Small Signal Stability Analysis of Micro-source Inverter System in Grid-connected Series Micro-grid

WANG Xinggui¹,², ZHANG Jianhua¹, ZHANG Jinjing¹ and YANG Weiman¹,²

¹College of Electrical Engineering and Information Engineering, Lanzhou University of Technology, Lanzhou, 730050, China
²Key Laboratory of Gansu Advanced Control for Industrial Processes, Lanzhou University of Technology, Lanzhou 730050, China
Wangxg8201@163.com, 363964601@qq.com, jinjingzh@nwnu.edu.cn, ggdywm@126.com

Abstract. In order to accurately analyze the small signal stability of micro-source inverter system in grid-connected series micro-grid, the paper establishes a small signal model of grid-connected series micro-grid system, including the series connection model, power controller model, phase locked loop model, power and current controller model, load and network model. Based on the model, the step response of the state variable of the system is calculated when the active load is increased, and the feasibility of the model is validated by MATLAB/Simulink software. Meanwhile, we can calculate the initial value of the system and the eigenvalues of the coefficient matrix of the equivalent resistance change, we further analyzes the small signal stability of micro-source inverter system in grid-connected series micro-grid. At the same time, the correctness of the theory is verified by simulation.

1. Introduction
At present, the structure of ordinary micro-grid structure mainly includes three kinds: DC structure, AC structure and AC-DC hybrid structure, and there are some problems which are difficult to solve in the systems with different structures. Micro-source inverter system in series micro-grids [1] (SMPGs) can solve the problems of harmonics and circulation in the ordinary micro-grid.

Small signal stability is the primary condition for the safe and stable operation of micro-grids. In recent years, the small-signal stability of the microgrid mainly uses the eigenvalue analysis method [2-5] to analyze the stability of the model of the system. COELHO E A has analyzed the small signal stability of micro-grid based on droop control in [6-10]. Wang li has analyzed the small signal stability of grid-connected micro-grids with multiple micro-sources in [11-13]. Yang weiman has studied the dynamic modeling of series micro-grid inverter system in isolated island mode in [14], but not perform systematic and complete modeling of the series micro-grids. Nowadays, there are few studies on the stability of series micro-grids system.

This paper presents a complete small signal modeling for SMPGs, mainly including series micro-inverter control system small signal model and network small signal model. We can use the modeled structure to calculate the eigenvalues of the coefficient matrix, and analyze the influence of changes in line parameters on the small signal stability of the system. Meanwhile, MATLAB/Simulink software was used to simulate the waveforms of the output power and voltage of the system when the line parameters were changed to verify the correctness of the theoretical derivation.
2. Micro-source Inverter System Structure in Series Micro-grid
The structure of SMPGs is studied in this paper is shown in Fig.1. The system is mainly composed of micro-source, series H-bridge micro-source inverter, load and network. The series H-bridge micro-source inverter uses the current inner loop and power outer loop to improve the dynamic response speed.

![Figure 1. Structure diagram of three phase series micro-grid system.](image)

In Fig. 1, idi is the micro-source output current; udci (i=1, 2, 3, ..., n) is the DC-side voltage of each micro-source inverter; uoi (i = a, b, c) is the AC-side voltage of the series micro-grid system of SMPGs; uci (i=a, b, c) is the voltage across the output filter capacitor; iLi and ioi are respectively the filter inductor current and load current; Lf and Cf are respectively the filter inductance and capacitance; re is the sum of the equivalent resistances of inverter unit, series lines, and filter inductors; Z is the equivalent load; isi is the line current; Rg is the line resistance, Lg is the line inductance, and usi is the grid voltage.

3. Small Signal Model of Micro-source Inverter System in Grid-connected Series Micro-grid

3.1 Series micro-grid control system
The PCC point left part of the series micro-grid control system is shown in Fig.2.

![Figure 2. Series micro-grid control system.](image)

3.2 Small signal model of series inverter
Small signal model of series inverter is.\[^1\]
\[
\begin{align*}
\frac{d\hat{u}_{dc}}{dt} &= \frac{1}{C} \left[ \hat{i}_{sd} - (D_{lab}\hat{i}_L + \hat{d}_{lab}I_L) \right] \\
\frac{d\hat{i}_L}{dt} &= \frac{1}{L_f} \sum_{i=1}^{n} \left( \hat{d}_{lab}U_{dc} + D_{lab}\hat{u}_{dc} \right) - r_c \hat{i}_L - \hat{u}_c \\
\frac{d\hat{u}_c}{dt} &= \frac{1}{C} \left( \hat{i}_c - \frac{\hat{u}_c}{Z} \right)
\end{align*}
\]

(1)

Where: \(\text{diab}\) is the equivalent duty cycle; \(U_{dc1}, I_L, U_c\) and \(\text{Diab}\) are the steady-state workload of the parameter; \(\hat{u}_{dc1}, \hat{i}_L, \hat{i}_c\) and \(\hat{d}_{lab}\) are the disturbance quantity of the corresponding parameter, and satisfies \(|\hat{u}_{dc1}|=U_{dc1}, |\hat{i}_L|=I_L, |\hat{i}_c|=U_c, |\hat{d}_{lab}|=\text{Diab}\).

The dq transformation of the formula (1) are

\[
\begin{align*}
\frac{d\hat{u}_{dc1}}{dt} &= \hat{i}_{sd1} - (D_{lab}\hat{i}_L + \hat{d}_{lab}I_L) + C\omega \hat{u}_{dc1} \\
\frac{d\hat{i}_{L1}}{dt} &= \hat{i}_{qL1} + \sum_{i=1}^{n} \left( \hat{d}_{lab}U_{dc1} + D_{lab}\hat{u}_{dc1} \right) - \hat{u}_{cd1} \\
\frac{d\hat{u}_{cd1}}{dt} &= \hat{i}_{qcd1} - \frac{1}{Z} \hat{u}_{cd1} + C\omega \hat{u}_{qcd1}
\end{align*}
\]

(2)

\[
\begin{align*}
\frac{d\hat{u}_{dc2}}{dt} &= \hat{i}_{sd2} - (D_{lab}\hat{i}_L + \hat{d}_{lab}I_L) + C\omega \hat{u}_{dc2} \\
\frac{d\hat{i}_{L2}}{dt} &= \hat{i}_{qL2} + \sum_{i=1}^{n} \left( \hat{d}_{lab}U_{dc2} + D_{lab}\hat{u}_{dc2} \right) - \hat{u}_{cd2} \\
\frac{d\hat{u}_{cd2}}{dt} &= \hat{i}_{qcd2} - \frac{1}{Z} \hat{u}_{cd2} + C\omega \hat{u}_{qcd2}
\end{align*}
\]

(3)

The matrix forms are

\[
\begin{align*}
\begin{bmatrix}
\Delta\hat{u}_{dc1}
\end{bmatrix} &= A_{se1} \begin{bmatrix}
\Delta u_{dc1}
\end{bmatrix} + B_{se1} \begin{bmatrix}
\Delta i_{dc1}
\end{bmatrix} + [\Delta L_{dc1}] \\
\begin{bmatrix}
\Delta\hat{u}_{dc2}
\end{bmatrix} &= A_{se2} \begin{bmatrix}
\Delta u_{dc2}
\end{bmatrix} + B_{se2} \begin{bmatrix}
\Delta i_{dc2}
\end{bmatrix} + [\Delta L_{dc2}]
\end{align*}
\]

(5)

\[
\begin{align*}
\begin{bmatrix}
\Delta i_{Ldc1}
\end{bmatrix} &= A_{se1} \begin{bmatrix}
\Delta u_{dc1}
\end{bmatrix} + C_{se} \begin{bmatrix}
\Delta i_{dc1}
\end{bmatrix} + [\Delta L_{dc1}] + [\Delta U_{dc1}]
\end{align*}
\]

(6)

In the formula, \(\Delta u_{dc1}, \Delta i_{Ldc1}\) and \(\Delta u_{dc2}\) are all vectors, such as \(\Delta u_{dc1}=[\Delta u_{dc1} \Delta u_{dc2}]^T\), and the other expressions in this paper are similar.

The coefficient matrices are

\[
A_{se1} = \begin{bmatrix}
\frac{1}{L_f} \sum_{i=1}^{n} D_{lab} & 0 \\
0 & \frac{1}{L_f} \sum_{i=1}^{n} D_{lab}
\end{bmatrix},
C_{se} = \begin{bmatrix}
0 & 0 & \frac{1}{L_f} \sum_{i=1}^{n} U_{dc1} & 0 \\
0 & 0 & 0 & \frac{1}{L_f} \sum_{i=1}^{n} U_{dc1}
\end{bmatrix}
\]

(7)
3.3 Power controller small signal model

The power controller mainly realizes the power calculation, instantaneous active power and reactive power components are calculated by the measured output voltage and output current.

\[ p = u_{cd}i_{od} + u_{cq}i_{aq}, q = u_{cd}i_{aq} - u_{cq}i_{od} \]  (8)

In order to reduce the influence of harmonics, the instantaneous active power \( p \) and reactive power \( q \) are obtained by the power controllers as active power \( P \) and reactive power \( Q \). \( \omega_c \) represents the cutoff frequency of the power controller.

\[ P = \frac{\omega_c}{s + \omega_c} p, Q = \frac{\omega_c}{s + \omega_c} q \]  (9)

Simultaneous the formula(8) ~ (9) and linearization, we can get the power controller's small signal state space model:

\[
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix} =
A_p \begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix} + B_p \begin{bmatrix}
\Delta I_{Ldq} \\
\Delta u_{cdy}
\end{bmatrix} + B_{pas} \begin{bmatrix}
\Delta I_{cdy}
\end{bmatrix} \tag{10}
\]

Where

\[
A_p = \begin{bmatrix}
-\omega_c & 0 \\
0 & -\omega_c
\end{bmatrix}, B_p = \begin{bmatrix}
0 & 0 & \omega_c I_{od} & \omega_c I_{aq} \\
0 & 0 & \omega_c I_{aq} & -\omega_c I_{od}
\end{bmatrix}, B_{pas} = \begin{bmatrix}
\omega_c U_{cd} & \omega_c U_{cq} \\
-\omega_c U_{aq} & \omega_c U_{cd}
\end{bmatrix} \tag{11}
\]

3.4 Phase locked loop(PLL) small signal model

The series inverter obtains the frequency reference value through PLL technology, and the PLL linearization model is [13]:

\[ \omega = k \left( k_p + \frac{k_s}{s} \right) (\theta_{ref} - \theta) \]  (12)
\[ \Delta \theta = k_d \Delta u_{cd} + k_q \Delta u_{cq} \quad (13) \]
\[ \Delta \omega = \Delta \dot{\theta} = k_d \Delta i_{cd} + k_q \Delta i_{cq} \quad (14) \]

Where
\[ k_d = -\frac{u_{cq}}{u_{cd}^2 + u_{cq}^2}, \quad k_q = \frac{u_{cd}}{u_{cd}^2 + u_{cq}^2} \quad (15) \]

Linearize the formula (12) into the formula (14)
\[ [\Delta \dot{\omega}] = A_{pL} [\Delta \omega] + B_{pL} \begin{bmatrix} \Delta i_{ld} \\ \Delta u_{cd} \end{bmatrix} \]
\[ A_{pL} = -kk_p, \quad B_{pL} = \begin{bmatrix} 0 & -kk k_d & -kk k_q \end{bmatrix} \quad (16) \]

3.5 Power outer loop and current inner loop model

The series inverter use the power outer loop and the current inner loop control method in this paper, all adopt PI control, \( K_{up} \) is the proportional coefficient, and \( K_{ui} \) is the integral coefficient. The power outer loop and current inner loop control block diagram are shown in Fig.4.

![Figure 4. Block diagram of power outer loop and current inner loop.](image)

The mathematical expression of the current inner loop control link is:
\[ \begin{align*}
    u_{dref} & = -\omega L_j i_{Lq} + k_{uq2} (i_{Lqref} - i_{Lq}) + u_{cd} + k_{u2} (i_{Lqref} - i_{Lq}) / s \\
    u_{qref} & = \omega L_j i_{Ld} + k_{up2} (i_{Lqref} - i_{Lq}) + u_{cq} + k_{u2} (i_{Lqref} - i_{Lq}) / s 
\end{align*} \quad (17) \]

The mathematical expression of the power outer loop control link is:
\[ \begin{align*}
    i_{Ldref} & = k_{up1} (P_{ref} - P) + k_{u1} (P_{ref} - P) / s \\
    i_{Lqref} & = k_{up1} (Q_{ref} - Q) + k_{u1} (Q_{ref} - Q) / s 
\end{align*} \quad (18) \]

In order to simplify the analysis of the current inner loop, new state variables \( u_d \) and \( u_q \) are introduced to satisfy:
\[ \frac{du_d}{dt} = i_{Ldref} - i_{Ld}, \quad \frac{du_q}{dt} = i_{Lqref} - i_{Lq} \quad (19) \]

Similarly, in order to simplify the analysis of the power outer loop, new state variables \( i_d \) and \( i_q \) are introduced to satisfy:
\[ \frac{di_d}{dt} = P_{ref} - P, \quad \frac{di_q}{dt} = Q_{ref} - Q \quad (20) \]
By linearizing formula (18), (19), and (20), the small signal model of the power outer loop is
\[
\begin{bmatrix}
\Delta i_{dq} \\
\Delta u_{dq}
\end{bmatrix}
= A_{p1}
\begin{bmatrix}
\Delta i_{dq} \\
\Delta u_{dq}
\end{bmatrix}
+ A_{p2}
\begin{bmatrix}
\Delta P_{ref} \\
\Delta Q_{ref}
\end{bmatrix}
+ A_{p3}
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix}
+ A_{p4}
\begin{bmatrix}
\Delta i_{Ldq} \\
\Delta u_{edq}
\end{bmatrix}
\]  
(21)

In (21)
\[
A_{p1} =
\begin{bmatrix}
0 & 0 & 0 & k_{u1} & 0 & 0 & 0 \\
0 & 0 & 0 & k_{u1} & 0 & 0 & 0 \\
0 & k_{u1} & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0
\end{bmatrix}
A_{p2} =
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
A_{p3} =
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
A_{p4} =
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]  
(22)

Formula (17) is brought into formula (18) for linearization. The small signal model of the current inner loop is
\[
\begin{bmatrix}
\Delta u_{edqref}
\end{bmatrix}
= A_{i1}
\begin{bmatrix}
\Delta i_{dq}
\end{bmatrix}
+ A_{i2}
\begin{bmatrix}
\Delta P_{ref} \\
\Delta Q_{ref}
\end{bmatrix} + A_{i3}
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix}
+ A_{i4}
\begin{bmatrix}
\Delta i_{Ldq} \\
\Delta u_{edq}
\end{bmatrix}
+ A_{i5}
\Delta \omega
\]  
(23)

The coefficient matrices are
\[
A_{i1} =
\begin{bmatrix}
k_{up2} & k_{up1} & 0 & 0 & 0 & 0 & 0 \\
0 & k_{up2} & k_{up1} & 0 & 0 & 0 & 0 \\
0 & 0 & k_{up2} & k_{up1} & 0 & 0 & 0
\end{bmatrix}
A_{i2} =
\begin{bmatrix}
k_{up2} & k_{up1} & 0 & 0 & 0 & 0 & 0 \\
0 & k_{up2} & k_{up1} & 0 & 0 & 0 & 0 \\
0 & 0 & k_{up2} & k_{up1} & 0 & 0 & 0
\end{bmatrix}
A_{i3} =
\begin{bmatrix}
-k_{up2} & -k_{up1} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -k_{up2} & -k_{up1} & 0 & 0 & 0
\end{bmatrix}
A_{i4} =
\begin{bmatrix}
-k_{up2} & -k_{up1} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -k_{up2} & -k_{up1} & 0 & 0 & 0
\end{bmatrix}
A_{i5} =
\begin{bmatrix}
-L_f & L_f \\
L_f & -L_f
\end{bmatrix}
\]  
(24)

3.6 Load and network small signal model
This paper uses a non-dynamic equivalent impedance model. According to the structure of SMPGs shown in Fig.1, the load current \(i_o\) and network model satisfies the following algebraic differential equations.
\[
\begin{align*}
L_s \frac{d i_{sd}}{dt} &= u_{sd} - r_{i} i_{sd} + \omega L i_{sq} - u_{sd} \\
L_s \frac{d i_{sd}}{dt} &= u_{sq} - r_{i} i_{sq} - \omega L i_{sd} - u_{p}\n
L_g \frac{d i_{sd}}{dt} &= -R i_{sd} + \omega i_{sq} + u_{pd} - u_{sd} \\
L_g \frac{d i_{sd}}{dt} &= -R i_{sq} - \omega i_{sd} + u_{pq} - u_{sq}
\end{align*}
\]  
(25)

In formula (25), \(u_b\) is the PCC point voltage; \(r_1\) and \(L_1\) are respectively the resistive and inductive components in the equivalent impedance model. Linearize the formula (25) to get
\[
\begin{bmatrix}
\Delta i_{sdq}
\end{bmatrix}
= A_{load}
\begin{bmatrix}
\Delta i_{sdq}
\end{bmatrix}
+ B_{load1}
\begin{bmatrix}
\Delta i_{Ldq} \\
\Delta u_{edq}
\end{bmatrix}
+ B_{load2}
\Delta u_{bdq} + B_{load3}\Delta \omega
\]  
(27)

Linearize the formula (26) to get
\[
\begin{bmatrix}
\Delta i_{sdq}
\end{bmatrix}
= A_{NET}
\begin{bmatrix}
\Delta i_{sdq}
\end{bmatrix}
+ B_{NET1}
\begin{bmatrix}
\Delta u_{bdq}
\end{bmatrix}
+ B_{NET2}
\Delta u_{sdq} + B_{NET3}\Delta \omega
\]  
(28)

Where
3.7 Small signal model of micro-source inverter system in grid-connected series micro-grid

A small signal model of SMPGs can be obtained by combining the models of series inverter, power controller, PLL, power outer loop, current inner loop and load, given by (5), (6), (10), (16), (21), (23) and (27):

\[
A_{load} = \begin{bmatrix}
-\frac{r_l}{L_1} & \omega_i \\
-\omega_i & -\frac{r_l}{L_1}
\end{bmatrix}, \quad B_{load1} = \begin{bmatrix}
0 & \frac{1}{L_1} \\
0 & 0
\end{bmatrix}, \quad B_{load2} = \begin{bmatrix}
-\frac{1}{L_4} & 0 \\
0 & -\frac{1}{L_4}
\end{bmatrix}, \quad B_{load3} = \begin{bmatrix}
I_{eq} \\
-I_{od}
\end{bmatrix},
\]

\[
A_{NET} = \begin{bmatrix}
-\frac{R_g}{L_g} & \omega_i \\
-\omega_i & -\frac{R_g}{L_g}
\end{bmatrix}, \quad B_{NET1} = \begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}, \quad B_{NET2} = \begin{bmatrix}
-\frac{1}{L_g} & 0 \\
0 & -\frac{1}{L_g}
\end{bmatrix}, \quad B_{NET3} = \begin{bmatrix}
I_{sq} \\
-I_{sd}
\end{bmatrix}
\]

(29)

In order to form a complete small signal model of SMPGs, the series inverter link and the small signal model of the network are combined with \( u_b \).

In order to better determine the intermediate variable \( u_b \), we can suppose that there is a virtual resistance \( r_n \) between the SMPGs and the ground. In order to reduce its impact on the dynamic stability of the system generally choose a relatively large \( r_n \) value, this paper takes \( r_n = 1000\Omega \). Therefore, the node voltage is expressed as
The linearization of the formula (33) can be obtained
\[
\Delta u_{bd} = R_N M_{inv} \Delta i_{sdq} \]
\[
\Delta u_{bq} = R_N M_{load} \Delta i_{sdq} \]
\[
(34)
\]
where
\[
R_N = \begin{bmatrix} r_n & 0 \\ 0 & r_n \end{bmatrix}, \quad M_{inv} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad M_{load} = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}
\]
\[
(35)
\]
Now, the complete small signal model of micro-source inverter system in grid-connected series micro-grid can be obtained by using individual subsystem models given by (28), (30), and (34).
\[
\begin{bmatrix} \Delta x_{inv} \\ \Delta i_{sdq} \end{bmatrix} = A_{inv} \begin{bmatrix} \Delta x_{inv} \\ \Delta i_{sdq} \end{bmatrix} + \begin{bmatrix} C_{inv} \Delta P_{ref} \\ B_{NET2} \Delta u_{sdq} \end{bmatrix}
\]
\[
(36)
\]
where
\[
A_{inv} = \begin{bmatrix} A_{inv} + B_{inv} R_N M_{inv} D_{inv2} & B_{inv} R_N M_{load} \\ B_{NET2} D_{inv1} & A_{NET} + B_{NET1} R_N M_{load} \end{bmatrix}
\]
\[
(37)
\]
4. Calculation and Simulation
4.1 Step response analysis of small signal model of SMPGs
Using MATLAB/Simulink software to build a micro-grid grid-connected system model with four micro-source, Table 1 and Table 2 are respectively the initial steady-state operating parameters and initial system control parameters.

Table 1. Steady-state operation parameters of the microgrid system

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| U_{dcid}  | 100V  | U_{dcid}  | 100V  |
| U_{id}    | 380V  | U_{eq}    | 0V    |
| I_{sd}    | 19A   | I_{eq}    | 0.6A  |
| I_{ld}    | 20A   | I_{eq}    | -5.5A |
| u_{sd}    | 311V  | u_{eq}    | 0V    |

Table 2. Control parameters of the system

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| L_f       | 3mH   | C         | 2500 uF |
| C_f       | 60uF  | r_1       | 2Ω    |
| L_1       | 6mH   | D_{ab}    | 0.85  |
| r_e       | 0.3Ω  | Z         | 20Ω   |
| \omega_c | 31.4Hz| \omega_s | 181   |
| K_{up1}   | 0.5   | K_{up1}   | 20    |
| K_{up2}   | 0.6   | K_{up2}   | 25    |
| K         | 15    | K_{p,K_f} | 10.5  |
| R_g       | 30Ω   | L_g       | 5mH   |

The time domain response waveform of the system when the active load is increased by 200W can be obtained through simulation. At the same time, calculate the step current \( \Delta i_L \) corresponding to 200W of active load. According to the small signal model of SMPGs of equation (37), and the related
parameters of Table 1 and Table 2, the time-domain response waveforms of \( u_{cd} \) and \( i_{Ld} \) are obtained, as shown in Fig. 5.

![Figure 5. System response when the active load changes](image)

(a) Filter capacitor voltage \( u_{c} \) response  (b) Filter inductor current \( i_{L} \) response

In Fig. 5, the solid line represents the simulation result, and the dashed line represents the result of the small signal model structure. From Fig. 5, it can be concluded that the MATLAB model simulation result and the small signal model obtained by the state-variable response waveform change are basically the same when the active load changes are the same. The simulation result and small signal model result prove the correctness of the established small signal model of SMPGs.

4.2 Eigenvalue analysis

(1) In Table 1 and Table 2, all the eigenvalues of the steady-state operation of the small-signal model of SMPGs are calculated according to formula (37). Fig. 6 shows the distribution of eigenvalues under the initial conditions of the system. It can be seen from the figure that all the real parts of the eigenvalues are on the left side of the imaginary axis, indicating that the four micro-source micro-grid system is small signal stable in the initial state.

![Figure 6. Distribution of initial state eigenvalue of micro-grid.](image)

The output active and reactive simulation waveform of SMPGs are

![Figure 7. Initial state system response](image)

(a) System active output  (b) System reactive output

Fig. 7, it can be seen that the curve shows a steady trend with no distortion, indicating that the system is small signal stable under initial conditions.

Effect of Equivalent Resistance Change on System Stability

(2) Keeping other parameters of Table 1 and Table 2 unchanged, when the equivalent resistance reduces from 0.3Ω to 0.2Ω, the eigenvalue change trajectory closest to the imaginary axis is shown in Fig. 8, and the output power waveform is shown in Fig. 9. It can be seen from Figure 8 that when the
equivalent resistance decreases, the eigenvalues will approach the imaginary axis. Therefore, the reduction of the line parameters will reduce the stability of SMPGs.

It can be seen from Fig. 9 that when the line parameters are changed, the system active output fluctuates within 0.05s-0.2s, remains stable after 0.2s, and the curve shows a steady trend. The simulation results and small signal stability analysis are basically consistent. Changes in the equivalent resistance will cause the system to oscillate. The power outer loop and current inner loop will be adjusted back in time. However, when the oscillation is large enough, it may affect the stability of SMPGs, which may affect the stable operation of the system.

![Figure 8](image1.png)

Figure 8. Trace the eigenvalue of the equivalent resistance decreases.

(a) System active output (b) System reactive output

Figure 9. System response when line parameters change

5 Conclusion
In this paper, a complete small signal model of SMPGs is established. The model is used to calculate the state-variable step response of the system when the active load is increased by 200W, and the MATLAB/Simulink software is used to simulate and verify the state-variable response waveforms when the system step change is the same. This proves the correctness of the small signal model of microsource inverter system in grid-connected series micro-grid. By calculating the eigenvalues of the coefficient matrix of the constructed model, it is found that the line parameter changes will degrade the small signal stability of the system. At the same time, the output power waveforms are simulated when the line parameters are changed, and the correctness of the eigenvalue analysis is verified.

Acknowledgement
This work is supported by National Natural Science Foundation of China (51467010).

References
[1] YANG Weiman and WANG Xinggui 2013 J. Power System Technology 37 2446-2451
[2] Wang Kewen and Shi Shuhong 2001 J. Automation of Electric Power System 25 20-23
[3] Zhang Jianfen 2004 D. Zhengzhou University
[4] Hao Sipeng and Tang Maolin 2009 J. Automation of Electric Power Systems 33 1-5
[5] Shi Shanshan and Lu Zongxiang 2011 J. Automation of Electric Power Systems 35 36-41
[6] Nagaraju Pogaku 2007 J. IEEE TRANSACTIONS ON POWER ELECTRONICS 33 613-625
[7] XIAO Zhaoxia and WANG Chengshan 2009 J. Automation of Electric Power Systems 33 81-85
[8] Xiao Zhaoxia 2008 D. Tianjin University
[9] ANTONIO E, COELHO A and CORTIZO P C 2000 C. Proceedings of 35th IAS Annual Meeting
and World Conference on Industrial Applications of Electrical Energy 2345-2352

[10] COELHO E A and CORTIZO P C 2002 J.IEEE Trans on Industry Applications 38 533-642
[11] WANG Li and LIN Ying-hao 2000 J.IEEE Conference Publications 40 476-480
[12] Zhang Jianhua, Su Ling and Liu Ruoxi 2010 J.Automation of Electric Power Systems 34 97-102
[13] Zhang Jianhua, Su Ling and Liu Ruoxi 2011 J.Automation of Electric Power Systems 35 76-80
[14] WANG Xinggui and YANG Weiman 2014 J.High Voltage Technology 40 2456-2463