A communication-free economical-sharing scheme for cascaded-type microgrids

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Abstract

This paper proposes an economical-sharing scheme without the needs of any communications for islanded AC microgrids (MGs) fed by cascaded inverters. The output voltage phase angle of each distributed generator (DG) is regulated by its corresponding incremental cost. Then the equal incremental principle used to guarantee the economic optimality is realized by synchronization conditions. In addition, a modification method is introduced with considering the capacity constraints. Stability analysis of the proposed method is carried out, and the conditions for economic optimality and stability are obtained. Because the communications are not needed, the advantages in cost and reliability are obvious. Simulations and experiments are implemented to verify the effectiveness of the proposed scheme.

1. Introduction

As a result of a new concept for integrating renewable distributed resources in distributed energy system, microgrids (MGs) have attracted increasing research interest recently [1,2]. The MG technology, that integrates various types of DGs, energy storage elements and loads, has become an effective approach to solve the permeation of large-scale DGs to power grid [3,4]. Usually, the DGs in MGs are commonly connected by power electronic converters in paralleled or cascaded manners [5]. Different DGs have different generation costs [6,7]. From the economical perspective, the cost-effective DGs are expected to provide more power.

The economical operation approaches in MGs could be classified into the centralized, distributed and decentralized schemes. The centralized schemes in MGs hold the advantages of better voltage and frequency regulations, and flexible operation modes [8–10]. However, the control decisions are performed with global information, complicated central controllers and extensive communication networks, which increases the capital cost and system complexity, and reduces reliability of MGs.

The distributed schemes are performed depended on information exchange for each DG from its neighbors [11–16]. Xu et al. [17] introduced a distributed consensus algorithm to realize the equal incremental costs of all DGs for economical operation, i.e., the equal incremental principle. The incremental cost is a derivative of the DG cost function with respect to output active power. To solve the economical dispatch problem, Zhang et al. [18] presented a distributed algorithm to realize the optimal economical operation. Further, Zhang et al. [19] introduced a consensus algorithm via selecting the incremental cost as a consensus variable. When the MGs are synchronized, the cost optimality is realized. Additionally, Yang et al. [20] focused on another consensus algorithm, which required a strongly connected communication topology to perform the equal incremental principle. However, [17–20] are highly dependent on communications for information exchange among the neighbouring DGs, and need no central controller compared to the centralized schemes.

Recently, decentralized approaches without any communications have been proposed to deal with the power dispatch problem [21–23]. By emulating the behavior of a synchronous generator, droop control method as a well-known decentralized approach has been widely applied in MGs [24,25]. It aims to dispatch active and reactive power applying the deviation of frequency and output voltage by adjusting the droop coefficients only with locally information [26,27]. However, the economical operation of MGs is usually not guaranteed in terms of the traditional droop scheme. In order to reduce the total active generation costs (TAGC) of MGs in decentralized manners, Nutkani et al. [6] presented the linear droop schemes by designing the maximum or mean generation costs as the droop coefficients. Actually, the generation costs of DGs is a nonlinear function of the active power output [6,28], therefore, the TAGC of MGs might not be optimized efficiently. Further,
Nuttkan | | et al. [28] proposed a nonlinear droop control scheme with applying the nonlinear cost functions to the typical droop scheme. However, the optimal economical-sharing of MGs is not obtained yet. Although it is a suboptimal solution, it is able to realize plug-and-play and has a wide range of practical value. A decentralized economic operation in [29] is proposed to reduce the TAGC without communications for MGs consisting of paralleled inverters.

Although many methods for economical dispatch have been proposed, they are mainly focused on the MGs fed by paralleled inverters. Nowadays, the MG which is made up of cascaded inverters (cascaded-type MGs) has been recognized as an important alternative in the medium voltage applications [30–32]. The cascaded-type MGs in islanded operation mode are firstly introduced in [33]. However, to best of our knowledge, there are no studies about the economic dispatch problems for this structure in the previous literature via decentralized approaches.

To address these concerns above, this paper proposes a communication-free economical-sharing scheme for cascaded-type MGs in islanded mode. The frequency is used to drive all DGs synchronize under the resistance-inductance (RL) and resistance-capacitance (RC) load. When the MGs are in the steady state, the economical power dispatch is obtained by regulating the phase angle of each DG according to the equal incremental principle. The implementation of the method only needs the local information of each DG, therefore, it offers increased reliability. The application conditions of the proposed scheme are demonstrated clearly, which could ensure the economy and stability of cascaded-type MGs. Finally, the proposed scheme has been verified through simulations and experiments.

The rest of the paper is organized as follows. Section 2 describes the economical optimization of the cascaded-type MG. The proposed communication-free economical-sharing scheme is introduced in Section 3. Stability analysis of the proposed scheme is presented in Section 4. Then, the simulation validations in Section 5 and the experimental results in Section 6 are provided to verify the effectiveness and performance of the proposed scheme. Finally the paper is concluded in Section 7.

2. Economical optimization of cascaded-type MGs

2.1. Cascaded-type MGs

The cascaded-type MG comprises a series of cascaded inverters [30–32] connected with the point of common coupling (PCC). It is shown in Fig. 1, in which $L_r, r_f$ are the filter inductance and its corresponding series resistance. $C_r, r_f$ are the filter capacitance and its corresponding series resistance. The equivalent circuit of cascaded-type MGs is shown in Fig. 2. $V_i e^{j\delta_i}$ is the output voltage of $i$th DG, $V_{PCC}e^{j\delta_{PCC}}$ is the voltage of the PCC, $V_i$ and $V_{PCC}$ are the amplitudes of the corresponding voltages, $\delta_i$ and $\delta_{PCC}$ are the phase angles of the corresponding voltages. $Z_{PCC}, z_{line}$ and $y'$ are load impedance, line impedance, and equivalent admittance, respectively. By Kirchhoff laws, the obtained load voltage is presented as:

$$V_{PCC}e^{j\delta_{PCC}} = y'z_{PCC} \sum_{i=1}^{n} V_i e^{j\delta_i}$$  \hspace{1cm} (1)

$$y' = \frac{1}{z_{PCC} + z_{line}}$$  \hspace{1cm} (2)

For convenience, $y'$ is denoted as:

$$Y' = |Y'|e^{j\theta'}$$  \hspace{1cm} (3)

where $|Y'|$ and $\theta'$ are the modulus and phase angle of $y'$, respectively. After obtaining the load voltage, it is easy to get the expressions of output active power $P_i$ and reactive power $Q_i$ of the $i$th DG,
where $P_i$ is the output active power of the $i$th DG. $P_{\text{ref}}$ is the generalized active power load demands including the intermittent sources and the transmission loss. $C_i(P_i)$ is the general comprehensive operational cost including fuel cost, maintenance cost, and so on, $i \in \{1, 2, \ldots, n\}$. The start-up cost of DGs is not considered in this paper.

Suppose all the cost function $C_i(P_i)$ is smooth and convex as $d^2C_i(P_i)/dP_i^2 > 0$ [17,18,34,35]. Then the optimization problem described by (6) has a global optimal solution when $\partial C_i(P_i)/\partial P_i = \partial C_i(P_i)/\partial P_0$ [29]. Note that $\partial C_i(P_i)/\partial P_i$ is the incremental cost (TIC) of the $i$th DG. The optimal real power sharing is determined by,

$$\sum_{i=1}^{n} P_i = P_L$$

(7)

Eq. (7) is the well-known equal incremental principle. While the main concern of this paper is how to incorporate the equal incremental principle via decentralized approach into the economical operation for the cascaded-type MGs.

3. Proposed Communication-free economical-sharing scheme

3.1. Proposed optimal economical-sharing scheme without considering capacity constraints

The proposed communication-free optimal economical-sharing scheme for the cascaded-type AC MGs is given by:

$$f = f^* + \gamma \text{sgn}(Q_i) \frac{\partial C_i(P_i)}{\partial P_i}$$

(8)

$$V_{\text{ref}} = \frac{V_{\text{PCC}}}{n}$$

(9)

where $V_{\text{PCC}}$ is the reference voltage at PCC, which is set to make the load voltage within its feasible ranges. $n$ is the total number of the dispatchable DGs in MG. $f_i$, $f^*$ are actual frequency and reference frequency, and $f^* = (f_{\text{max}} + f_{\text{min}})/2$. $\gamma$ is a certain positive for all DGs, which is determined by $\gamma \partial C_i(P_i)/\partial P_i \in [0, (f_{\text{max}} - f_{\text{min}})/2]$. $f_{\text{max}}$ and $f_{\text{min}}$ are the set maximum and minimum frequencies allowed by the MG. $\text{sgn}(\cdot)$ is a signum function. When the MG is connected by RL load ($Q_i > 0$) and RC load ($Q_i < 0$), the corresponding $\text{sgn}(Q_i)$ is 1 and $-1$, respectively. Note that the proposed scheme in (8) and (9) only needs the local information of each DG, and the communications between different DGs are not needed. The $P_f$ characteristics of the proposed scheme are shown in Fig. 3, where inverse droop and droop control are applied in case of RL and RC loads.

The power dispatch of cascaded-type AC MGs can be regulated...
through the following methods. From $P_i = V_i \cos \varphi_i$, the real power dispatch is $P_i = V_i \cos \varphi_i$; $V_i \cos \varphi_i$ due to the same current $I_i = I_j$ for cascaded-type MGs. $\varphi_i$ is the difference between the output voltage $V_i$ and the output current $I_i$ of the $i$th DG. For simplicity, when the phase angle $\varphi_i$ is controlled as the same value for each DG in the steady state of MGs, the real power can be regulated by changing the magnitude of $V_i$, note that, $P_i = V_i \cos \varphi_i$, which is shown in Fig. 4(a). $\omega_i$ is the synchronous frequency in the steady state of MGs in Fig. 4. In addition, from (9), the output voltage of each DG is assigned as the same value, thus the real power dispatch is $P_i = V_i \cos \varphi_i$ shown in Fig. 4(b), which is the main control idea of this paper.

When the MG is in the steady state, (8) becomes,

$$\frac{\partial C_i(P_i)}{\partial P_1} = \frac{\partial C_i(P_2)}{\partial P_2} = \cdots = \frac{\partial C_i(P_n)}{\partial P_n}$$

(10)

Combining the power balance $\sum P_i = P_L$ and (10), the operating point can be obtained based on the proposed scheme, which agree with the optimal solution in (7). Therefore, the optimal economical power dispatch is realized via the decentralized approach without considering capacity constraints.

3.2. Modification with considering capacity constraints

Define that $P_{i,\text{min}}$ and $P_{i,\text{max}}$ are the allowable minimum and maximum active power outputs of the $i$th DG, the feasible regions of the economical dispatch problem are:

$$P_{i,\text{min}} \leq P_i \leq P_{i,\text{max}}$$

(11)

For the economical dispatch problem with capacity constraints,
when there is saturation of DGs (reaching its limitation), just set it at the limiting value and perform optimization for the rest of DGs based on the equal incremental principle. It should simply go into current/power control mode, and only can be realized through the communication-free control strategy.

As seen in Section 4, when $\frac{d^2 C_i(P_j)}{dP_j^2} > 0$, the system is stable. From the perspective of the stability, we introduces a polynomial fitting method [35] to modify $\frac{dC_i(R)}{dR}$ near the boundaries shown in Fig. 5.

4. Stability analysis

According to the analysis above, if and only if the system is stable, the economical dispatch will be achieved. Thus, the systems stability will be investigated in this section. For simplicity, the small signal stability analysis is carried out in [36–38]. Eq. (8) could be rewritten as:

$$\omega_i = \omega^* + 2\pi \text{sgn}(Q_j) \left\{ \frac{dC_i(P)}{dP_i} \right\}^\prime $$

(12)

where $\omega_i$, $\omega^*$ are actual and reference angular frequency, and $\omega^* = 2\pi f^*$. Let $\delta_i = \int \omega_i dt$, and denote $\delta_i = \delta_i - \delta_o$, then (12) is rewritten as:

$$\delta_i = \delta^* - \omega_o + 2\pi \text{sgn}(Q_j) \left\{ \frac{dC_i(P)}{dP_i} \right\}^\prime $$

(13)

Neglecting the voltage dynamics of fast-time scale, and linearization of (4) and (13) around its equilibrium point in the Laplace domain yields,

$$\Delta P_i = -V_i |Y_i| \sum_{j=1}^{n} V_j \sin(\delta_i - \delta_j^* - \delta_o) (\Delta \delta_i - \Delta \delta_j)$$

(14)

$$\Delta \delta_i = 2\pi \text{sgn}(Q_j) \gamma M \Delta P_i$$

(15)

where $\omega^o$ is the corresponding steady state values around the equilibrium point. By substituting (14) into (15), and neglecting $\delta_o - \delta_j^*$, we can get,

$$\Delta \delta_i = -2\pi \text{sgn}(Q_j) \gamma MV_i |Y_i| \sum_{j=1}^{n} V_j \sin(-\delta^*) (\Delta \delta_i - \Delta \delta_j)$$

(17)

Express (17) in the matrix form:

$$\mathbf{x} = \mathbf{A} \mathbf{x}$$

(18)
where
\[
\begin{align*}
X &= [\Delta \tilde{x}_1 \cdots \Delta \tilde{x}_n]^T, \quad A = -[a_{ij}]
\end{align*}
\]
\[
\begin{align*}
a_{ii} &= 2\pi \text{sgn}(Q_i)\gamma M V_i^\prime n \sum_{j=1,j\neq i}^n V_j \sin(-\beta') \\
a_{ii} &= -2\pi \text{sgn}(Q_i)\gamma M V_i^\prime n V_i \sin(-\beta')
\end{align*}
\]  

(19)

Obviously, \(a_{ii} + \sum_{j=1,j\neq i}^n a_{ij} = 0, a_{ii} = a_{ii}. \) If \(a_{ii} > 0, -A \) is a Laplacian matrix [39], the eigenvalues of \(A\) are non-positive. There is a simple eigenvalue at zero corresponding to rotational symmetry, which has been proven in [40]. Therefore, the system will be stable.

In order to ensure \(a_{ii} > 0\), there should be,
\[
2\pi \text{sgn}(Q_i)\gamma M V_i^\prime n \sum_{j=1,j\neq i}^n V_j \sin(-\beta') > 0
\]  

(20)

Assume \(M > 0\). When the MG is connected by RL load, \(Q_i > 0, \) \(\text{sgn}(Q_i) = 1, \) and \(\beta' < 0, \) \(\sin(-\beta') > 0\), thus (20) is satisfied. When the MG is connected by RC load, \(Q_i < 0, \) \(\text{sgn}(Q_i) = -1, \) and \(\beta' > 0, \) \(\sin(-\beta') < 0\), therefore, the MG stability is also ensured. If \(Q_i = 0, \) (20) is undermined, the system is unstable. Thus, \(Q_i \neq 0\) is assumed in this paper, which is quite rare in practice.

From the stability analysis above, when \(M > 0, \) the MG can realize stable operation, that is, \(d^2C_i(Q) / dP_i^2 > 0\). In addition, the optimal solution (7) can be achieved when \(d^2C_i(Q) / dP_i^2 > 0\). Therefore, it is concluded that \(d^2C_i(Q) / dP_i^2 > 0\) can ensure both economy and stability, which is the application conditions of the proposed scheme.

5. Simulation validations

The proposed communication-free economical-sharing scheme is verified through MATLAB/Simulink. The associated parameters are listed in Table 1. The cascaded-type MG (see Fig. 1) consisting of three DGs is employed. A typical general comprehensive cost function \(C_i(Q) = a_i P_i^2 + b_i P_i + c_i \exp(d_i P_i) \) [6,28,34,35] is used in this paper and the coefficients for different DGs are listed in Table 2. For convenience, \(p.u. \) values are used in this paper. The detail configuration of the single-phase DG unite is depicted in Fig. 6. The optimal solution is calculated through the interior point method [41] with respect to load demands as shown in Fig. 7.

5.1. Case 1: Performance of proposed scheme for the MG under RL load and RC load

In this case, the simulations are implemented under the RL and RC load for the cascaded-type MG. The load demands are scheduled as RC, RL, RC loads in the interval \([0s, 1s], [1s, 2s], [2s, 3s], \) respectively. The variations of the frequency over time are shown in Fig. 8(a), which reach a common value quickly with the load variations. The reactive power sharing among DGs is shown in Fig. 8(b). Accordingly, the proposed scheme could maintain the MG stability under the RL and RC load, and obtain a satisfying transient response.

When the MG is in the steady state, the waveforms of voltage \(V\) near \(t = 1s\) are shown in Fig. 9. Based on the simulation result, the power sharing among DGs is obtained by regulating the phase angle \(\phi\) (see Fig. 4(b)).

5.2. Case 2: Performance of the proposed scheme under the RL load

For comparison, the performance of the proportional-sharing scheme is introduced for the DGs in MG under the RL load. The load demands are scheduled as 0.6 \(p.u.\), 1.2 \(p.u.\), 1.8 \(p.u.\) in the interval \([0s, 1s], [1s, 2s], [2s, 3s], \) respectively. The fluctuations of the total active power loads are shown in Fig. 10(a). When the MG is in the steady state, the frequencies converge to a certain value as shown in Fig. 10(b). It is controlled within the feasible ranges \([49 Hz, 51 Hz]\). The active power
The allocations of all DGs shown in Fig. 10(c) are proportionally sharing as 0.2 p.u., 0.4 p.u., 0.6 p.u., respectively. The corresponding TAGC is calculated in Fig. 9(d) as 0.0428, 0.1284, 0.2600, which exceeds the optimal solution in Fig. 7(b).

The proposed scheme is performed with the same load schedules as Fig. 10(a) under the RL load. When the MG gets into the steady state, the frequencies converge to a constant as shown in Fig. 11(a). Fig. 11(b) shows the behaviour of TIC during the transient process, in which TIC are equal during the steady state, i.e., the equal incremental cost principle.

The power allocations are shown in Fig. 11(c), and the corresponding TAGC are calculated in Fig. 11(d) as 0.042, 0.124, 0.249, which is always lower than it in Fig. 10(d). Thus, the proposed scheme is a low-cost solution compared to the proportional-sharing scheme.

Compared with the optimal solution shown in Fig. 7, the simulation results in Fig. 11(c) and (d) agree with it. Therefore, the proposed scheme can realize the optimal economical-sharing for the MG under the RL load.

### 5.3. Case 3: Performance of proposed scheme for the MG under RC load

In order to verify the performance of the proposed scheme under the RC load, the simulation is carried out with the same load schedules as Fig. 10(a). As shown in Fig. 12, in case when the frequencies of all DGs converge to a certain value in Fig. 12(a), TIC of all DGs is also equal in Fig. 12(b). The power sharing is obtained shown in Fig. 12(c), and the corresponding TAGC is calculated in Fig. 12(d). The simulation results in Fig. 12(c) and (d) agree with optimal solution shown in Fig. 7. Therefore, the proposed scheme can realize the optimal active power economical-sharing under the RC load.

### 5.4. Case 4: Economy comparisons between the proposed scheme and the global optimal solution with capacity constraints

The capacity constraints \([P_{\text{min}}, P_{\text{max}}]\) of DGs are set as [0 p.u., 1 p.u.]. The optimal power allocations with respect to load demands among DGs through the interior point method [41] are shown in Fig. 13(a). Meanwhile, the operation point with respect to load demands based on the proposed scheme is shown in Fig. 13(b), in which...
$d^2C(P)/dP^2 > 0$ always holds. The corresponding TAGC of the two results is shown in Fig. 13(c), in which there are some subtle distinctions. As seen, in most cases, the TAGC of the proposed method is in good agreement with the global optimal results even in the presence of capacity constraints.

6. Experimental results

A MG prototype shown in Fig. 14 is built in lab to verify the effectiveness and performance of the proposed scheme. It comprises two DGs based on the single phase voltage source inverters which are controlled by digital signal processors (TMS320F28335). The DG1 and DG2 are considered and the corresponding generation characteristics are same as the simulation validations listed in Table 2. The experimental parameters are listed in Table 3. The optimal solution with respect to load demands is shown in Fig. 15.

Due to the limitations of experimental conditions, the considered MG (see Fig. 1) comprises only two DGs. For comparison, the proportional-sharing scheme and the proposed scheme are presented in this case under the RL load. The experimental voltage and current waveforms with the proportional-sharing scheme are shown in Fig. 16. The load schedules are 0.54 p.u., 1.08 p.u., 1.55 p.u., 0.54 p.u., 1.08 p.u., respectively. The variations of load demands over time are shown in Fig. 17(a). From Fig. 17(b), the frequency of all DGs reaches a common value quickly regardless of load variations. The active power allocations of DG1 and DG2 are proportional sharing in Fig. 17(c). The corresponding TAGC is calculated in Fig. 17(d).

The proposed scheme is implemented with the same load schedules in Fig. 17(a). The waveforms of the load voltage and current in terms of the proposed scheme are shown in Fig. 18. The load voltage could be controlled within its feasible ranges. The corresponding waveform of frequencies is as shown in Fig. 19(a), and the TIC of DG1 and DG2 are equal shown in Fig. 19(b). Again, the active power allocations and TIC are shown in Fig. 19(c) and (d). Accordingly, the proposed scheme is a low-cost solution compared to the proportional-sharing scheme shown in Fig. 17(d).

Compared to the optimal solution in Fig. 15 and the experimental results in Fig. 19(c) and (d), it is concluded that the proposed scheme can realize the optimal economical-sharing, and maintains stable operation of the MG.

7. Conclusion

In this paper, a communication-free economical-sharing scheme has been proposed to reduce the TAGC to a minimum for the cascaded-type MGs. As long as $C(P)$ satisfy $d^2C(P)/dP^2 > 0$, the proposed scheme is applicability, which can ensure both the economy and stability of system. Since the equal incremental cost principle is guaranteed by the frequency consistency for cascaded-type MGs in the steady state, communications are not needed. Therefore, it is a reliable and low-cost solution. Effectiveness of the proposed scheme has been verified through the small signal stability analysis method. More dispatch scheme will be studied in the future, such as considering the start-up cost of DGs, the minimum on/off time of DGs.

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