S4–04

Circulating Current Minimization among Multiple Distributed Generations Using Distributed Virtual Impedance Regulation

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Summary

In islanded Microgrid, the power sharing among distribution generations (DGs) is realized with the droop control. However, in the case of considering the effect of line impedance, the inaccurate proportional power sharing could result in the large circulating current among the DGs. This paper proposes a distributed virtual impedance regulation method in which it is applied both consensus control algorithm and the adaptive virtual impedance regulation for suppressing the large circulating current effectively. Simulation results are presented to verify the effectiveness of the proposed method.

Keywords: Distributed generation (DG); microgrid; circulating current; virtual impedance; power sharing.

1. Introduction

With growing concerns about the renewable energy resources such as photovoltaic cells, small wind turbines, and microturbines worldwide, more renewable energy sources have been integrated in the microgrid.

As the low voltage generation and distributed system of interconnected loads and DGs, the microgrid is the effective grid–connecting method which can overcome the impact on power system when numerous DGs are connected with the power system The microgrid acts as a single controllable entity with respect to the grid and connects and disconnects from such grid to enable it to be operated in both grid–connected and islanded mode.

This paper investigates the circulating current suppressing method in the islanded microgrid. In the case of the islanded microgrid, slight differences in phases and amplitudes of the DG output voltages due to different line impedances connected the DGs with the point of common coupling (*PCC*) can result in large circulating currents among the DGs and increase losses of the microgrid [6].

In order to overcome this problem, various methods have been introduced for the circulating current minimization; the current vector control method in which both the active power and reactive power are controlled in proportion to the DGs power rating, the zero–sequence circulating current control method of three–phase inverter, and the method for minimizing the circulating current among the DGs by common–mode and the differential–mode.[3, 6~9, 10]

In the past, the virtual impedance was also added in the conventional droop control loop used in the islanded microgird to suppress the circulating current among the DGs [2]. The performance of virtual impedance is to make the inverter output impedance modify and to make them of all DGs equal accordingly. However, this method considered the mismatched output impedance of inverter, but not considered the mismatched line impedance.

The virtual impedance regulation method was presented in [4], which is regulated adaptively according to the different line impedance. However, this method needs the central controller which collects the information of all DGs and prior measurement of the line impedance.

Recently, the multi–agent system control theory has been applied to the microgrid for the load restoration, the DG reconnection, and so on. [1, 5, 11, 12]

On the basis of research on above–mentioned method, this paper proposes a distributed adaptive virtual impedance control method using the consensus algorithm, and the mismatched line impedances are compensated. Accordingly, the reactive power is shared accurately and the circulating currents are suppressed effectively among the DGs.

Compared with the central controller which needs whole information on the reactive power, the proposed method only needs its own DG and its neighbor's DG information, and the control reliability is improved. Also this method does not need the accurate magnitude of line impedance which is difficult to measure in reality.

2. Virtual Impedance Regulation Method for Circulating Current Minimization

The equal voltage drop between the DG and the PCC means the minimization of the circulating current among the DGs[7], which is achievable only with the power sharing control method. The task of power sharing is to make all DGs share load power according to their power rating.

In order to realize accurate reactive power sharing, the DG equivalent impedance X_i should be in inverse proportion to DG power rating Q_i [2].

$$X_1 Q_1 = X_2 Q_2 = \cdots = X_N Q_N \tag{1}$$

On the other hand, each DG voltage which is obtained from the droop controller can be represented as

$$E_i = U_{PCC} + \frac{X_i Q_i}{U_{PCC}} \tag{2}$$

where U_{PCC} is the *PCC* voltage.

If the Eq. (1) is satisfied, each DG output voltage will be the same.

However, there are mismatched line impedances in practice, and it results in the inaccurate reactive power sharing accordingly.

Therefore, any virtual impedance is added in the line impedance to make the Eq. (1) satisfy, which should be adaptively regulated according to the mismatched amount of reactive power sharing.

The line equivalent impedance including the virtual impedance is written as

$$X_i = X_{line,\ i} + X_{V,\ i} = X_{line,\ i} + X_{SV,\ i} + X_{AV,\ i} \tag{3}$$

where $X_{line,\ i}$ and $X_{V,\ i}$ are ith line reactance, and ith virtual reactance, respectively. $X_{SV,\ i}$ is the static virtual reactance which is performed that the line impedance is always the inductive reactance. $X_{AV,\ i}$ is the adaptive virtual reactance for accurate reactive power sharing.

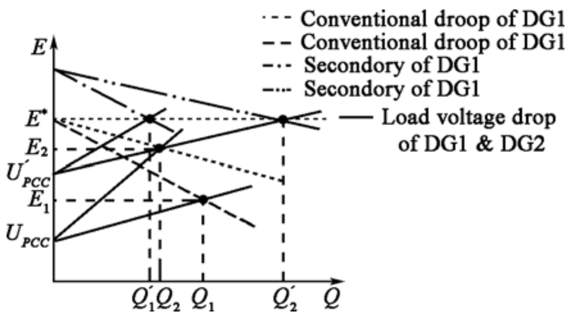


Figure 1. Conventional droop characteristic and secondary control characteristic with adaptive virtual impedance regulation for two DGs.

Fig. 1 shows that the reactive power is accurately shared with adaptive regulation of the virtual impedance. With adaptive regulation of the virtual impedance, the reactive power sharing error is compensated and according as the slope of load voltage drop (solid black line) is modified, each output voltage becomes equal (the cross points between solid red/blue lines and black line).

3. Consensus–Based Adaptive Virtual Impedance Regulation

For the circulating current minimization of the DGs, directed graph (digraph) which describes the communication topology between the DGs should be adopted. A digraph is usually expressed as G=(V, E, A), which consists of a node set V={v_1, v_2, ⋯, v_n} an edge set $E \subset V \times V$, and the weighted adjacency matrix A=[a_{ij}].

In a micro grid, the nodes of digraph denote each DG agent; the edges denote communication links between the DGs. Each edge (v_i, v_j)∈E represents that agent i obtains information from agent j. The set of neighbors of agent i is denoted as N_i={$j \in N${i, j}∈E}. For a digraph, an agent i only receives information from its neighbors N_i. [a_{ij}] is the weight of edge (v_i, v_j) and a_{ij}=1 if (v_i, v_j)∈E, otherwise a_{ij}=0. Hence the Laplacian matrix is defined as L=diag{$S_{j \in N_i}$-A}. Finally, a digraph has or contains a directed spanning tree if there is a root node with a direct path from that node to every other node in the graph.

The adaptive virtual impedance control is designed to realize accurate reactive power sharing in the subsection.

In order to realize the accurate reactive power sharing, if Q_i/Q_{i0} is defined as per unit imbalance power of the DG$_i$, and then per unit imbalance power of each DG should be the same to accurately share the imbalance power.

$$Q_1^{pu} = Q_2^{pu} = \cdots = Q_N^{pu} \tag{4}$$

where $Q_i^{pu} = Q_i/Q_{i0}$; Q_i is the imbalance power of ith DG; Q_{i0} is the imbalance power rating of ith DG.

In this paper, the consensus algorithm is used to make the per unit reactive power equal, and the distributed cooperative control for ensuring the proportional reactive power sharing can be considered to the regulation synchronization problem [1].

$$\dot{Q}_i^{pu} = u_{Q_i} \tag{5}$$

where u_{Q_i} is the reactive power sharing mismatch.

The reactive power sharing controller of each DG discovers the reactive power sharing mismatch with comparing its own information with its neighbor's information.

$$u_{Q_i} = -C_{nQ} e_{nQ_i} \tag{6}$$

where C_{nQ} is the coupling coefficient, e_{nQ_i} is the local reactive power sharing error.

$$e_{nQ_i} = \sum_{j \in N_i} a_{ij}\left(\dot{Q}_i^{pu} - \dot{Q}_j^{pu}\right) \tag{7}$$

On the basis of Eq. (5)~(7), the entire system for accurate reactive power sharing among all DGs can be written as

$$N\dot{Q}^{pu} = U_Q \tag{8}$$

$$U_Q = -C_{nQ} e_{nQ} \tag{9}$$

$$e_{nQ} = LNQ \tag{10}$$

where

$$NQ^{pu} = [n_1 Q_1^{pu} \quad n_2 Q_2^{pu} \quad \cdots \quad n_N Q_N^{pu}]^T ,$$

$$U_Q = [u_{Q1} \quad u_{Q2} \quad \cdots \quad u_{QN}]^T ,\ e_{nQ} = [e_{nQ_1} \quad e_{nQ_2} \quad \cdots \quad e_{nQ_N}]^T$$

And then the reactive power sharing mismatch is fed the proportional integrator $D_i(s)$, and the virtual impedance correction term can be obtained as

$$\delta Q_i = D_i(s) u_{Q_i} \tag{11}$$

By using the obtained reactive power sharing mismatch, the virtual impedance to regulate adaptively is written as.

$$X_{V,\ i} = X_{SV,\ i} + X_{AV,\ i} = \omega(L_{SV,i} - k_L \delta Q_i) \tag{12}$$

$$R_{V,i} = R_{SV,i} + R_{AV,i} = R_{SV,i} - k_R \delta Q_i \tag{13}$$

where ω is the angle frequency; $L_{SV,\ i}$ and $R_{SV,\ i}$ are the static virtual inductance and resistance, respectively; k_L, and k_R are the proportional coefficient for regulating the virtual reactance and the proportional coefficient for regulating the resistance, respectively.

It should be noted that the proposed consensus–based method is not to regulate the reactive power of each DG directly, but to regulate the virtual impedance to a value that eliminates the reactive power sharing error without the requirement of knowledge on the line impedances. If it is only used the consensus algorithm, the reactive power is shared accurately, but it can result in the severe circulating line current among the DGs due to the unequal voltage drop from each DG inverter to the *PCC*.

Therefore, the proposed method not only ensures accurate reactive power sharing among the DGs but also makes the output voltage of each DG equal to suppress the circulating currents effectively.

4. Simulation Results

As shown in Fig. 2, the microgrid including the three DGs is connected through the communication network. The three DGs power ratings are 20, 30 and 40kVA, respectively; the three–phase system voltage is 220V; the system frequency is 60Hz; the line impedances are 0.017 5+j0.075Ω, 0.03+j0.132Ω, and 0.04+j0.189Ω, respectively.

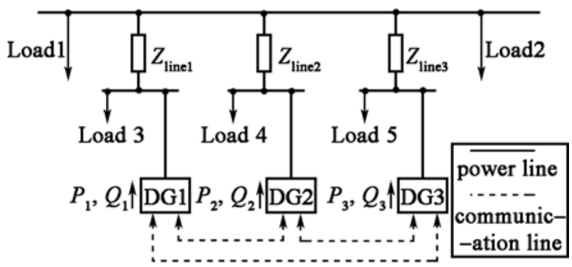
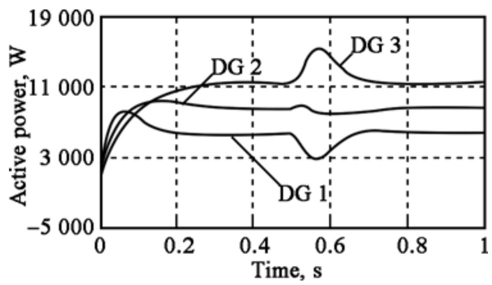


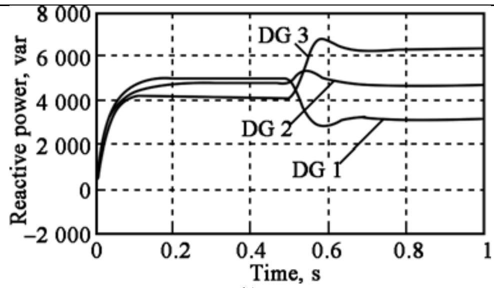
Figure 2. Microgrid test system including three DGs

At first, to detect the performance of the proposed adaptive virtual impedance regulation, the conventional method is used, and after 0.5s, the proposed method is applied.

As shown in Fig. 3a, and 3b, due to the mismatched line impedance, the reactive power does not share in proportion to 1: 1.5: 2. That is, the DG1 shares more reactive power; the DG3 shares less reactive power. After 0.5s, the three DGs share the reactive power proportionally, and the proposed method does not impact the proportional active power sharing.



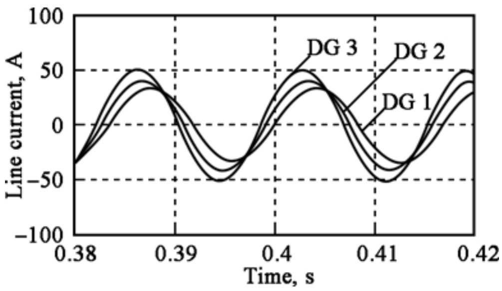
a)



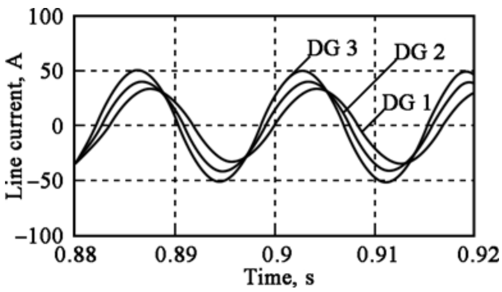
b)

Figure 3. Power sharing among three DGs
a) Active power sharing, b) Reactive power sharing

The phase–A current waveforms of three DGs are shown in Fig. 4. Before applied the proposed method, the proportion of phase–A currents at the three DGs is not 1: 1.5: 2; after applied the proposed method, the phase–A currents of the DGs are proportionally shared, and the phases of phase–A currents is almost equal.



a)



b)

Figure 4. Three–A current waveform of three DGs
a) Before applied proposed method, b) After applied proposed method

5. Conclusions

In this paper, the circulating current minimization has been investigated considering the line impedance.

The distributed adaptive virtual impedance regulation is proposed to eliminate the reactive power sharing error for the circulating current minimization, in which the combination of consensus algorithm and virtual impedance are used. The effectiveness of this method was proved by simulation analysis.

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