A novel control strategy of virtual synchronous generator in island micro-grids

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ABSTRACT

The control strategy of virtual synchronous generator (VSG) is an effective and efficient technique to provide frequency supporting for distributed generations. However, the effect of damping is often neglected in a large number of control strategies about VSG. The damping is often used to reduce the active power oscillation, and it relates to the steady-state performance of the system in island micro-grids. This paper analyses the influence of the parameters of damping and inertia on the system in island micro-grids. Furthermore, a hybrid control method of the inertia and the damping is proposed to optimize the frequency curve of the system and enhance the stability of the system. By deploying this method, the decay rate of frequency under load disturbance becomes slower, and the recovery rate of frequency becomes faster after disturbance. Finally, the simulation results show that the proposed method improves the dynamic and static performance of the system in island micro-grids.

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1. Introduction

With the popularization of high proportion of renewable energy, more and more distributed generations and energy storage units are connected to the traditional power grid through power electronic devices (Bai, Xin, & Liu, 2015; Kang & Yao, 2017; Wang, Blaabjerg, & Wu, 2014; Zhou, Lu, & Liu, 2014). The power electronic device itself has no inertia and damping, and it is more susceptible to power fluctuations and system failures (Balaguer, Lei, & Yang, 2011). Therefore, the frequency stability of power systems with distributed generations is greatly threatened (Li, Liu, & Li, 2009; Soni, Doolla, & Chandorkar, 2013).

Most of the traditional power grid is provided by many large synchronous generators, and the traditional generator rotor has the moment of inertia and the damping. It will fluctuate under the load disturbance, which affects the frequency stability of the system. The kinetic energy of the traditional generator rotor is released to suppress the change of frequency. Obviously, distributed generations has no inertia structure of traditional generators (Zeng, Zhao, & Tang, 2013). As a result, the response time of the system is very fast, which is very unfavourable for maintaining the frequency stability of the power grid. In order to solve the problem of distributed generations, the technology of virtual synchronous generator (VSG) has been proposed by (Bevrani, Ise, & Miura, 2014; Driesen & Visscher, 2008; Du, Jiang, & Chen, 2011; Lu, Sheng, & Zhong, 2014). The fixed inertia and damping, characteristics of the traditional generators, are simulated in the virtual synchronous generator (VSG). However, the flexibility of power electronic devices has not been well applied.

Zhong and Weiss (2011) proposed systematically a control strategy of virtual synchronous generator (VSG). It is proved that the virtual synchronous generator (VSG) is completely equivalent to the traditional generators in physical structure and mathematical equation based on the principle of inverters and synchronous generator. A number of studies adopting the virtual synchronous generator (VSG) for increasing inertia have also been reported in the literature (Alipoor, Miura, & Ise, 2015; Zheng, Chen, & Chen, 2015; Zhong, 2016). These control strategies of the virtual synchronous generator (VSG) simulated the effect of the inertia and damping in traditional synchronous generators. For instance, when the load disturbance of power system, the virtual inertia and damping is used to suppress its own power fluctuation and improve the response times of the system in the virtual synchronous generator (VSG). Moreover, the adjusting of reactive power and voltage is realized by adding the proportion link in the virtual synchronous generator (VSG). Considering that power electronic devices in the inverters has great flexibility, the value of virtual inertia in the virtual synchronous generators (VSG) is selected according
to different operating conditions (Soni et al., 2013; Zhang, Zhu, & Zhang, 2016).

Cheng, Yang, and Zeng (2015) presented the complex relationship between the size of virtual inertia and the rate of change of frequency and gave the quantitative selection method of virtual inertia. But the relationship between damping and the frequency variation was not mentioned in it. Li, Zhu, Lin, & Bian (2017) proposed a quantitative selection method for the combination of inertial and damping in the grid-connected condition and analysed in detail the impact of damping on the system. However, there is no specific analysis on the influence of damping coefficient for the system in island micro-grids. So it has considerable limitations. Chen, Wang, and Zheng (2016) designed the control strategy of adaptive inertia and the damping which optimized the curve of transient response times. However, it did not explicitly give the parameters range of the control strategy, and the effect of the damping on the system was not analysed in it.

On the basis of the above researches, the main contribution of this paper is to propose the hybrid control of \( J \) and \( D \) of virtual synchronous generator (VSG) in island micro-grids. The control strategies are composed by three steps: firstly, if the frequency is less than the set value, the traditional control strategy (fixed inertia and damping) is used, and the values of inertia and damping are determined by the stability of the system at this point; secondly, supposing the frequency is more than the set value, the control strategy includes adaptive inertial control and constant damping, and the value of damping are determined by the steady state of the system at this moment; thirdly, assuming that the rate of frequency change is reverse, the control strategy is adaptive damping control and constant inertial. In addition, this paper also proposed a pre-synchronized control for the VSG to connect the micro-grids. By deploying the control strategy, the flexibility of power electronic devices is well demonstrated, and the curve of the frequency in island micro-grids is optimized. Hence, the dynamic and steady-state stability of the system has been greatly enhanced.

The rest of the paper is organized as follows. The complex relationship between traditional droop control and the virtual synchronous generators (VSG) control is analysed in Section 2. According to the stable characteristics of the system in the parallel virtual synchronous generators (VSG), a hybrid control strategy of \( J \) and \( D \) is proposed in Section 3. Section 4 presents the detailed results of applying the control strategy to the power generation units in island micro-grids. Some concluding remarks are given in Section 5.

2. Analysis of VSG control

2.1. Parallel VSG structure and control block diagram

Figure 1 shows the parallel VSG structure. The distributed generations is equivalent to the DC side of VSG in it. The inverters are connected to the common bus through LC filter and power line. The switch \( S \) controls the connection and disconnection between the inverters and the micro-grids. \( L, C, Z \) are respectively the filter inductance, filter capacitance and line impedance. \( U_{dc} \) is the bus voltage at DC side. \( C_{dc} \) is the bus capacitance at DC side.

Considering the important features of the traditional synchronous generator and its complex analysis of electromagnetic coupling, this paper adopts the second order model of synchronous generator as the control model of VSG. Therefore, in order to simulate better the characteristics of synchronous generator, the virtual governor is added in frequency control of VSG. The virtual rotor equation and the virtual governor equation in the virtual synchronous generator can be expressed as

\[
\begin{align*}
J_0 \frac{d\omega}{dt} &= P_m - P_e - D(\omega - \omega_0), \\
P_m &= P_{ref} - k(\omega_0 - \omega), \\
\delta &= \omega - \omega_0,
\end{align*}
\]

where \( P_e \) is the virtual electromagnetic power; \( P_{ref} \) and \( P_m \) are the given active power of the system and the virtual mechanical power, respectively; \( J \) is the virtual inertia; \( D \) is the coefficient of virtual damper winding; \( \omega_0 \) is rated angular velocity and \( \omega \) is the value of actual angular velocity; \( \delta \) is the power angle of the system; \( k \) is the virtual governor parameter.

According to Equation (1), the detailed control block diagram of VSG is given in Figure 2. The input mechanical
power and the input electromagnetic power are respectively provided by the virtual governor and the actual output active power of VSG. And the principle of virtual governor is to adjust the size of active power according to the change of power angle. Hence, the electric angle output by VSG active control loop and the electromotive force amplitude output by reactive control loop generate a three-phase sine modulated wave. The control of VSG system is realized by pulsing width modulation generator and controlling the opening and breaking of switch tube in the double loop control of inverters.

2.2. Connection between VSG control and droop control

Thinking about the existence of first-order filter in the power loop of traditional droop control, the equation of traditional droop control can be given as

\[ \omega = \omega_0 - \frac{m_p}{\tau s + 1} (P - P_{ref}), \]

\[ U = U_0 - \frac{m_q}{\tau s + 1} (Q - Q_{ref}), \]

where \( m_p \) is the coefficient of active power droop; \( m_q \) is the coefficient of reactive power droop.

The proper deformation of Equation (2) is

\[ \tau \frac{d\omega}{dt} = P_{ref} - \frac{1}{m_p} (\omega - \omega_0). \]  

According to Equation (1), the whole VSG active power control equation can be derived as

\[ J\omega_0 \frac{d\omega}{dt} = P_{ref} - P - (k + D\omega_0)(\omega - \omega_0). \]  

By comparing Equation (4) with Equation (5), the relationship between traditional droop control and the virtual synchronous generator (VSG) control parameters can be deduced as

\[ m_p = \frac{1}{k + D\omega_0}, \tau = \frac{J\omega_0}{k + D\omega_0}. \]  

According to Equations (4), (5) and (6), as the existence of first-order filter in the droop control, it has a small inertia and damping. The size of the inertial is positively proportional to \( \tau \) and inversely proportional to the value of \( m_p \). And the size of the damping is inversely proportional to the value of \( m_p \). Hence, they caused the parameters to be difficult to adjust. However, the size of inertia in VSG control is only in a positive ratio with \( J \). The bigger \( J \) is, the longer the dynamic response times is, which is easy to adjust. The damping property is related not only to \( D \), but also to \( k \). In general, the droop control has a little inertia, but it is too small to suppress the frequency variation on the system. Then, the inertia of VSG is only related to \( J \), and the response times can be controlled by adjusting \( J \). Compared with the droop control, the parameter adjustment of VSG control is more flexible. In conclusion, VSG control is a kind of improved droop control. Its performance is much better than droop control.

2.3. Influence of inertia and damping for the frequency

The inertia can optimize the transient process of the system but has nothing to do with the steady-state operation in the power system. To ensure the stable operation of the power system, a certain amount of positive damping is required. If the damping of the system is large enough, the low-frequency oscillation can be avoided. Therefore, the effect of damping effect in island micro-grids cannot be ignored.

By simplifying Equation (5), the relationship between active power change and frequency can be expressed

\[ \Delta P = (k + D\omega_0 + J\omega_0)\Delta \omega. \]  

On the basis of Equations (6) and (7), it can be divided into two stages. One is to increase the load (namely \( \Delta P/dt > 0 \)). In this stage, the angular frequency of the system drops. The rate of angular frequency decrease is related to \( k \), \( J \) and \( D \), and all inversely proportional in the transient time. The greater the \( J \) is, the smaller the frequency variation is. Another stage is the time to load disturbance elimination, that is \( \Delta P/dt < 0 \). In that stage, the angular frequency of system will rise. The smaller the \( J \) and \( D \) are, the larger the frequency variation is. Therefore, a fast response time will be obtained and the system will reach steady state rapidly. If the value of steady-state can be reached as soon as possible, the frequency value...
of the system will be kept at the power frequency during the next load disturbance.

3. Hybrid control of J and D

3.1. The influence of J and D on the stability of the system

Analysing the stability of the system is very important in the process of adaptive adjustment of inertia and damping during the multi-VSGs parallel operating system in island micro-grids. Firstly, the multi-VSGs parallel operating system should be modelled, and then their stability is analysed by using the automatic control principle. Taking two VSG as an example, the parallel structure of Figure 1 is modelled, and as shown in Figure 3.

According to Figure 3, first of all, the linearization treatment of Equation (1) at the stable working point can be obtained

\[
\frac{d\Delta \delta_1}{dt} = \Delta \omega_1, \quad \frac{d\Delta \delta_2}{dt} = \Delta \omega_2, \\
\frac{d\Delta \omega_1}{dt} = -\left(\frac{k_1}{J_1\omega_0} + \frac{D_1}{J_1}\right)\Delta \omega_1 - \frac{\Delta P_{e1}}{J_1\omega_0}, \\
\frac{d\Delta \omega_2}{dt} = -\left(\frac{k_2}{J_2\omega_0} + \frac{D_2}{J_2}\right)\Delta \omega_1 - \frac{\Delta P_{e2}}{J_2\omega_0},
\]

As shown in Figure 3, the line impedance is transformed by \(Y - \Delta\), and the triangle connection impedance \(Z_{12}\) can be given

\[
\Delta P_{e} = \frac{d\Delta P_{e}}{dt}\Delta \delta_{ij} = U_i U_j (|G_{ij}| \cos \delta_{ij} + |B_{ij}| \sin \delta_{ij}) \Delta \delta_{ij}, \quad \Delta P_{e} = U_i U_j |B_{ij}| \Delta \delta_{ij} = N_i \Delta \delta_{ij}, \quad \Delta \omega_1 = \frac{2(k + D_0) \omega_1}{J_0} \quad \Delta \omega_2 = \frac{2(k + D_0) \omega_2}{J_0}.
\]

By substituting Equation (10) into Equation (8), Equation (11) can be derived

\[
\begin{pmatrix}
\frac{d\Delta \delta_{12}}{dt} \\
\frac{d\Delta \omega_1}{dt} \\
\frac{d\Delta \omega_2}{dt}
\end{pmatrix} =
\begin{pmatrix}
0 & 1 & -1 \\
-\frac{N_1}{J_0\omega_0} & -\left(\frac{k}{J_0\omega_0} + \frac{D}{J_0}\right) & 0 \\
-\frac{N_2}{J_0\omega_0} & 0 & -\left(\frac{k}{J_0\omega_0} + \frac{D}{J_0}\right)
\end{pmatrix}
\times
\begin{pmatrix}
\Delta \delta_{12} \\
\Delta \omega_1 \\
\Delta \omega_2
\end{pmatrix}.
\]

By sorting out Equation (11), the characteristic Equation (12) of two VSG parallel operating systems can be deduced

\[
s^3 + As^2 + Bs + C = 0, \quad (12)
\]

where

\[
A = \frac{2(k + D_0) \omega_0}{J_0}, \quad B = \frac{(k + D_0)^2 \omega_0}{J_0}, \quad C = \frac{(k + D_0)(N_1 - N_2)}{J_0\omega_0}.
\]

Then, according to Figure 3, the analysis results of the influence of different \(J\) and \(D\) on the system. Figure 4 shows the effect of different frequency modulation coefficient \(k\) for the systemic stability. With the increasing of \(k\), it increases the damping of the system and enhances the stability of the system.
3.2. Pre-synchronized of parallel virtual synchronous generator

When VSG1 runs independently, VSG2 must be pre-synchronized before it can be connected to VSG1. The pre-synchronized control requires that the voltage amplitude, frequency and phase angle of both sides of the static switch be consistent rapidly, so as to reduce the impact when grid-connected.

The block diagram of pre-synchronized control of parallel system is shown in Figure 5. Firstly, the voltage signals on both sides of the static switch are measured, and the voltage amplitude difference, frequency difference and phase angle difference between the two sides are calculated and adjusted.

The system closed switch \( S_1 \) and \( S_3 \) to start voltage amplitude control and frequency control at some point before the two parallel running VSG. After 0.1 s, it closes switch \( S_2 \) and start up phase control, which make the difference of phase decrease in two parallel VSG.

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**Figure 4.** Influence of \( J, D \) and \( k \) for the stability of the system (a) \( J = 0.2 \sim 8 \text{ kg m}^2, k = 2000, D = 0 \), (b) \( J = 2 \text{ kg m}^2, k = 2000, D = 0.5 \sim 8 \), (c) \( J = 2 \text{ kg m}^2, D = 2, k = 10 \sim 3000 \).

**Figure 5.** Pre-synchronized control of parallel system. (a) Phase and frequency control, (b) Voltage amplitude control.
When it reaches the grid-connected condition, it can realize the pre-synchronized control by disconnecting three switches and closing the static switch $S_{n2}$.

### 3.3. Principle analysis for the hybrid control of J and D

In the operation of parallel inverters system, when a VSG is connected to the micro-grids, the control of presynchronization is first required, and then the small inertia and large damping are required to suppress the power oscillation. Under the large load disturbance, it is expected that $J$ is large to slow down the frequency variation but it also took account of the frequency difference of the system. After the end of the load disturbance, $J$ and $D$ must take larger value. It can make the frequency recover quickly and shorten the recovery time. If the frequency is not restored to the power frequency, it will affect the frequency gravely deviates from the rating system under the second disturbance. Therefore, the constant damping and inertia of VSG have great limitations.

It is assumed that damping control is ignored in the system. The virtual inertia control strategy is only studied. Considering the frequency variation of the island micro-grids, it writes the inertia as a function of the frequency variation. Through this method, the system can achieve the purpose of adjusting frequency automatically. $J$ is written as the equation of frequency variation. $K$ is the upper limit of frequency change, and the value is 1 Hz. The specified frequency change is less than 0.3 Hz, and the inertia cannot change. The corresponding virtual inertia control expression is

$$
\begin{align*}
J &= J_0, \\
J &= J_0 + k_f |f - 50|, \quad 0.3 < |f - 50| < K, \\
J &= J_0, \quad \frac{df}{dt} < 0.
\end{align*}
$$

(14)

For the system, there is a minimum value $J_0$ that does not cause the system to oscillate. When the VSG inputs the load, the inertia of $J_0$ satisfies the requirement of system non-oscillation.

When the load in parallel VSG system is disturbed, the frequency of the system will change in a range. Firstly, compared $|f - 50|$ with 0.3 Hz, it can get two different outcomes. The one is less than this value, and the system adopts constant inertia control. The other is the value is greater than this value, and the proposed adaptive inertial control strategy is adopted to control the system. In this time, the inertia is related to the change rate of frequency and the coefficient of adaptive inertial. When the disturbance ends up, the frequency starts to enter the recovery phase. The frequency conversion rate is reversed, and it needs to reach the working frequency as soon as possible. So the system adopts control strategy with the minimum constant inertia.

According to the above analysis and Equation (14), it can be obtained that the change of inertia only affects the system response time in the adaptive inertia time, and it is independent of the steady state of the system. Therefore, the inertial time constant of the system can be given

$$
\tau_1 = \frac{J_0 + k_f |\omega - \omega_0|\omega_0}{k + D\omega_0}.
$$

(15)

Compared Equation (15) with Equation (6), the system response time becomes longer and the change of frequency is slowed down under the control of adaptive inertia. Therefore, adaptive virtual inertial control is better than fixed virtual inertial control.

After the disturbance is over, the system enters the frequency recovery phase, which the inertial time constant of adaptive inertial control can be given

$$
\tau_{11} = \frac{J_0\omega_0}{k + D\omega_0}.
$$

(16)

Compared it with Equation (15), the frequency recovery time is less than the system’s disturbed transient time, which accelerates the system recovery time.

Although the above control strategy optimizes the frequency variation curve of the parallel VSG system, it does not consider the influence of damping on the system. Meanwhile, it does not explicitly give damping parameter settings.

The damping is related to the frequency change of the next state of the system in island micro-grids with load disturbance. And the larger the damping is, the smaller the frequency offset value of the system is. Therefore, considering the stability value of the next state of the system, a hybrid control of $J$ and $D$ is proposed in island micro-grids. Similarly, damping is also written as a function of frequency variation. The corresponding inertial control expression is shown in Equation (14), and the damping control can be expressed

$$
\begin{align*}
D &= D_0, \quad |f - 50| < 0.3, \\
D &= D_0 + D_2, \quad 0.3 < |f - 50| < K, \\
D &= D_0 + k_d |f - 50|, \quad \frac{df}{dt} < 0.
\end{align*}
$$

(17)

For the system, the VSG needs large damping to suppress power oscillation when it is incorporated into the micro-grids. Moreover, the increase of damping can help stabilize the system and slow down the rate of change in frequency in island micro-grids with the load disturbance. However, in order to avoid the instability of the system caused by the adaptive control of $J$ and $D$ together, the
staggered control of J and D needs to be realized. Therefore, the overall control strategy is shown in Equations (14) and (17).

According to Equations (6) and (17), the inertial time constant and frequency droop coefficient under the hybrid control of J and D can be deduced

\[ \tau_2 = \frac{(J_0 + \frac{k_f}{\omega_0^2} (\omega - \omega_0)) \omega_0}{k + (D_0 + D_2) \omega_0}, \]  
\[ m_{p2} = \frac{1}{k + (D_0 + D_2) \omega_0}. \]  

Obviously, the frequency deviation of the system can be controlled by damping. When the system frequency varies widely, the system has to meet the requirements for frequency deviation. It is necessary to consider the system deviation to meet the requirements, and then appropriately increase the value of \( k_f \) to extend the system response times.

After the disturbance is over, the system enters the frequency recovery time, which the inertial time constant of a hybrid control of J and D can be obtained

\[ \tau_{21} = \frac{J_0 \omega_0}{k + (D_0 + D_2) \omega_0}. \]

Compared it with Equation (16), the hybrid control of J and D enormously reduces the frequency recovery time and speeds up the system recovery time. When the local load disturbance is over, the frequency can be quickly restored to the steady-state value.

In the hybrid control of J and D, \( k_d \) and \( k_f \) are the maximum multiple of regulation, which can be obtained from the stability theory of control system, reflecting the critical upper limit of VSG system stability. Assuming that the frequency deviation should not exceed 1 Hz, then the value of \( D_2 \) can be calculated according to the steady-state angular frequency deviation

\[ \Delta \omega = -\Delta P \frac{1}{k + (D_0 + D_2) \omega_0}. \]

4. Results

In order to verify the effectiveness of the proposed control method, the simulation model of a single VSG independent and multi-VSGs in the micro-grids is respectively built in MATLAB/Simulink, and the parameters are set as follows.

4.1. Case 1: A single VSG in island micro-grids

In this case, the performance of the proposed control method is compared with that of the droop control method and the VSG control which uses the fixed virtual inertia and damping. The simulation results are presented in Figure 6(a–f). As shown in Figure 6(a), the initial active power of micro-grid is 14 kW. There are two stages of load disturbance: first, the active power of load experienced a large change, and the time of duration with disturbance was 0.4 s; second, the active power of load experienced a small change, and the time of duration with disturbance was 0.3 s. Figure 6(b) shows that the size of inertia only affects the transient characteristics of the system, and the greater the inertia, the longer the response times. Figure 6(c) shows that the size of the damping is related to the steady state of the system, and the greater the damping, the smaller the falling frequency of the system. They

\[ \text{Figure 6. Frequency response of load disturbances. (a) Change in active power of the system, (b) The effect of inertia on frequency, (c) The effect of damping on frequency, (d) Droop control, (e) Fixed virtual inertial control, (f) The hybrid control of J and D.} \]
verified the above analysis of the influence of damping and inertia on the system in Section 3.

As seen from Figure 6(d,e), compared with the results from the conventional droop method, the VSG control can provide inertia and damping for the system. But the fixed virtual inertia and damping cannot take account of the operating state of the system. As shown in Figure 6(f), compared it with the fixed virtual inertia and damping, the response curve of the frequency is optimized. The initial frequency has a slow change with the load disturbance by adopting the hybrid control of J and D, and the fall range of frequency is also smaller than before in the system. At the end of the first disturbance, the recovery time of frequency is faster than before in the system. When the second load disturbance starts, the effect of disturbance on frequency will be reduced owing to the fast recovery of frequency. In a word, the stability of the island micro-grids is improved by adopting the hybrid control of J and D.

Table 1. The simulation coefficient of VSG.

| parameter | Value       | parameter | Value       |
|-----------|-------------|-----------|-------------|
| Vdc       | 800 V       | k         | 2229 kW/Hz  |
| L         | 0.3 mH      | Pe        | 1500 W      |
| C         | 1.5 μF      | Xr        | 3 mH        |
| U0        | 311 V       | w0        | 314 rad/s   |
| J0        | 0.2 kg m²   | D0        | 0.5         |

Figure 7. Presynchronous control.

4.2. Case2: multi-VSGs in island micro-grids

In this case, the simulation parameters of VSG are consistent with Table 1, and the simulation model of the parallel VSG illustrated in Figure 1 is constructed. The simulation is carried out as follows: VSG1 runs with 14 kW load, and VSG2 runs in no-load. The system starts the pre-synchronized synchronous unit at 0.25 s, and the voltage and phase of the two VSGs are consistent at 0.35 s. The pre-synchronized unit is removed and the switch S1/2 in Figure 1 is closed. The system input the load 20 kW at 1.1 s, and the load was removed after 0.5 s.

Figure 7 shows the pre-synchronized control of the system. It can be concluded that the phase voltage of the system before the interconnection is consistent based on the method provided in this paper, which meets the requirements of the parallel power grid.

As seen from Figure 8(a), the oscillation of the system occurred by adopting the control strategy with fixed inertia and damping in the moment of the connected micro-grids. Due to the existence of inertia and damping, the system extended the response times after the load disturbance started. But, the recovery time of frequency was affected by inertia and the frequency of system cannot be recovered quickly after the end of load disturbance. Therefore, it is infeasible that the inverters adopted the control strategy with fixed inertia and damping in island micro-grids.

As seen from Figure 8(b,c), compared with the results from the control strategy with fixed inertia and damping, the oscillation of system is suppressed in the moment of the connected micro-grids. In the beginning of the load disturbance, the system extended the response times
with the control strategy with adaptive inertia. However, by adopting the hybrid control of J and D, the system frequency is raised by 0.2 Hz. When the load disturbance ends, the system enters the frequency recovery stage. The recovery time of frequency is the shortest after the system adopts the hybrid control of J and D. Hence, the hybrid control of J and D is the best control strategy in three control strategies, and the curve of frequency curve is optimized by it. In addition, the increase of damping, to a certain extent, inhibits the influence of the increase in inertia on the stability of the system and greatly improves the stability of the system.

5. Conclusion

This paper analyses the relationship between traditional droop control and the virtual synchronous generator (VSG) control strategy in island micro-grids. Compared with the droop control, the control strategy of virtual synchronous generator (VSG) has good performance in the systems. Due to the shortage of traditional virtual synchronous generator (VSG) control strategy, the hybrid control strategy of J and D is proposed to improve the active power and frequency characteristics. It gives the effects of virtual inertia and virtual damping on the stability of the system and demonstrates the feasibility of adaptive changes of virtual inertia and damping. By deploying the control strategy, the steady and transient characteristics of the system have been greatly improved. Therefore, compared with the adaptive inertia, the hybrid control of J and D can improve the steady-state characteristics of the system and optimize the disadvantages of adaptive inertial control under the load disturbance situation in the island micro-grids. Finally, compared with the traditional droop control and adaptive inertia of the VSG control, the
advantages of hybrid control of $J$ and $D$ are verified by using MATLAB/Simulink for simulation.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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