradiation and load condition. The system can operate in both isolated and grid connected modes with the same control algorithm.
PV source utilized in this architecture always operate at the MPPT mode to increase the system efficiency. Thanks to the adopted technique, this intermittent feature cannot affect the uninterrupted and economical operation of the microgrid.

The converter of dispatchable sources acts as a voltage source to provide a stable voltage for the DC microgrid. It also operates applying the economic droop control technique to optimize the power dispatch of DG units and power exchange with the main grid in both islanded and grid connected modes.
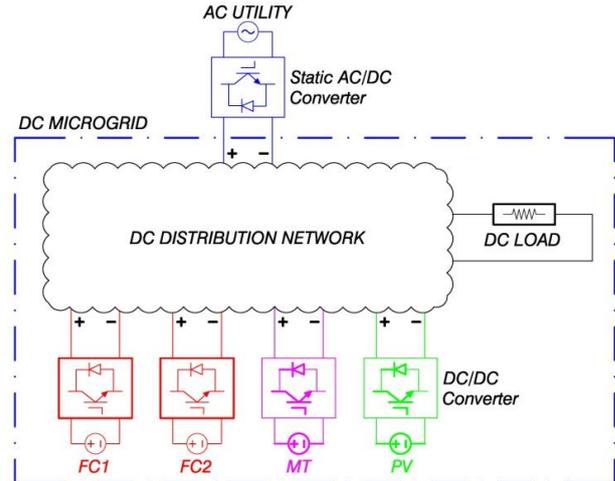

Fig. 1 DC microgrid under consideration.

When the microgrid connects to the utility via the static converter, the converter role may be different. Whenever the open market price is less than the bids of the involved DGs, the converter plays as a DC/AC inverter to inject the power from the utility. While the bids of the participant DGs are less than the energy price of the utility, the microgrid can participate in the open market competition. In this case, the static converter works as an AC/DC rectifier.

3 Power Management System

As mentioned in Section II, in the grid-connected mode, the static converter acts as an inverter to deliver the energy to the main grid or acts as a rectifier to receive the required energy from the main grid. The amount of power in hour and the amount of energy for 24-hour period are determined based on the system power balance and the energy price.

The power under various load and supply conditions in the islanded and grid-connected modes should be balanced as follows:

$$\sum_{i=1,2,3} P_{dis}^i(t) + P_{und}(t) + P_{grid}(t) = P_{load}(t),$$

$$t = 1, 2, \ldots, 24 \qquad (1)$$

where $P_{dis}^i(t)$ represents the power generated by three dispatchable sources (one MT and two FCs) at hour t and P_{und} refers to the intermittent output power of PV at hour t. $P_{grid}(t)$ is the power received from the main grid, and $P_{load}(t)$ is the load demand at hour t. According to the definition, it is assumed that $P_{grid}(t) \geq 0$, whenever the utility supplies the microgrid loads.

The purpose of the power management system is thus to optimize the injected power from dispatchable sources and the main grid in each hour. According to this logic, the power share of each dispatchable DG and the main grid is determined based on the hourly cost to minimize the total generation cost of the whole system.

To this aim, the objective function for the total generation cost of the microgrid is formulated as:

$$\text{minimize}\,(F):$$

$$F(t) = \sum_{i=1,2,3} B_i(t)P_i(t) + B_{grid}(t)P_{grid}(t)$$

$$, t = 1, 2, \ldots, 24 \qquad (2)$$

where superscript i represents the type of dispatchable DGs, $i.e.$ FC no.1, FC no.2 and MT. $B_i(t)$ and $P_i(t)$ refer to the bid and the output power of the DG units at time t, respectively. $B_{grid}(t)$ and $P_{grid}(t)$ are the bid and the power delivered by the main grid, respectively.

subject to:

(i) Generation output limits

$$P_i^{min} < P_i(t) < P_i^{max} \qquad (3)$$

$$P_i^{min} \geq 0, \quad \text{for DGs}$$

$$P_i^{max} \geq 0, \quad \text{for DGs} \qquad (4)$$

$$P_i^{min} = -P_i^{max} \leq 0, \quad \text{for static DC/AC converter}$$

where $P_i(t)$ is the power of unit including DGs and the main grid. P_i^{min} and P_i^{max} are the minimum and maximum power production of unit i.

(ii) Voltage constraints: the optimal power management has to prevent bus voltage violations.

$$V^{min} < V_i(t) < V^{max} \qquad (5)$$

where V^{min} and V^{max} are respectively the minimum and maximum operation voltages.

In centralized control system, the power share dedicated to the dispatchable DGs and the main grid is straightforward related to the determination of day-ahead scheduling for PV production and load consumption for the next day. Any mismatch in the prediction layer then result in power mismatch between generations and demand which cause a voltage limit violation in the microgrid.

In order to overcome the aforementioned obstacle, the proposed method utilizes an economic droop control technique implemented in the control system of each inverter.

Conventional Droop Controller

DC conventional droop scheme applied in the control system of DG units is presented in (6) [22]. According to this equation, the output voltage of each DG unit is determined based on the output current of the respective converter [23]. The aim is to enforce the involved DG units to dispatch the proportional current based on their capacities. Therefore, the internal virtual resistance (R_d) shown in (6) plays the main role to share the desired current of each DG unit. Evidently, R_d is inversely

relevant to its capacity and defined in (7).

$$V_{o,i} = V_{max} - R_{d,i}I_{o,i} \qquad (6)$$

$$R_{d,i} = \frac{\Delta V}{I_{i,max}} \qquad (7)$$

where index i represents DG number, V_{oi}, I_{oi} and I_{imax} are respectively the output voltage, the output current and the current capacity of the DG number i. V_{max} and ΔV refer to the reference voltage and the voltage deviation of the system, respectively.

A typical two-DG DC microgrid equipped with the droop control strategy is illustrated in Fig. 2 [30]. The droop curve of DG units with different droop gain are depicted in Fig. 3.a. In general, the reference voltages of all DG units are identical, whereas the virtual impedances are certainly different for DG units of various capacities. It is obvious that the droop controller of DG units makes them work as a unidirectional source which inject the power to the grid. In a grid-connected scenario with the droop control technique, a bidirectional converter has to be utilized to transfer the power between the main grid and the microgrid. In this case, a bidirectional droop control scheme for the static converter as shown in Fig. 3.b can be applied [17], [18].

Taking Fig. 3 as an example, it is evident that for a common output voltage, the injected power from DG1 is proportional to the output power of DG2 with (8). Meanwhile, in the presence of the load, both DGs are always involved in the power sharing.

$$R_{d,1}I_{o,1} = R_{d,2}I_{o,2} \qquad (8)$$

However, in order to intentionally employ some DGs in a specific load condition, the reference voltage ($V_{i,max}$) and the voltage variation range (ΔV_i) of each DG should be different. An example of this method for a microgrid with two DGs is shown in Fig. 4. It is obvious that in the voltage range of [V2max V1max], DG1 is the only source which supplies the load as long as the load current is less than Itr.
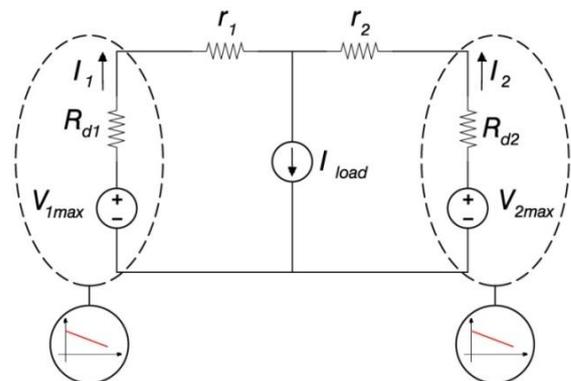

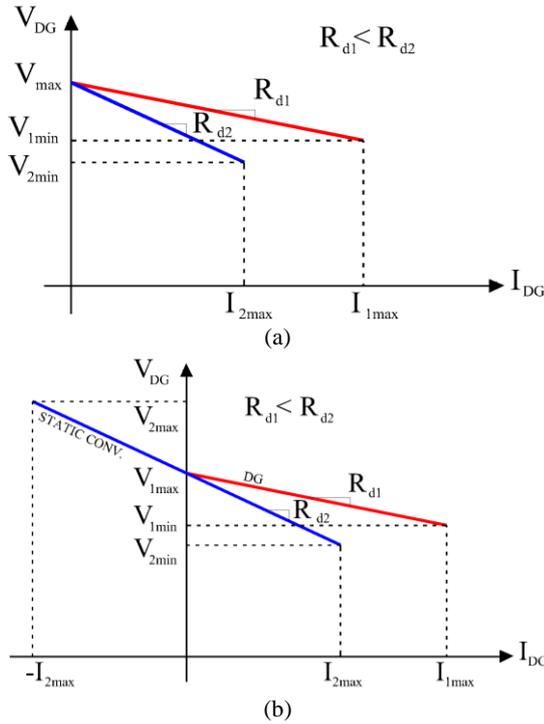**Fig. 2** A simple DC microgrid with two DGs.

(a)

(b)

Fig. 3 Droop Control curves for a) two DGs involved in an islanded microgrid, and b) a DG involved in an islanded microgrid and a static converter to connect to the main grid.
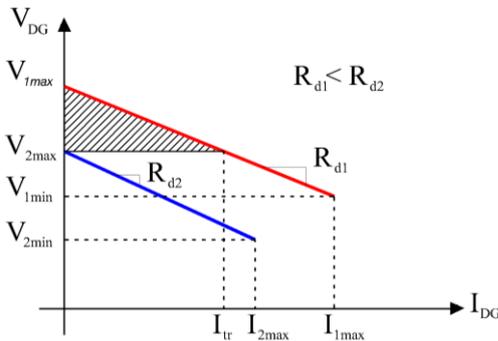

Fig. 4 Droop control curves for two DGs of different reference voltage in DC microgrid.

4 Description of the Proposed Method

As discussed in Section V, to intentionally involve an intended DG in a 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 curve of each converter in the DC microgrid. The proposed algorithm is shortly depicted in a flowchart shown in Fig. 5.

At each hour, the dispatchable DGs and the main grid are classified in an ascent sorting rule according to their bids and the electricity market price. For more participation of the sources with higher capacity in the power sharing, a new parameter, namely "cost energy" can be described based on the rating of the involved sources as follows:

$$CE_i\left(t\right) = B_i\left(t\right) \times \left(P_i^{max} - P_i^{min}\right), \text{ for DGs}$$
$$CE_{grid}\left(t\right) = B_{grid}\left(t\right) \times P_{grid}^{max}, \text{ for main grid} \tag{9}$$

where $CE_i(t)$ and $CE_{grid}(t)$ refer to the cost energy of ith DG and the main grid, respectively. The cost energy defined in the proposed method directly implies the cost weight of each source in the power sharing.

1. The permissible voltage drop of each source is then related to the CE factor as follows:

$$\Delta V_i\left(t\right) = \Delta V_{tol} \times \frac{CE_i\left(t\right)}{\sum_{j=1}^{n} CE_j\left(t\right)}, i = 1, \ldots, n \tag{10}$$

where $\Delta V_i(t)$ is the maximum voltage drop on ith source (DGs or utility) and ΔV_{tol} is the safe operating voltage deviation of the microgrid. The reference (maximum) voltage of each source is then obtained from (13):

$$\begin{cases} V_{k,max}\left(t\right) = V_{max}, & \text{for } k = 1 \\ V_{k,max}\left(t\right) = V_{k-1,max}\left(t\right) - \Delta V_k\left(t\right), & \text{for } k = 2, \ldots, n \end{cases} \tag{11}$$

where index k refers to the sorted DGs rearranged in step 1, V_{max} is the maximum operation voltage of the system, and $V_{k,max}(t)$ is the maximum (reference) voltage of kth source at the zero generation. When $P_{grid} \leq 0$, the maximum voltage of the static converter may be reached to $-P_{grid}^{max}$.

2. The internal virtual resistance $R_d(t)$ is determined according to the conventional method as introduced in (7). Moreover, this parameter is indirectly dependent to the cost function.

5 Simulation Results and Discussion

In order to verify the performance of the proposed method, the DC microgrid of Fig. 1 is considered. Table 1 lists the general specifications of the microgrid, DGs and the load.

The converter of PV source operates as a current source; whereas the converter of dispatchable sources including MT, FC and the static DC/AC converter acts as a voltage source to provide a stable voltage for the microgrid. It can operate with the economic droop control technique to optimize the power dispatch of DGs and the main grid in both islanded and grid-connected scenarios.

The control block of the proposed droop scheme with an inner current loop and two Proportional-Integral (PI) compensators is illustrated in Fig. 6. The outer loop PI controller is adopted to track the converter voltage reference extracted from the droop control unit. The outcome then applied to the inner loop PI compensator to generate the PWM signals of the converter. The transfer functions for voltage and current compensators
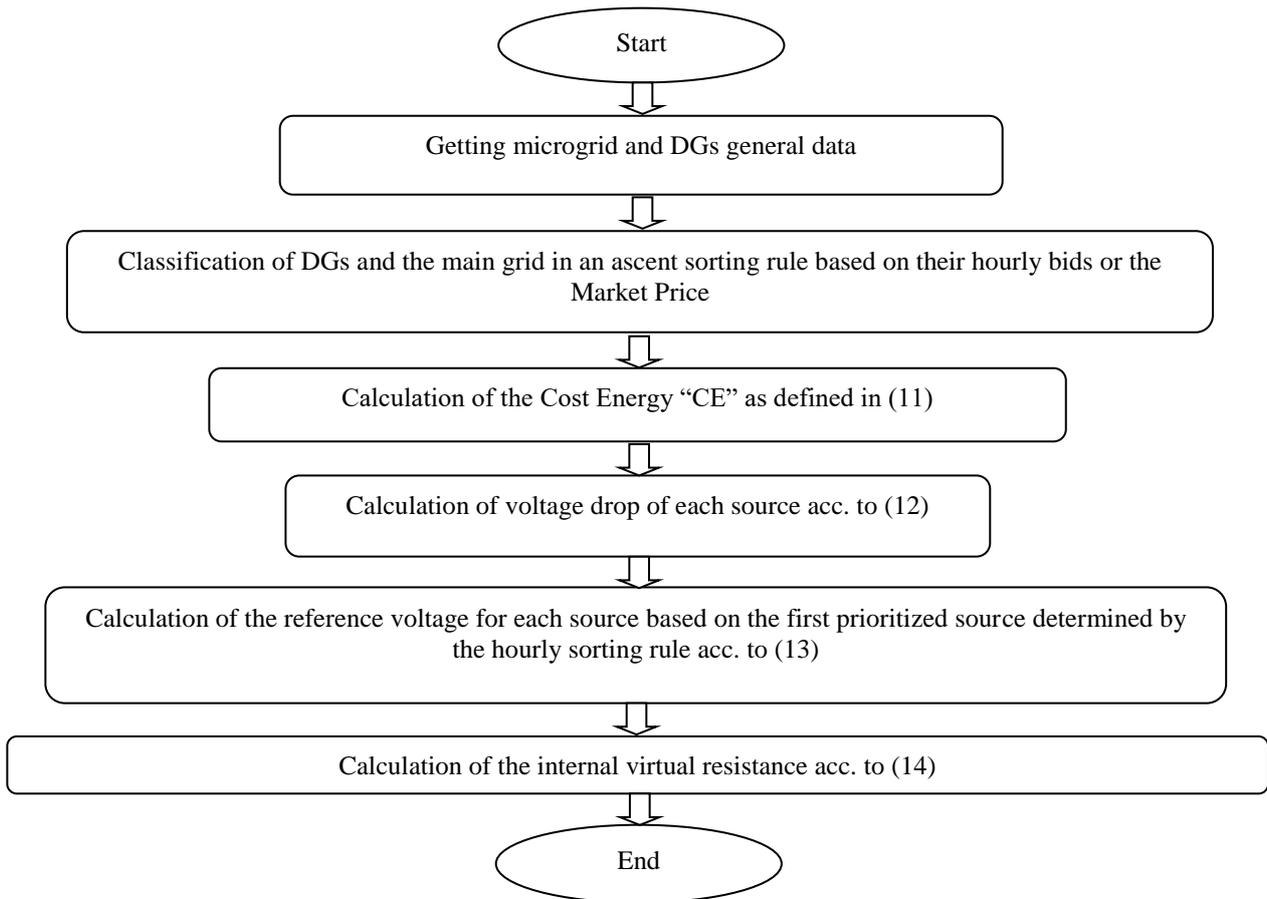
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        ┌─────────────────────┐
        │        Start        │
        └─────────────────────┘
                  │
        ┌─────────────────────────────────────┐
        │ Getting microgrid and DGs general data │
        └─────────────────────────────────────┘
                  │
 ┌──────────────────────────────────────────────────────────────┐
 │ Classification of DGs and the main grid in an ascent sorting   │
 │ rule based on their hourly bids or the Market Price            │
 └──────────────────────────────────────────────────────────────┘
                  │
     ┌─────────────────────────────────────────────┐
     │ Calculation of the Cost Energy "CE" as defined in (11) │
     └─────────────────────────────────────────────┘
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     ┌─────────────────────────────────────────────┐
     │ Calculation of voltage drop of each source acc. to (12) │
     └─────────────────────────────────────────────┘
                  │
 ┌──────────────────────────────────────────────────────────────┐
 │ Calculation of the reference voltage for each source based on  │
 │ the first prioritized source determined by the hourly sorting  │
 │ rule acc. to (13)                                              │
 └──────────────────────────────────────────────────────────────┘
                  │
 ┌──────────────────────────────────────────────────────────────┐
 │ Calculation of the internal virtual resistance acc. to (14)    │
 └──────────────────────────────────────────────────────────────┘
                  │
        ┌─────────────────────┐
        │         End         │
        └─────────────────────┘
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Fig. 5 Flowchart of the proposed algorithm.

Table 1 General specification of the microgrid.

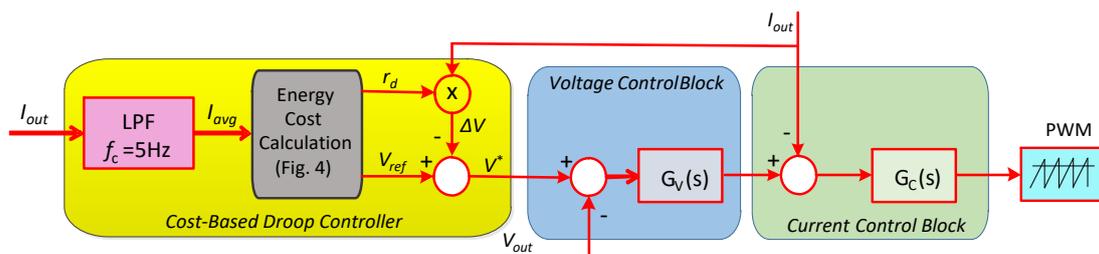| GENERAL DATA		
Description	Value	
Nominal voltage	110 V	
Voltage range	±5%	
Max. capacity	100 kW	
DISTRIBUTED GENERATORS/UTILITY		
ID	Designation	Capacity
1	MT	30 kW
2	FC1	30 kW
3	FC2	20 kW
4	PV	20 kW
5	UTILITY	100 kW
LOAD		
Description	Type	Value
Controllable load	DC	0 to 100 kW

Fig. 6 Control block diagram of the proposed droop scheme.

are

$$G_V(s) = k_{Pv} + \frac{k_{Iv}}{s} \tag{12}$$

$$G_C(s) = k_{Pi} + \frac{k_{Ii}}{s} \tag{13}$$

where k_{Pv} and k_{Iv} are respectively the proportional and integral parameters of the voltage control loop and k_{Pi} and k_{Ii} refer to the proportional and integral parameters of the current control loop. Table 2 summarizes the bids coefficients of the DGs and the hourly energy price of the open market [13]. Table 3 provides the load demand.

The voltage range of the microgrid is defined as $0.95 \text{ p.u.} \le V_{nom}^{grid} \le 1.05 \text{ p.u.}$ with the nominal voltage of 110 V. Based on this limit, the reference voltage of the least costly source is set to the maximum grid voltage. Meanwhile, according to the procedure described in the previous Section, equations (12) and (13), the voltage drop of each source and the reference voltage of the other sources will be obtained at each hour.

Table 2 Bids of the DGs ($/kWh).

Hour	MT	FC1	FC2	Open Market
1	0.107	0.166	0.175	0.033
2	0.107	0.166	0.176	0.027
3	0.108	0.167	0.176	0.020
4	0.108	0.1677	0.177	0.017
5	0.109	0.167	0.178	0.017
6	0.109	0.168	0.179	0.029
7	0.110	0.168	0.180	0.033
8	0.111	0.169	0.181	0.054
9	0.112	0.170	0.183	0.215
10	0.112	0.171	0.186	0.572
11	0.116	0.172	0.187	0.572
12	0.117	0.171	0.188	0.572
13	0.115	0.170	0.187	0.215
14	0.115	0.170	0.186	0.572
15	0.115	0.170	0.187	0.286
16	0.117	0.171	0.187	0.279
17	0.118	0.173	0.189	0.086
18	0.119	0.173	0.190	0.059
19	0.118	0.174	0.191	0.050
20	0.115	0.173	0.189	0.061
21	0.112	0.171	0.186	0.181
22	0.110	0.170	0.185	0.077
23	0.109	0.169	0.183	0.043
24	0.108	0.167	0.182	0.037

Table 3 24-hour typical load demand (kW).

t	1	2	3	4	5	6
P_{load}	52	50	50	51	56	63
t	7	8	9	10	11	12
P_{load}	70	75	76	80	78	74
t	13	14	15	16	17	18
P_{load}	72	72	76	80	85	88
t	19	20	21	22	23	24
P_{load}	90	87	78	71	65	56

Accordingly, the droop lines of the dispatchable DGs and the main grid for 24 hours are plotted in Fig. 7. From this figure, the hourly power dispatch priorities are identified for three time intervals as follows:

A. Section 1 (at t=1-8, 17-20, 22-24)

From 1:00 A.M to 8:00 A.M, 5:00 P.M to 8 P.M and 10:00 P.M to 12:00 P.M, the main grid is the least costly source with the minimum "cost energy" coefficient participating in the generation, while the total demand is less than I_{grid}^{max}. Afterward, MT and FC no.1 as the second and the third prioritized generator cooperate with the utility in supplying the microgrid loads. FC no.2 is the last source to generate as depicted in Fig. 7.a.
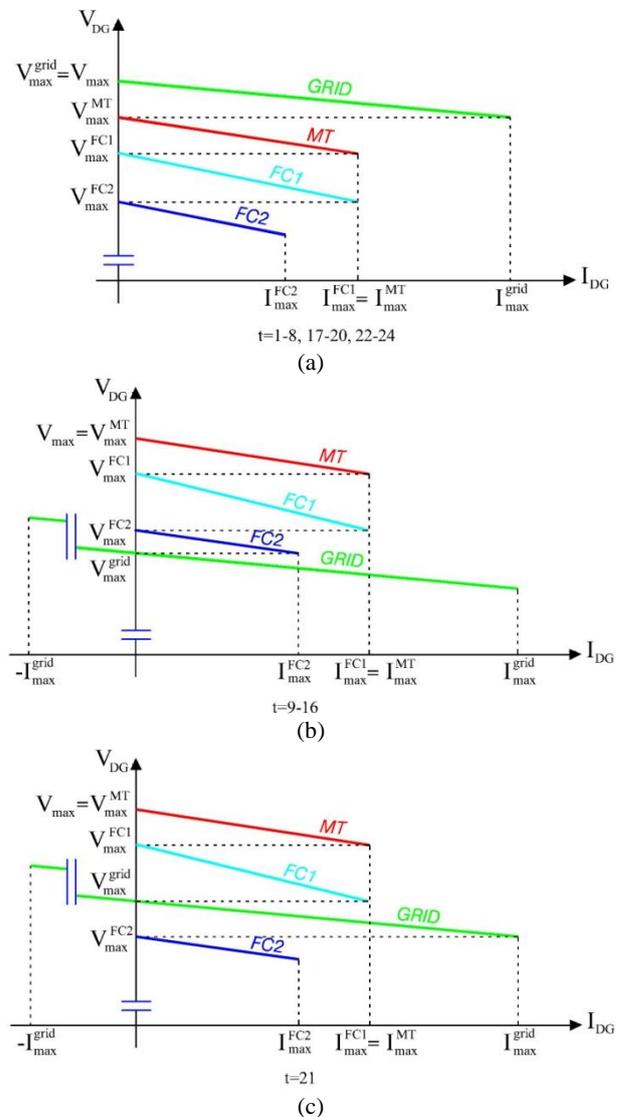

Fig. 7 Droop curves of three DGs and utility utilized in the typical DC microgrid a) at t=1-8, 17-20, 22-24, b) at t= 9-16, and c) at t= 21.

B. Section 2 (at *t*= 9-16)

Fig. 7.b shows the droop curves utilized for DGs and the utility from 6:00 A.M to 4:00 P.M. In this interval, the utility is the costliest source to supply the microgrid demand. It means that in the light-load condition, DGs can fully supply the main grid with the predefined droop curves.

C. Section 3 (at *t*=21)

In this case, the priority of MT and FC no.1 is higher than the priority of the utility to supply the microgrid loads. In the full-load condition, FC no.2 participates in the power sharing, while superior DGs and the utility operate at their full capacity. In the light-load condition, it is expected that only these two DGs can participate in the open market competition.

Simulation is performed for a 24-hour period and compared with the traditional droop control method. Fig. 8.a shows the power dispatch of the involved DG units and the main grid for the proposed droop control strategy. Based on the droop lines derived from Fig. 7, the upstream grid sells the energy to the consumers of the microgrid and also purchase the excess power generated by the DG units in the open market. At *t*=1-8, the utility with the least costly energy is the only source which supplies the inner demand. At *t*=9-16, the market price of the energy is increased and the involved DG units operate at their full capacity to supply the microgrid loads as well as to sell the extra energies to the upstream grid. At the interval of *t*=17-20, the DG units decrease their generation to zero and the microgrid
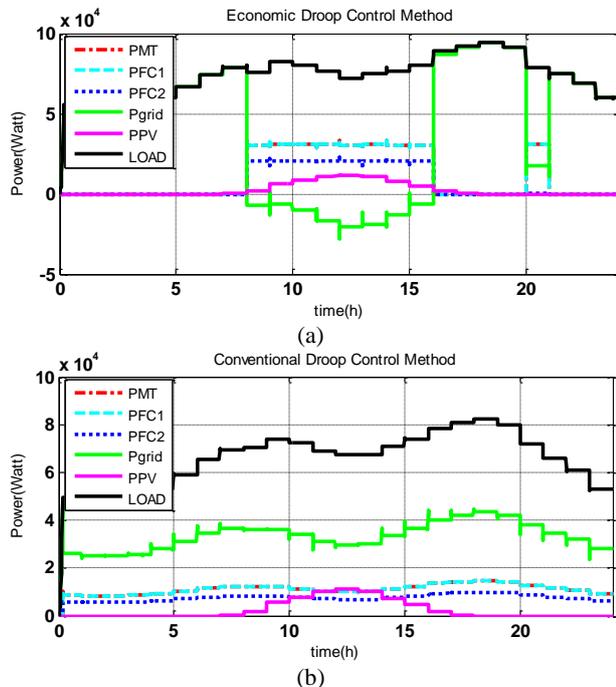
loads are again served by the main grid. At *t*=21, MT and FC no.1 with the higher priority supply the inner loads. At *t*=22-24, the demand power of the microgrid is also bought from the upstream network to minimize the total generation cost.

The simulation results for the conventional droop control scheme are different. As can be seen in Fig. 8.b, the involved DGs and the utility ever participate in the power sharing based on their capacity. For more realization, the total hourly energy cost of the microgrid is illustrated in Fig. 9. From this figure, the total energy cost of the microgrid with the proposed method at all times is less expensive than the cost determined in the conventional method. Table 4 shows the total energy cost of the microgrid in the two methods in one day. As it can be derived, the daily generation cost of the proposed method is reduced about 51%.

6 Conclusions

A decentralized control strategy has been proposed to ensure the economic operation of a DC microgrid in both grid-connected and islanding modes. To achieve this, the hourly bids of DGs along with the open market prices have been applied to determine the droop parameters. The DC microgrid can include non-dispatchable DG units (such as photovoltaic power systems) and dispatchable DG units. In this method, an economic power sharing technique among various types of DGs was adopted that appropriately minimizes the daily total energy cost without MGCC. Unlike other energy management techniques, the proposed method suffers neither from forecasting errors for both load demand and renewable energy production module, nor from the complicated optimization techniques. In the proposed method, all DGs are classified in a sorting rule based on their hourly bids, and then the parameters of their droop controllers are determined. The simulation results are presented to verify the effectiveness of the
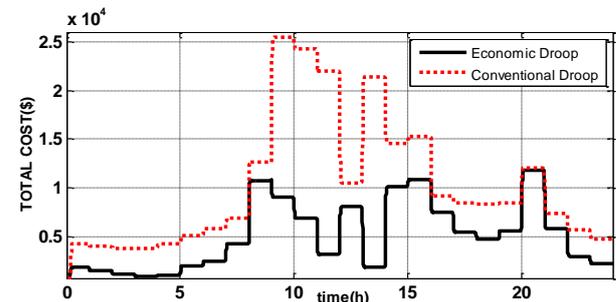

Fig. 8 Power dispatch of the sources a) with the proposed droop control method, and b) with the conventional droop control method.

Fig. 9 Total hourly cost of the microgrid with the proposed and the conventional droop control methods.

Table 4 Economic Savings.

Method	Total generation cost ($/day)	Savings
Conventional Droop	248,016	-
Economic Droop	121,336	51%

proposed method using MATLAB/SIMULINK software. The simulation results show that the proposed strategy is able to be implemented in the several operation conditions of the microgrid with resistance to uncertainties of the system.

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