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# Adaptive Inertia and Damping Control of Parallel System with Multi-VSGs in Microgrids

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***Abstract:***

With the rapid development of new energy, the wide application of microgrids has become the main trend of energy structure reform in the world. Virtual synchronous generator (VSG) control technology makes the microgrids inverter have the operation characteristics of synchronous generator, provides the necessary inertia and damping support for the system, and realizes the friendly grid connection of lots of new energy. In order to better realize the coordination of multi-VSGs units in the microgrids when providing inertial damping support, a small signal model of steady-state working point is established to analyze the influence of key control parameters on the stability of the system. Combined with the dynamic and stability characteristics of VSG, the comprehensive value area of virtual moment of inertia and damping coefficient of VSG is determined. According to the frequency variation, the adaptive control strategy of moment of inertia and damping can be adopted to improve the transient stability and dynamic frequency response of the system. Finally, simulation result shows that the presented strategy can suppress the system frequency and active power oscillation under different working conditions, and can well meet the operation requirements of microgrids.

***Keywords:*** *VSG parallel, Microgrids, Distributed new energy, Adaptive inertia damping control, Small signal model.*

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## I. INTRODUCTION

In order to deal with the dual crisis of energy and environment, microgrid has become the main form of building new energy system because it can absorb lots of distributed new energy. Microgrid cooperates with various heterogeneous energy sources, energy storage devices and loads to conduct two-way energy flow between microgrids and grid through grid connection interface [1,2]. Due to lack inertia and damping support for stable operation of grid connected inverter device, it is sensitive to the fluctuation of new energy output and load, which makes

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the microgrid prone to oscillation when disturbed, thus posing a huge threat to the stable and reliable operation of the system[3,4]. Virtual synchronous generator (VSG) technology, by introducing virtual inertia and damping similar to traditional synchronous generator into grid connected inverter control, improves its ability to participate in the dynamic regulation of grid voltage and frequency, and becomes an effective solution for lots of distributed new energy connected to grid friendly[5,6].

As a form of energy organization, microgrids can realize the effective integration of multiple energy sources, improve the utilization of new energy, and interact with power grid in a friendly way, and can flexibly operate in grid connected and island mode [7,8]. In order to improve capacity and redundancy, multi-VSGs parallel connection are used in microgrids, but it also makes the stability analysis and control of power grid more complex. The control strategy and parameters selection of inverter in multi-VSGs will affect the stable operation of parallel system [9,10]. In order to meet the working requirements of power grid, it has become the focus of research to make use of the advantages of flexible adjustment of control parameters of virtual synchronous generator, and change the control strategy according to the actual working conditions [11].

Over the last decades, there are many researches on the single VSG moment of inertia J in VSG control. Through the comparison between VSG control algorithm and traditional control algorithm, references [12-14] regulated the moment of inertia and suppressed the system frequency fluctuation caused by load change, but did not analyze the multi-VSGs parallel system. In references [15, 16], by establishing a small signal model of parallel VSGs, the influence of system internal parameters on stability was analyzed in detail, which provided a reference for system optimization parameters. In reference [17], the problem of power oscillation in parallel microgrids was analyzed, and it was pointed out that the reasonable setting of moment of inertia and damping coefficient can suppress the power oscillation, but the VSG control parameters in this paper were fixed, which cannot meet the performance requirements of microgrids in different modes. In reference [18], an adaptive parameter adjustment of moment inertia J and damping coefficient D was proposed according to the change rate and deviation of rotor angular velocity, which can reduce the overshoot of active power and frequency under different operation modes. However, the selection principle of two formulas and the selection basis of correlation coefficient in self-adaptive control algorithm were not given. In reference [19], using the principle of synchronous generator, a virtual inertia matching method for parallel operation of VSG were proposed to study the power distribution problem. However, the influence of parameter variation on system stability was not analyzed, and the parameters could not be adjusted adaptively. In this paper, based on the analysis of power angle transient regulation process under different operation modes of microgrids, the

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small signal model of multi-VSGs parallel system is established to analyze the influence of key control parameters change on system stability. Combined with the stability and dynamic characteristics of VSG parallel system, the comprehensive value area of virtual moment of inertia and damping coefficient of VSG are obtained and the VSG control strategy which can adaptively adjust the moment of inertia and damping according to the frequency change is proposed to reduce output power and frequency oscillation of microgrids operation. Finally, the simulation results of MATLAB/Simulink show that the proposed control strategy can not only ensure the parallel dynamic performance, but also restrain the frequency fluctuation too fast, and improve the stability of microgrids operation.

## II. BASIC PRINCIPLE OF VSG

The VSG control idea is to introduce frequency and voltage control into synchronous generator, and improve the frequency stability of independent microgrid by simulating rotor the operating characteristics [20]. Fig 1 is the control structure diagram of the microgrids composed of the inverter controlled by VSG. $L_f$ is the filter inductance, $C_f$ is the filter capacitor. Selecting the control algorithm and parameters of analog synchronous generator can make the inverter show the operation characteristics of synchronous generator. $u_{abc}$ and $i_{abc}$ are the output voltage and current of VSG, $U_{dc}$ is the DC bus voltage.

VSG control mainly include *PQ* power calculation, VSG control and voltage current double loops tracking link. Based on the collected output voltage and current signals of grid connected terminal, the voltage reference command $U_{ref}$ and angular frequency $\omega$ are generated by *PQ* calculation and VSG control module. The virtual impedance link is introduced to compensate the voltage to achieve accurate power distribution. Then, the SPWM drive signal required by grid connected inverter elements is modulated by voltage and current double loop tracking $U_{ref}$. Finally, the power is regulated by inverter control to ensure the stability of voltage and frequency.

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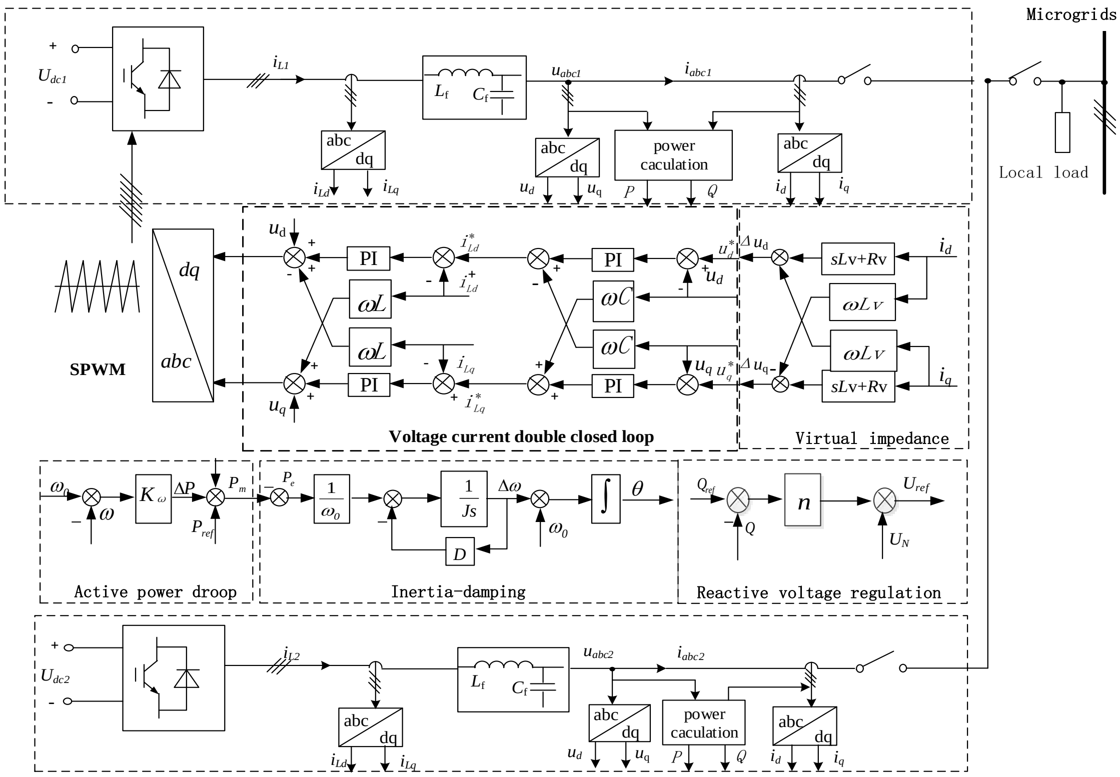


Fig 1: microgrid control structure diagram

2.1 Active Frequency Modulation ($P_e$-$\Omega$) Control

Based on the principle of synchronous generator governor and rotor motion equation, when the sudden change of active load in the power system causes the imbalance of active power of synchronous generator and the change of system frequency, the existence of moment of inertia and damping of traditional synchronous generator can buffer the frequency of power system in the process of primary frequency regulation. According to the change relationship between $P_e$ and $\omega$, the power is adjusted until a new power balance state is reached.

According to the VSG control principle, the mechanical part of synchronous generator is as following.

$$P_m - P_e - D(\omega - \omega_0) = J\omega_0 \frac{d\omega}{dt} \tag{1}$$

Where $J$ is the virtual moment of inertia, $D$ is the damping coefficient, $\omega$ is the angular

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frequency of the system, $\omega_0$ is the rated angular frequency of the system, $P_m$ and $P_e$ are mechanical power and electromagnetic power respectively.

Compared with the principle of traditional synchronous generator governor and VSG primary frequency regulation process, $P_m$ can be expressed as active power droop characteristics:

$$P_m = P_{ref} + K_\omega(\omega_0 - \omega) \tag{2}$$

Where $K_\omega$ is the active droop coefficient and $P_{ref}$ is the given active power.

2.2 Reactive Power Regulation (*Q*-*U*) Control

When the system reactive load changes suddenly, it will also lead to the change of reactive power, which will causes the fluctuation of system voltage. Similar to synchronous generator excitation regulation process, VSG maintains voltage stability by providing reactive power. VSG reactive voltage (*Q*-*U*) control is as following:

$$U_{ref} = U_N + n(Qm_{ref} - Q) \tag{3}$$

Where: $U_N$ is the rated voltage, $n$ is the droop coefficient of reactive voltage, and $Q_{ref}$ and $Q$ are the given and output reactive power respectively.

2.3 Virtual Impedance

Considering that there is a certain coupling between active and reactive power control, the introduction of virtual impedance can suppress the circulating current between parallel VSGs, achieve accurate power sharing, and improve the stability of parallel operation of multi-VSGs. Equation (4) is the given voltage expression with virtual impedance, and it is also the second-order equation mathematical model of synchronous generator.

$$\begin{cases} u_d^* = -R_V i_d - L_V \dfrac{di_d}{dt} + \omega L_V i_q + U_{ref} \\ u_q^* = -R_V i_q - L_V \dfrac{di_q}{dt} + \omega L_V i_d + 0 \end{cases} \tag{4}$$

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Where: $R_V$ and $L_V$ are virtual resistance and inductance respectively, $u_d^*$ and $u_q^*$ are *dq* components of voltage reference signal of voltage current outer loop respectively, $u_d$ and $u_q$ are *dq* components of output reference voltage of VSG control loop, $\Delta u_d$ and $\Delta u_q$ are the voltage compensation signal generated by the virtual impedance loop.

## III. CONTROL PARAMETERS ANALYSIS OF MULTI-VSGS PARALLEL SYSTEM

### 3.1 Small Signal Modeling of VSG Parallel System

For designing the parameters of multi-VSGs independent microgrid, in order to facilitate the analysis, the dual VSGs system is modeled based on the engineering approximate analysis of the traditional static stability method of synchronous generator parallel structure [21]. The parallel structure of dual VSGs as shown in Fig 2. In the figure, $E_1$ and $E_2$ are VSG output voltage respectively, $U_{pcc}$ is the AC bus voltage, $\delta_1$, $\delta_2$ is the phase difference between VSG and AC bus, $Z_1$ and $Z_2$ are the output impedances of VSG, $Z_L$ is the parallel load impedance.

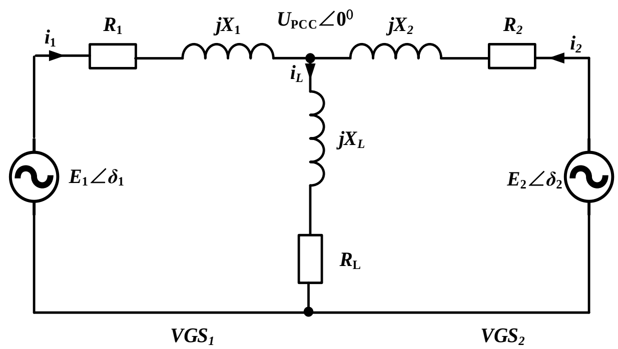


Fig 2: VSG parallel equivalent circuit model

Based on steady working point（$\omega_s$, $\delta_s$, $P_{es}$）, after linearization of VSG mechanical motion equation, the following formula can be obtained.

$$\begin{cases} \dfrac{d\Delta\omega_i}{dt} = -(\dfrac{K_{\omega i}}{J_i\omega_0} + \dfrac{D_i}{J_i})\Delta\omega_i - \dfrac{\Delta P_{ei}}{J_i\omega_0} \\ \dfrac{d\Delta\delta_i}{dt} = \Delta\omega_i \end{cases} \tag{5}$$

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Among the formula (5), $\Delta\omega_i$, $\Delta\delta_i$, $\Delta P_{ei}$ are angular frequency, power angle and active power increment, $J_i$, $D_i$ and $K_{\omega i}$ are the moment of inertia, damping coefficient and adjustment coefficient of the *i*th VSG.

$$\begin{cases} \Delta P_{ei} = S_{Ei}\Delta\delta_{12} \\ S_{E1} = E_1E_2(-|G_{12}|\sin\delta_{12} + |B_{12}|\cos\delta_{12}) \\ S_{E2} = E_1E_2(-|G_{12}|\sin\delta_{12} - |B_{12}|COS\delta_{12}) \end{cases} \tag{6}$$

$\delta_{12}=\delta_1-\delta_2$ is the relative power angle difference. $S_{E1}$、$S_{E2}$ are the whole step power coefficients of VSG, $G_{12}$、$B_{12}$ are conductance and susceptance between nodes 1 and 2.

Combining (5) and (6), the small signal characteristic equation of two parallel dual VSG can be written as equation (7).

$$s^3+As^2+Bs+C=0 \tag{7}$$

The coefficients of characteristic equation are as shown in equation (8):

$$\begin{cases} A = \frac{K_{\omega1}}{J_1\omega_0} + \frac{K_{\omega2}}{J_2\omega_0} + \frac{D_1}{J_1} + \frac{D_2}{J_2} \\ B = \frac{K_{\omega1}K_{\omega2}}{J_1J_2\omega_0^2} + \frac{D_1K_{\omega2}}{J_1J_2\omega_0} + \frac{D_2K_{\omega1}}{J_1J_2\omega_0} + \frac{D_1D_2}{J_1J_2} + \frac{S_{E1}}{J_1\omega_0} - \frac{S_{E2}}{J_2\omega_0} \\ C = \frac{K_{\omega2}S_{E1} - K_{\omega1}S_{E2} + \omega_0(D_2S_{E1} - D_1S_{E2})}{J_1J_2\omega_0^2} \end{cases} \tag{8}$$

In order to simplify the modeling, dual VSGs with the same parameters are considered. That mean $J_1 = J_2 = J$, $D_1 = D_2 = D$, $K_{\omega1} = K_{\omega2} = K_\omega$, and $\delta_1=\delta_2$, $\delta_{12}=0$, $\sin\delta_{12}\approx0$, $\cos\delta_{12}\approx1$. Then the coefficients can be expressed as equation (9).

$$\begin{cases} A = \frac{2(K_\omega + D\omega_0)}{J\omega_0} \\ B = \left(\frac{K_\omega + D\omega_0}{J\omega_0}\right)^2 + \frac{S_{E1} - S_{E2}}{J\omega_0} \\ C = \frac{(K_\omega + D\omega_0)(S_{E1} - S_{E2})}{(J\omega_0)^2} \end{cases} \tag{9}$$

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After star angle transformation of the structure in Fig 2, the impedance between dual VSGs is obtained as following:

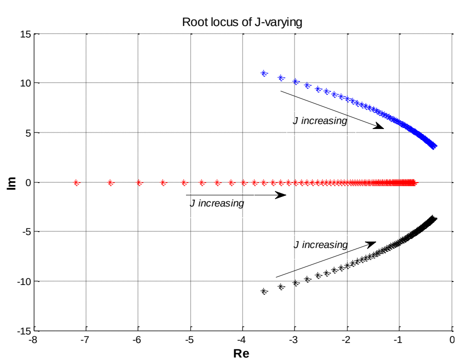
$$Z_{12} = \frac{Z_1 Z_2 + Z_L Z_1 + Z_L Z_2}{Z_L} = R_{12} + jX_{12} \tag{10}$$

Considering the output inductive circuit of VSG and setting the $Z_L$=1Ω, $Z_1$=$Z_2$=$j\omega_0 L_0$, then equation (11) can be concluded from equation (6).

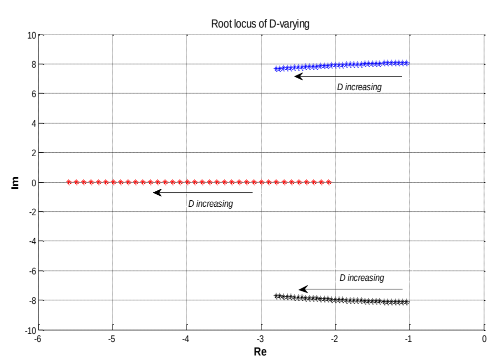
$$S_{E1} - S_{E2} = \frac{4E_1 E_2}{\omega^3 L_0^3 + 4\omega L_0} \tag{11}$$

3.2 Small Signal Stability Analysis of VSG Parallel Connection

Based on the established parallel VSG small signal model, combined with the characteristic root locus in control theory, the stability influence of VSG control parameters is analyzed, and the parameters are optimized to meet the needs of system performance. Fig 3 shows the eigenvalue distribution of VSG parallel system when the parameters $J$, $D$, $K_\omega$, $L_0$ vary. It can be seen from the root locus distribution that with the increase of $J$, the characteristic roots move towards the virtual axis, the inertia of the system increases, but the oscillation intensifies, and the stability of the system becomes worse. With the increase of $D$, $K_\omega$ and $L_0$, the eigenvalue moves to the left half plane, the damping of the system increases, the overshoot is suppressed, and the stability of the system is enhanced.




(a)




(b)

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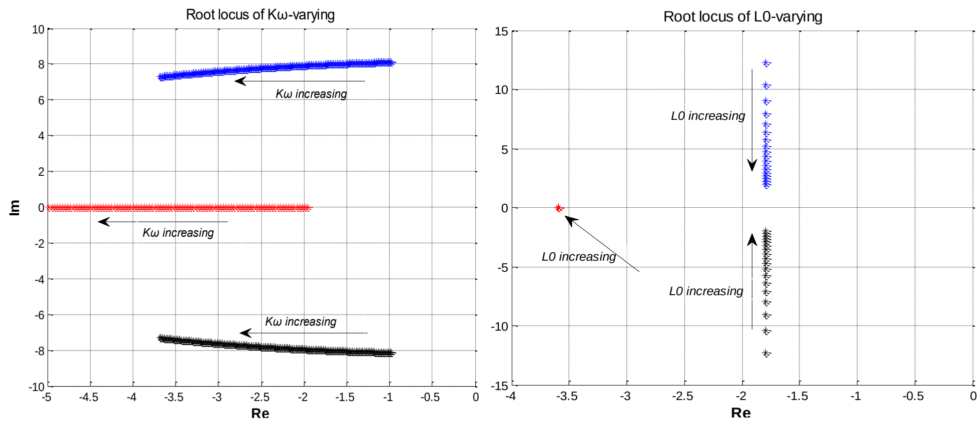


(c) (d)

Fig 3: stability analysis results of VSG parallel parameters variation

Specifically, increasing $J$ can increase the system inertia, but it will slow down the frequency response, and the dynamic adjustment process of output frequency of each VSG and grid frequency under disturbance will be longer. And reduce $D$ and $K_{\omega}$, it will reduce the system damping ratio, which will make the frequency response faster, but it will cause the greater the power grid frequency fluctuation amplitude oscillation and the slower the attenuation speed, which will adversely affect the stability of the system.

## IV. Adaptive Inertia and Damping Control Strategy

When multi-VSGs are connected to the microgrids, virtual damping and inertia are introduced to suppress power fluctuation and slow down the frequency change caused by load disturbance kinetic energy, which can enhance the dynamic characteristics of frequency effectively. If microgrid operating in connecting mode, the smaller moment of inertia $J$ is selected, while operating in island mode, the larger $J$ is selected to provide more inertia to reduce the influence of load fluctuation on frequency and make the system have time to complete the primary frequency modulation process.

Fig 4 shows the power angle and rotor angle frequency variation curve of synchronous generator. According to the frequency oscillation, the process is divided into several stages: $a$~$b$, $t_1$~$t_2$; $b$~$c$, $t_2$~$t_3$; $c$~$b$, $t_3$~$t_4$; $b$~$a$, $t_4$~$t_5$. In the interval $a$~$b$, the input power of the system increases from $P_a$ to $P_b$. At $t_1$ time frequency change rate $d\omega/dt$ is larger and if $d\omega/dt$ continues to increase, there will be a large frequency deviation $\Delta\omega$. So $J$ need to be increase to decrease $d\omega/dt$, and the frequency deviation $\Delta\omega$ is small, and $D$ just keep the initial value. At $t_2$ time $d\omega/dt$=0, $\Delta\omega$ is at maximum. In the interval $b$~c, it is necessary to increase $D$ to decrease the

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$\Delta\omega$, and decrease $J$ to increase $d\omega/dt$. The analysis process of other intervals $c$~$b$ and $b$~$a$ are similar to $a$~$b$. According to the change of microgrid frequency, the switching threshold is set to adaptively adjust the $J$ and $D$ parameters.

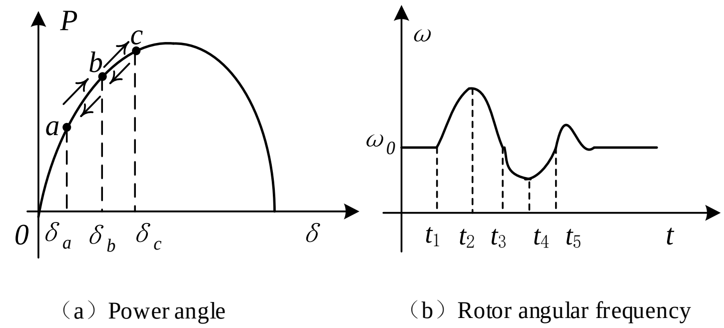


Fig 4: power angle and frequency change curve of synchronous generator

When two VSGs are running in parallel in microgrids, the equation (12) can be obtained from equation (1).

$$P_{e1}-P_{e2}=P_{m1}-P_{m2}+J_1\frac{d\omega_1}{dt}-J_2\frac{d\omega_2}{dt}+D_1\Delta\omega_1-D_2\Delta\omega_2 \tag{12}$$

For the microgrids power supply with the same power frequency control parameters and capacity, then the following formula can be obtained.

$$P_{e1}-P_{e2}=(J_1-J_2)\frac{d\omega}{dt}+(D_1-D_2)\ \Delta\omega \tag{13}$$

Among the equation (13), $J$ mainly affects the dynamic part of power change, while $D$ mainly affects the steady-state part. In view of the influence of $J$ and $D$ parameters on the system stability, this paper analyzed the frequency variation of the system reference value and the actual feedback $\Delta\omega$ and $d\omega/dt$ setting adjustment threshold and change the fixed parameters $J$ and $D$ into the adjustable frequency change functions $J_s$ and $D_s$, which can be adjusted dynamically according to the microgrids operation mode and system frequency change, so as to get the fast frequency response ability and reduce the frequency impact.

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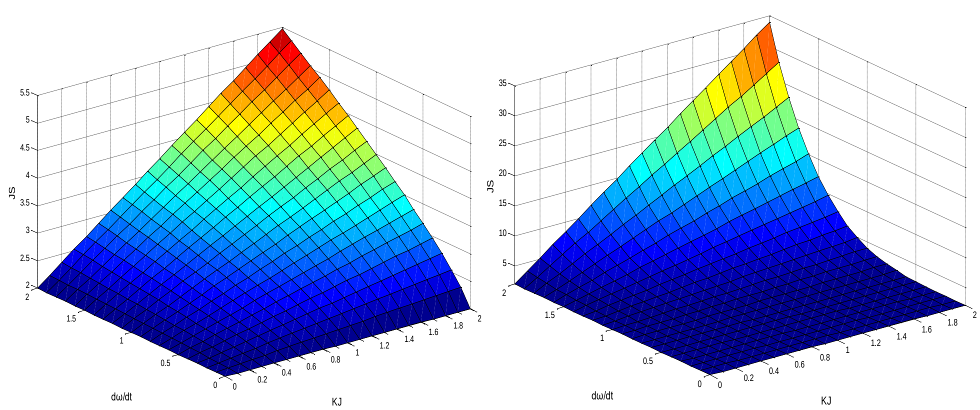
$$J_s=\begin{cases} J_0 & \Delta\omega\dfrac{d\omega}{dt}\le 0 \cup \left|\dfrac{d\omega}{dt}\right|\le M_J \\ J_0+K_J\left|\dfrac{d\omega}{dt}\right|^{\alpha} & \Delta\omega\dfrac{d\omega}{dt}>0\cap\left|\dfrac{d\omega}{dt}\right|>M_J \end{cases} \tag{14}$$

$$D_s=\begin{cases} D_0 & |\Delta\omega|\le M_D \\ D_0+K_D|\Delta\omega|^{\beta} & |\Delta\omega|>M_D \end{cases} \tag{15}$$

Where $J_0$ and $D_0$ are the initial values of moment of inertia and damping when VSG is put into microgrids without power oscillation.

Fig 5 shows the three-dimensional space of the system moment of inertia $J_S$ with $d\omega/dt$ and coefficient $K_J$, $\alpha$ variation. With the increase of index $\alpha$ the surface changes from "convex" to "concave", and the moment of inertia $J_S$ increases rapidly with $\alpha$ increasing. The exponential inertia algorithm can flexibly select the upper and lower boundaries of $J$. When the system frequency changes, by adjusting $K_J$、$\alpha$ the fast change of $d\omega/dt$ can be restrained and the frequency dynamic process can be adjusted.

When selecting the adjustment coefficients $K_J$ and $K_D$, the transient performance index of the system should not be ignored, whether the overshoot and overshoot time meet the requirements. The principle of choosing α and $\beta$ based on the small signal model of control system, the overshoot and regulation time of transient response should be considered.




(a) $\alpha$=0.9 (b) $\alpha$=4

Fig 5: relationship among JS and parameters dω/dt and KJ

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The distributed power system with inertia in the microgrids provides guarantee for the frequency of the system. $J$ is closely related to the requirements of microgrids operation and dynamic characteristics of micro source and energy storage device. When the load power fluctuates, the minimum moment of inertia needs to be determined. The expression of the system frequency response can be obtained from the rotor motion equation as following:

$$f = f_0 - \frac{\Delta P_e}{2\pi(D\omega_0 + K_\omega)}(1 - e^{-\frac{D\omega_0 + K_\omega}{J\omega_0}t}) \tag{16}$$

When the load changes, the frequency variation can be expressed as equation (17):

$$\Delta f = -\frac{\Delta P_e}{2\pi J\omega_0} e^{-\frac{D\omega_0 + K_\omega}{J\omega_0}t} \tag{17}$$

It can be seen from equation (17) that at t=0 time there is a maximum value of frequency change $\Delta f_{max}$, so the moment of inertia satisfies the relation as inequality (18):

$$J > \frac{2\pi\omega_0 \Delta f_{max}}{\Delta P_e} \tag{18}$$

According to the relationship between system damping and parameters, the system should work in under damping state to ensure good dynamic performance when the load fluctuates. Then the relationship between the $J$ and $D$ of the system satisfies the inequality (19).

$$J > \frac{D^2 X}{EU\omega_0} \tag{19}$$

Referring to the specific determination method of $J$ given by VSG scheme of University of Leuven [22], if $P_{max}$ is the upper limit of inverter output active power, the value range of $J$ is obtained as follows:

$$J \le \frac{P_{max}}{\max(\omega \frac{d\omega}{dt})} \tag{20}$$

In combination with inequality (18) and (19), the lower boundary of $J$ for stable operation

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of the system can be obtained.

The traditional VSG control method in microgrids with multi-VSGs is a kind of fixed parameters control. When the microgrids are in different operating conditions, an improved VSG control strategy with adaptive parameters is adopted.

(1) When the dynamic process of VSG access or cut-off microgrids is controlled by VSG, $J$ takes the smaller value to suppress the power oscillation caused by traditional VSG control.

(2) When the frequency change caused by local load fluctuation exceeds the given value, switch the VSG control with adaptive adjustment of inertia damping, increase the value of $J$ accordingly, and the frequency change rate will become smaller, which can take a regulatory role of excessive frequency change.

(3) When the load fluctuation disappears, the frequency gradually tends to the steady-state value, and then switches to VSG control by the change of frequency to realize dynamic response process quickly. The frequency adaptive adjustment process is realized through the switching of two control modes.

## V. Simulation Results Analysis

To verify the effect of VSG adaptive control strategy, a simulation model is built to compare the change of system frequency under load changing conditions. The independent microgrids simulation model including dual VSGs shown in Fig 1 is constructed, and the simulation parameters are shown in Table I.

**TABLE I. Simulation parameters of paralleled VSGs**

| Simulation parameters | Value |
|---|---|
| DC Bus Voltage $U_{dc}$/V | 700 |
| AC rated voltage $U_N$/V | 311 |
| Filter inductance $L$/$m$H | 2 |
| Filter capacitance C/$\mu F$ | 100 |
| Virtual reactance $L_v$/$m$H | 5 |
| Moment of inertia $J$/($K$g·m$^2$) | 0.2 |
| Damping coefficient D | 8 |

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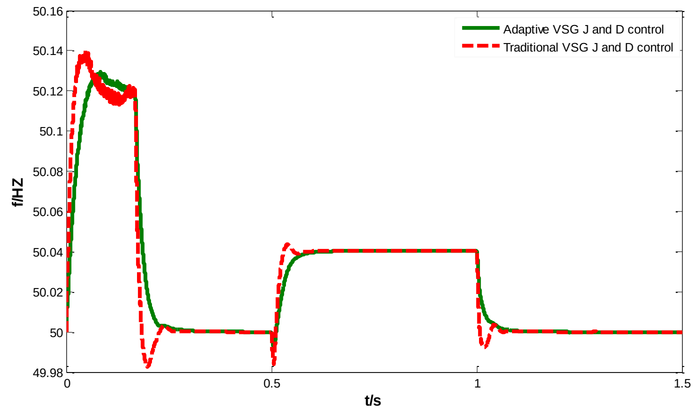


Fig 6: comparison of frequency variation curves

Fig 6 shows the frequency *f* change of VSG parallel system during the sudden increase and decrease of load. Comparing the two control results, during the process of 0~0.2s, the system frequency change rate decreases, a certain inertial support is obtained, and the process of frequency entering the stable range is shortened; When the 0.5s load increases suddenly, the change rate of system frequency decreases obviously, the overshoot is suppressed, and the frequency adjustment range is shortened. When the load decreases in 1s, the frequency changes slowly, which effectively alleviates the impact of frequency mutation on grid connected inverter in traditional droop control. In short, in VSG control by adaptive adjustment, the virtual *J* is increased in the initial stage of frequency change adjustment to suppress excessive frequency change rate and overshoot, and the *J* is moderately reduced in the later stage, so that the frequency can reach the steady-state quickly. During the whole operation process, the frequency fluctuationis always maintained within ±0.2Hz, the overshoot is suppressed, the duration of frequency transition process is shortened, and the system frequency transient response is improved.

VSG1 operates alone with 10kw load, VSG2 operates without load, and VSG1 and VSG2 operate in parallel for 0.5s. The active power variation curves are shown in Fig 7.

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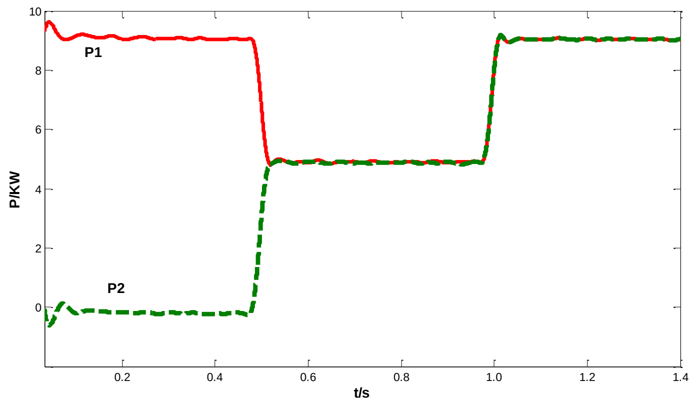


Fig 7: VSG parallel system active power variation curve

In the dynamic process of integrating VSG into microgrids, it is expected that *J* and *D* take reasonable values to avoid active power oscillation. It can be seen that after the parameter self-adjusting optimization control is adopted, the real-time changing *J* and *D* not only suppress the active power oscillation when VSG1 is incorporated into the AC bus, but also increase the frequency inertia by using a reasonable large value when the load changes suddenly, and *D* ensures the active frequency droop characteristic of the inverter output by using a reasonable small value.

## VI. CONCLUSION

In view of the fact that the VSG control parameters *J* and *D* in an independent microgrids with multi-VSGs cannot be adjusted adaptively and dynamically, a small signal model for the dual VSG parallel system was established, and the influence of the system stability control when *J* and *D* changed was analyzed, and then proposed a VSG control strategy with adaptive parameters to enhance the system frequency and power stability, Finally, through simulation verification and comparative analysis, the output active power and frequency response characteristics of the system under sudden load conditions were verified and analyzed. The adoption of adaptive adjustment of inertia and damping parameters was conducive to enhance the frequency and power stability of the system. In addition, the stable control effect of virtual synchronous generator can be brought into full play by flexibly switching the adaptive parameters adjustment mode.

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