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Automatika
Journal for Control, Measurement, Electronics, Computing and Communications

ISSN: 0005-1144 (Print) 1848-3380 (Online) Journal homepage: https://www.tandfonline.com/loi/taut20

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To cite this article: A. Khaledian & M. Aliakbar Golkar (2018) A new power sharing control method for an autonomous microgrid with regard to the system stability, Automatika, 59:1, 87-93, DOI: 10.1080/00051144.2018.1501462

To link to this article: https://doi.org/10.1080/00051144.2018.1501462

AUTOMATIKA
2018, VOL. 59, NO. 1, 87–93
https://doi.org/10.1080/00051144.2018.1501462

REGULAR PAPER

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A new power sharing control method for an autonomous microgrid with regard to the system stability

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ABSTRACT
Droop control is the conventional way to share the demand power among the generators in a microgrid. Analyzing this control method shows that it has poor performance in reactive power sharing. Generated reactive power of each microsource depends on the active load demand. In this paper, a control method is proposed to improve the reactive power sharing performance. It is indicated that higher reactive power droop gains make the generated reactive power to be less influenced from the changes in active load. However, high droop gains can lead the system to instability. Hence considering eigenvalue analysis of the microgrid, a new auxiliary controller is proposed to damp the oscillations caused by high droop gains. In the new method, there is not the need for monitoring the grid impedance to tune the controllers. To verify the proposed method, load step is applied to a test microgrid and the results are shown. In the new method, total generated reactive power is reduced in comparison to the conventional droop controller and the system stability is maintained.

ARTICLE HISTORY
Received 9 April 2016
Accepted 22 December 2017

KEYWORDS
Distributed generation; microgrid; power control; power system stability; reactive power

Nomenclature

DG	Distributed generator
VSC	Voltage source converter
PWM	Pulse width modulation

Introduction

Recently an increasing attemp is made in the utilization of DGs. Performing clean and low cost energy especially by renewable energy resources has increased the attention to develop new technologies in this research area. Solar photovoltaic system, fuel cell, wind turbine and microturbine are the most common DGs being utilized. They have given decentralized control capability to electric power system [1–5].

A microgrid comprises a set of DGs and local loads as a part of electric distribution network [6]. DGs are usually connected to the utility by a VSC and often known as inverter interfaced DGs [7–8]. Microgrids can be planned to operate in islanding mode which is also known as autonomous or grid connected mode. They also can be operated in both modes, switching from grid connected to the islanding mode in predetermined situations [9–11].

In islanding mode of operation, demand power should be shared among DGs considering their capacity. Using communication infrastructures, control signals can be sent to each DG to regulate the power generation according to the load demand. This method has low reliability because of high dependency to the physical structures. Also, the cost of implementing of such a system is high and even non economical [12–13].

Droop control method is a way to achieve decentralized power sharing for parallel inverter interfaced DGs [14]. It mimics the operation of governor and exciter of a synchronous generator to adjust the frequency and voltage of each micro source. This method does not need any communication link between the grid components and is based on local measurements [15].

Basic principle of the droop control method is by the assumption that the impedances of the transmission lines of the grid are predominantly inductive. In such condition, the active power generated by each source is highly dependent on the output voltage angle, while the reactive power is mainly controlled by the voltage amplitude [16].

In microgrids due to the resistive characteristic of the coupling impedances of the network, active power is not totally controlled by the power angel and it also depends on the voltage amplitude. The same scenario is appointed for the reactive power [17]. Therefore, the proper power sharing control in islanding microgrids plays an important role in microgrid studies.

In [18], virtual impedance method is applied to adjust the output impedance of inverter interfaced DGs and thus the power sharing is improved. Transformation of the voltage and frequency frame to virtual frame

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is proposed in [19] to decouple the active and reactive power control. These two methods need the real time monitoring of the output impedance of each DG in the microgrid and the other network parameters. Therefore, the implementation of such controllers is impractical for large scale microgrids and they can only be applied to small sized grids with fixed loads and network components.

Active droop controllers are proposed in [20–21] for VSCs in resistive electric grids. In this method active power is related to the voltage instead of the frequency and reactive power is related to the frequency. By this opposite droop control scheme, active power is not properly shared while the reactive power sharing is improved.

In [22] the voltage-reactive power droop equation consists of the integral of load bus voltage and reference voltage. Although the proposed method has good results in the reactive power sharing, small signal stability is not verified in the mathematical analysis. The adaptive voltage droop control scheme is proposed in [23], where in droop equation gains are defined as a function of both impedance and output (active and reactive) powers. Implementation of this study is complicated because it needs the continuous monitoring and computation of the network impedance.

The variable horizontal shift is presented in the conventional reactive power-voltage droop characteristic, as a function of microgrid load level in [24]. Active power sharing accuracy in steady-state condition is high and by injecting the active power to the voltage-reactive power droop characteristic, reactive power sharing is enhanced. Also, small signal analysis is provided to show the impact of droop gains on system stability. This method does not have the previous methods complications but it does not consider the transient coupling of active and reactive powers and the negative impact of the poor transient active power sharing.

Most recent studies have utilized the communication infrastructures to overcome the reactive power sharing problem. A multi-agent based control method in [25] consists of two layers. The bottom layer is the electrical grid, while the top layer is a communication network including the agents. It has satisfactory results in proportional reactive power sharing. In [26] nonlinear state feedback control with event-triggered communication among inverters is proposed. In [27], using virtual impedance, the control strategy does not require the knowledge of the line impedances. In these studies, there is the problem of communication time-delay between DGs in the distributed consensus control that uses the network information. Despite having precise reactive power sharing among the inverters, these methods have low reliability due to the communication infrastructures.

In this article, a new structure is proposed for power sharing in combination with droop control method. By this innovation, an enhancement is made in power sharing. It is less complicated in comparison to the impedance monitoring based schemes. Sharing the reactive power is less influenced by the change made in the active load demand.

Proposed method is based on the stability analysis of the microgrid and by modifications of droop control, the system stability is maintained. In the second section the basic principles of conventional droop control scheme are introduced and its poor reactive power sharing is discussed in a sample network. In the third section the new control method is presented and the proper operation of proposed controller is verified by Matlab simulation results. Finally, the fourth section is the conclusion.

Problem statement of droop controller

Droop controller mimics the operation of governor and exciter in synchronous generators. It determines the output frequency and voltage of generators according to the active and reactive powers delivered from their terminals to the utility. Droop control mathematic analysis is usually conducted in dq0 reference frame. It facilitates control process by transforming time variant quantities of voltage and current in three-phase reference frame to part-time-constant quantities.

Figure 1 shows a DG unit connected to the microgrid by inverter. In order to determine frequency and voltage by droop equations, instantaneous powers should be calculated from the generator output voltage and current ($v_o$and i_o) in dq0 coordinate frame. It is assumed that the input source of inverter is an ideal dc link. Output filter ($L_f C_f$) and coupling inductance (L_c) are also connected before the terminal bus.

Instantaneous active (p) and reactive (q) powers generated by each micro source are calculated as follows in (1) and (2).

$$p = v_{od} i_{od} + v_{oq} i_{oq}, \tag{1}$$

$$q = v_{od} i_{oq} - v_{oq} i_{od}. \tag{2}$$

Instantaneous quantities should be passed through low pass filter with ω_f as cut-out frequency according to (3) and (4) to derive active (P) and reactive (Q) powers. Reference voltage and frequency can be obtained by (5)

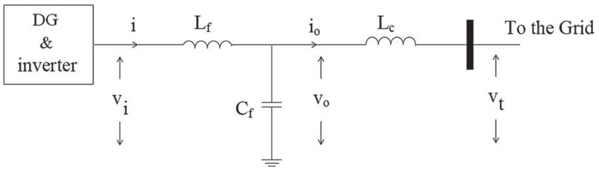

Figure 1. Inverter-based DG with output filter and coupling inductance.

and (6).

$$P = \frac{\omega_f}{s+\omega_f} p, \tag{3}$$

$$Q = \frac{\omega_f}{s+\omega_f} q, \tag{4}$$

$$\omega = \omega_n - k_1 P, \tag{5}$$

$$v^*_{od} = V_n - k_2 Q. \tag{6}$$

In above equations ω_n and V_n are the nominal frequency (in radian per second) and voltage in the microgrid. k_1 and k_2 are active and reactive power droop gains respectively. The component of reference voltage along the q-axis is set to be zero. By adjusting the reference voltage amplitude and frequency, switching pulses can be determined by the pulse PWM switching technic for VSC based DGs in the microgrid.

In order to evaluate the performance of conventional droop control scheme, a test microgrid system is considered for the simulations. Figure 2 shows the microgrid single phase schematic. It contains three buses with a DG in each bus.

To observe DGs generated active and reactive powers, a step change is made in the active load by switching the load3 in bus1 and the total active load is increased. Network and controller parameters like impedance of transmission lines and filters and droop gains are given in Table 1 [28]. Switching frequency is 8 kHz. For simplicity, droop gains are kept the same for all generators in the microgrid.

Figure 3 shows the active powers generated by DGs in all buses. All DGs produce equal active power in the steady-state time because the frequency droop gains have the same value. But in transient state, the active power of DG1 has much greater value with respect to two other DGs. It shows that the droop control does not properly share the active load in the transient time. Meanwhile, it is not the goal of this paper to study the transient power sharing.

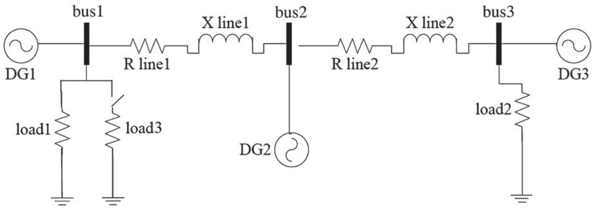

Figure 2. Single phase schematic of the test microgrid.

Table 1. Network and controller parameters of the test system [28].

L_f	1.35 mH	C_f	50 μF
L_c	0.35 mH	ω_f	31.41
k_2	1.3×10^{-3}	k_1	9.4×10^{-5}
x_{line1}	0.1 Ω	r_{line1}	0.23 Ω
x_{line2}	0.58 Ω	r_{line2}	0.35 Ω

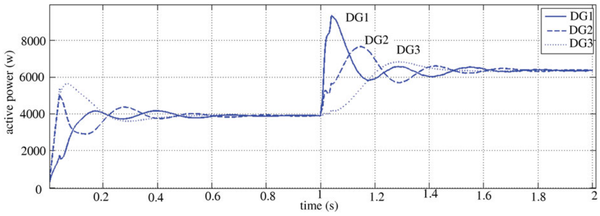

Figure 3. Active power generated by DGs in all buses.

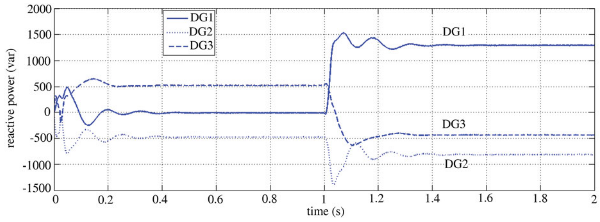

Figure 4. Reactive power generated by DGs in all buses.

According to droop control concept, the frequency of each DG changes continuously by variation in its generated active power. When a change in the load level occurs, frequency reaches the steady-state point after the transient time. DGs have different frequencies in compare to each other during the transient time.

As one frequency set point is possible for generators in a microgrid, active power is divided between DGs in a way that determines same frequency for them. Therefore DGs produce same active power when having same active power droop gain (k_1). In the other words, the conventional frequency-voltage droop technique shares the active load perfectly, because the frequency is a global variable in the steady-state condition. However, as it can be seen in Figure 4, the reactive power is not shared according to the same determined droop gains (k_2).

In addition to the obvious difference of three DGs reactive powers, it can be seen in Figure 4 that the reactive power generation is strongly affected by active load increment. In the other words, there is a coupling between active and reactive powers. Therefore, in an islanding microgrid, the conventional droop controller could not properly share the reactive power. To improve the power sharing, a new control method is proposed and discussed in the next section.

Proposed power sharing method

Reactive power droop gain and stability analysis

In order to decrease the coupling of active and reactive powers, power sharing control structure is modified. The principles of the proposed scheme are discussed in this section. Considering (6), increasing the droop gain from k_2 to k'_2 reduces the required reactive power for a desired reference voltage as it can be seen in Figure 5. In this case, active powers of the generators are the same as

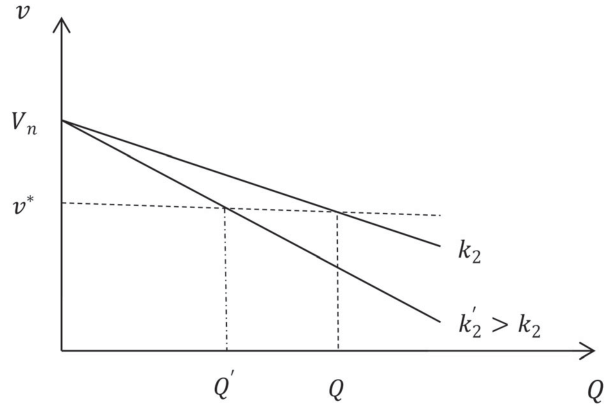

Figure 5. Effect of increasing reactive power droop gain on required reactive power for a desired reference voltage.

previous case because the active power droop gain (k_1) is kept the same.

Increasing the reactive power droop gain seems to be effective to reduce the impact of active load characteristic on reactive power generation. Stability analysis should be conducted before applying droop change. To do this, eigenvalues of the system should be observed. The test microgrid eigenvalues can be derived by the whole microgrid system state space equations [28].

According to Figure 1 coupling impedance equations of each DG can be given by (7)–(12).

$$\frac{di_d}{dt} = \omega i_q + \frac{1}{L_f} v_{id} - \frac{1}{L_f} v_{od}, \tag{7}$$

$$\frac{di_q}{dt} = -\omega i_d + \frac{1}{L_f} v_{iq} - \frac{1}{L_f} v_{oq}, \tag{8}$$

$$\frac{dv_{od}}{dt} = \omega v_{oq} + \frac{1}{C_f} i_d - \frac{1}{C_f} i_{od}, \tag{9}$$

$$\frac{dv_{oq}}{dt} = -\omega v_{od} + \frac{1}{C_f} i_q - \frac{1}{C_f} i_{oq}, \tag{10}$$

$$\frac{di_{od}}{dt} = \omega i_{oq} + \frac{1}{L_c} v_{od} - \frac{1}{L_c} v_{td}, \tag{11}$$

$$\frac{di_{oq}}{dt} = -\omega i_{od} + \frac{1}{L_c} v_{oq} - \frac{1}{L_c} v_{tq}. \tag{12}$$

Equations of the transmission lines can also be explained in dq reference frame. Considering Figure 2, equations of line1 are given as an example in (13) and (14).

$$\begin{aligned} \frac{di_{line1_d}}{dt} &= -\frac{r_{line1}}{L_{line1}} i_{line1_d} + \omega i_{line1_q} \\ &\quad + \frac{1}{L_{line1}} v_{bus1_d} - \frac{1}{L_{line1}} v_{bus2_d}, \end{aligned} \tag{13}$$

$$\begin{aligned} \frac{di_{line1_q}}{dt} &= -\frac{r_{line1}}{L_{line1}} i_{line1_q} - \omega i_{line1_d} \\ &\quad + \frac{1}{L_{line1}} v_{bus1_q} - \frac{1}{L_{line1}} v_{bus2_q}. \end{aligned} \tag{14}$$

By linearizing and rearranging (5)–(14) for all lines and generators of the test microgrid, state space equations can be obtained in the format of (15).

$$\frac{dx_i}{dt} = Ax_i + Bu. \tag{15}$$

In (15), $x_i$is the ith state variable and $u$is a matrix including input variables. For the observed system, state variables are ΔP, ΔQ, Δi_{dq}, $\Delta v_{o_{dq}}$ and $\Delta i_{o_{dq}}$ for three DGs and $\Delta i_{line_{dq}}$ for the two lines. According to Equation (15), eigenvalues are found as the roots of the denominator of the system transfer function which can be obtained in form of a polynomial by taking the determinant of sI-A. Stability of the microgrid can be studied from these eigenvalues [29].

Figure 6 shows the traced trajectory of critical low-frequency eigenvalues of the test system as a function of reactive power droop gain. By increasing k_2, these low-frequency modes are moved to the right hand side of the complex conjugate plane. This will lead the system to oscillations and instability.

In microgrids the physical inertia of VSC based DGs is low. Therefore in autonomous mode of operation, the system is potentially susceptible to oscillations resulting from the changes in load or network parameters.

One of the most important concerns for the stable operation of autonomous microgrids is small signal stability. As a result, in microgrids, any modification in reactive power controller should be implemented in a way to share the reactive power accurately while maintaining the system stable operation.

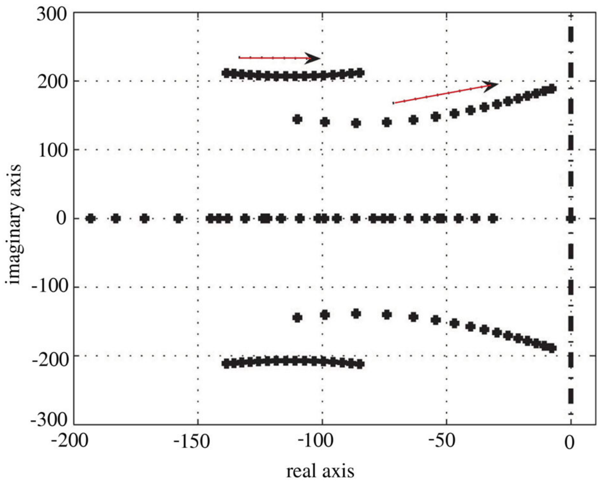

Figure 6. Trajectory of low-frequency modes by increasing reactive power droop gain.

Proposed controller for microgrid stability enhancement

Further, the new control structure for damping the oscillations due to the increment in reactive power droop gain is proposed. By damping the oscillations while applying larger reactive power droop gain, DGs generated reactive power will be less affected in the changes occurred in the active load. The structure of proposed controller is shown in Figure 7.

This controller is added to the conventional droop control structure, being fed by the outputs of droop controller (ω, v^*_{od} and v^*_{oq}). Input signals are added to two back to back voltage and current controllers.

An auxiliary controller is embedded for the reactive power sharing improvement in which the input is the reactive power generated by each micro source and the output is added with a negative gain to the reference voltage of the PWM. v^*_{oq} was set zero in droop controller in order to have symmetrical positive sequence sinusoidal output voltage.

According to Figure 7, the auxiliary loop consists of a gain, a lead-lag transfer function, a low pass filter with T_f as time constant and a wash out function. The gain K is for improving the system stability. Lead-lag transfer function is required to shift the oscillatory modes of the microgrid system to the left half plane and have phase lead. Low pass filter is for high frequency disturbance rejection and washout filter is embedded to make the transitions caused by changes in the input source smoother.

The gain K is chosen to provide sufficient damping to the mode of concern and is taken as one-third of the instability gain. Wash out time constant (T_w) is usually chosen 5–10 seconds [30].

Lead-lag transfer function parameters are determined as follows [30]:

$$\gamma = \frac{1 - \sin(\varphi_{comp})}{1 + \sin(\varphi_{comp})}, \tag{16}$$

$$T_{lag} = \frac{1}{\omega' \sqrt{\gamma}}, \tag{17}$$

$$T_{lead} = \gamma . T_{lag}. \tag{18}$$

In (16) φ_{comp} is the desired phase lead which causes damping the oscillatory modes and ω' is the frequency of the dominant oscillatory mode in radian per second. Voltage and current controllers are responsible for damping high frequency oscillations caused by the switching system and disturbances [31].

According to Figure 6, after increasing the reactive power droop gain, oscillatory modes with low frequency move toward the right side of root locus. Proposed control compensating method provides phase lead and shifts the eigenvalues to the left side of imaginary axis, which enhances the system stability. Also, the disturbance rejection capability of the embedded auxiliary loop facilitates the occurrence of load change and reaching the new stable operating point.

Inner PI controllers in voltage and current controllers guarantee zero steady-state error and improve system transient response. Also, feed-forward loops survive DGs from load disturbances. Coefficients of inner PI controllers are tuned by trial and error method.

For the test microgrid with the proposed controller, a load step-up is applied similar to what happened in the second section. In other words, the microgrid initial active load is 12 kw. After $t = 1$ s the active load is suddenly increased to 20 kw. The microgrid has no reactive load and reactive power generation of DGs are due to the inductance of transmission lines. Active power sharing is accurate like Figure 3. DGs generated reactive power is shown in Figure 8.

By comparing Figures 4 and 8, it can be seen that generated reactive power has been less affected when the change is made in the active load. This has been achieved by increasing the reactive power droop coefficient. Also by applying the auxiliary controller, we have

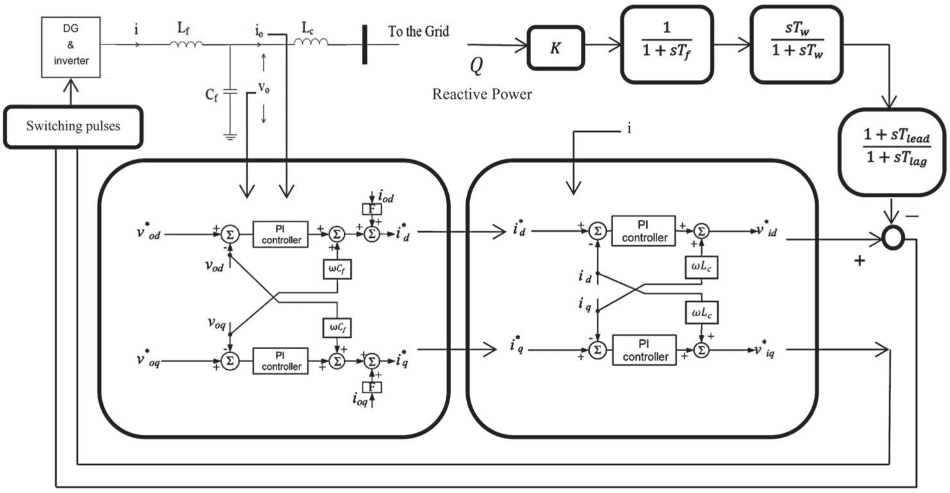

Figure 7. Structure of the proposed control system.

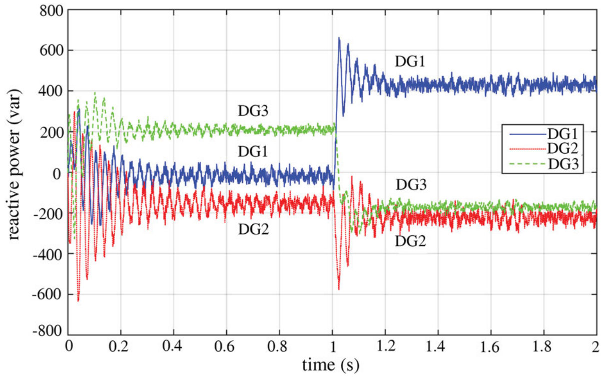

Figure 8. Reactive power sharing result for the new control method.

Table 2. Total generated reactive power by DGs in the microgrid.

	Conventional method	Proposed method
Before load change	1000	350
After load change	2500	800

less oscillation in the output power of the micro sources and the system stability is maintained.

In order to evaluate the benefit of the proposed method, a comparison is made between the new and conventional power sharing methods. Table 2 shows the total generated reactive power (Q) by the DGs in the microgrid in two cases which can be calculated as (19).

$$Q = \sum(|Q_1| + |Q_2| + |Q_3|). \qquad (19)$$

It can be observed that the exchanged reactive power is reduced in the proposed method. Generating equal reactive power is not possible for DGs while having equal droop gains. It is due to the correlation of the reactive power and the output voltage for each DG. Unlike the frequency which is a global variable in the microgrid, the voltage of terminal bus of each DG is a local parameter. Bus voltages are mainly determined by grid configuration. The major achievement of this research is to reduce the correlation between reactive power and voltage.

In a microgrid with the limited installed capacity of generation and transmission system, it is so important to manage the power sharing. The proposed method has prepared a released capacity for inductive loads by the reactive power generation mitigation.

As discussed in this section, the proposed approach is based on the modified droop control method. In comparison to the conventional power sharing methods, the new approach does not use the communication link among distributed generators, hence it has lower cost and high reliability. Also, there are not the complications due to the grid impedance monitoring which is a challenge in conventional methods especially for large scale grids. The new method guarantees the system stability because the auxiliary controller parameters are tuned based on the provided small signal stability analysis. As proven by simulation results, the accuracy of reactive power sharing is properly enhanced as well as reducing the coupling of active and reactive power control.

Conclusion

In this paper, power sharing quality of conventional droop control method is analysed in an islanding microgrid. It is shown that the active power is properly shared when a step change occurs in the active load. In this case, assigned reactive powers to the DGs are strongly increased by stepping up the active load. To solve this problem a control method has been proposed to improve the power sharing. New auxiliary controller is combined with conventional droop control method and voltage and current controllers.

Reactive power droop gain increment to decouple the generated active and reactive powers of DGs has been considered. Embedded auxiliary controller is responsible for damping the low-frequency oscillations caused by droop gain. Also, voltage and current controllers have the high frequency disturbance rejection capability. Proposed power sharing structure is applied to a test microgrid system and the simulation results for a load step are shown. It has been concluded that the new method can release remarkable part of the total generators capacity by reducing the reactive power consumption.

Disclosure statement

No potential conflict of interest was reported by the authors.

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