TELKOMNIKA, Vol. 11, No. 9, September 2013, pp. 5461~5470
ISSN: 2302-4046

Equivalent Simplification Method of Micro-Grid

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Abstract

The paper concentrates on the equivalent simplification method for the micro-grid system connection into distributed network. The equivalent simplification method proposed for interaction study between micro-grid and distributed network. Micro-grid network, composite load, gas turbine synchronous generation, wind generation are equivalent simplification and parallel connect into the point of common coupling. A micro-grid system is built and three phase and single phase grounded faults are performed for the test of the equivalent model of micro-grid. The simulation results show that the equivalent model of micro-grid is effective, and the dynamic of equivalent model is similar with the detailed model of micro-grid. The equivalent simplification method for the micro-grid network and distributed components is suitable for the study of micro-grid.

Keywords: *micro-grid, equivalent simplification, dynamic simulation, power system*

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1. Introduction

Distributed generation (DG) is a new form of energy with economic and environmental benefits. DG technology has matured enough to present capability of providing ancillary services with reduced investment costs so that it can be seriously considered as a robust solution for the electricity consumption growing needs. Micro-grid is a new electricity network paradigm, which consists of distributed generation, load and energy storage systems [1-6]. There are two operation mode can be envisaged in micro-grid, grid connected operation mode and stand-alone operation mode. In grid connected mode, most of the system-level dynamics are dictated by the main grid due to the relatively small size of distributed generations. And in stand-alone mode, the system dynamics are dictated by micro sources themselves and its power regulation control of the network itself. Micro-grid can transition from one mode to another smoothly.

One of the important concerns of micro-grid in grid connected operation is the dynamic equivalent modeling of micro-grid and components. With the raising of the number and capability of micro-grid, the interaction between micro-grid and distributed network should be considering in the operation of distributed network, which needs a suitable micro-grid model for digital simulation. Micro-grid equivalent model can meet the new problems [7-12]. In grid connected operation mode, micro-grid can be seen as a special controllable load or a controllable generator, which will absorb power form distributed network or output power injured to distributed network [13-17].

The distributed generation control strategy ensures the safe and stable operation of micro-grid in stand-alone operation mode. However, in grid connected operation mode, the voltage and frequency of micro-grid can be maintained by distributed network, and the interaction between micro-grid and distributed network become more important in power system analysis focus on the micro-grid equivalent dynamic characteristics, as well as the mechanism of interaction of the micro-grid and distribution networks. Based on the simplification model of micro-grid and equivalent model of distributed generation, the components of micro-grid is connected to the PCC in parallel, which provides a better method for the studying of the interaction of micro-grid and distributed network [18].

Received January 23, 2013; Revised June 16, 2013; Accepted June 25, 2013

Micro-grid contains various kinds of distributed generations. If the equivalent model of distributed generation is utilized, dynamic simulation of the micro-grid can simplified. The singular perturbations theory was applied to reduce the order of the model of the wind farm in [19], and the dynamics of reduced order model matches those of the detailed model under different operational conditions. Aggregate modeling and detailed modeling for the transient interaction studies between a large wind farm and a power system are discussed in [18], and the aggregate modeling can decrease the simulation time without significantly compromising the accuracy in different conditions.

The paper built a micro-grid consists of wind generation, photovoltaic, micro-turbine, and load, which can operation two modes based on the control of distributed generation. A simplification method is proposed for the equivalent simplification of micro-grid network and distributed components. The parameters of micro-grid network and distributed components are alternative and the equivalent model is obtained parallel in the PCC for the studying of interaction of micro-grid and distribution network. Simulations are performed to evaluate the effectiveness of equivalent simplification method of distributed components in micro-grid.

2. Network Simplification of Micro-grid

Micro-grid constituted by a large number of distributed components, lines and transformers, the Network Simplification can decouple the various distributed components which will connect to the PCC bus through the transformer. Network simplification can reduce the interaction of different distributed components in micro-grid. From Figure.1, it can be seen that the equivalent simplification of micro-grid network should meet the follow criterions:

(1) The bus voltages $\dot{U}_1$、 should remain constant.

(2) The power between micro-grid and distributed network should remain, and the total current remain constant $\dot{I}_\Sigma = \dot{I}_1 + \dot{I}_2 + ... + \dot{I}_m$.

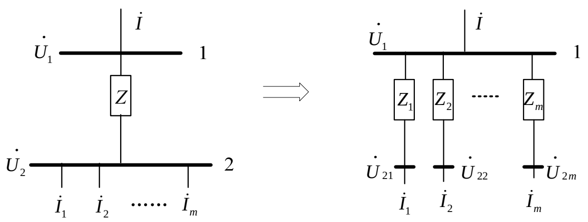

Figure 1. The Diagram of Network Simplification

Based on the above criterions, the current can be rewritten as:

$$(\dot{U}_1 - \dot{U}_2)\frac{1}{Z} = (\dot{U}_1 - \dot{U}_{21})\frac{1}{Z_1} + ... + (\dot{U}_1 - \dot{U}_{2m})\frac{1}{Z_m} \tag{1}$$

As $\dot{U}_2 = \dot{U}_{21} = ... = \dot{U}_{2m}$, the relationship of each branch impedance can be written as:

$$Z_i = \frac{(\dot{U}_1 - \dot{U}_{2i})}{\dot{I}_i} \tag{2}$$

It can been seen that power is the product of the current and the voltage.

$$\dot{I}_i = \left(\frac{\hat{S}_i}{\hat{U} - \hat{U}_L}\right) \tag{3}$$

So:

$$Z_i = \left(\frac{\sum_{i=1}^{m} \hat{S}_i}{\hat{S}_i} \right) Z = \frac{Z}{\rho_i} \quad (4)$$

Where, Z_i is the equivalent impedance of each branch, $\rho_i = \frac{\hat{S}_i}{\sum_{i=1}^{m} \hat{S}_i}$ presents the impedance ratio coefficient of each branch, $\hat{S}_i$ is the rated power of each branch.

3. Distributed Components Equivalent Simplification of Micro-grid

The equivalent principle is that the dynamic characteristics of equivalent model and detailed model should be stability. The distributed components parallel into PCC bus directly or through transformers after micro-grid network simplification. So, for the components parallel PCC through, the equivalent method is to simplify the transformers, conversion the components parameters from one sides of the transformers to another. For the components that parallel PCC directly, the equivalent method is to eliminate the line.

3.1. Composite Load Equivalent Simplification

3.1.1. Motor Equivalent Simplification

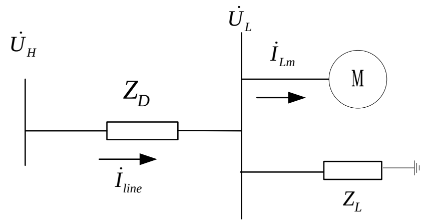

Figure 2. Composite Load Model

It can be seen from Figure 2 that practical load connect to power grid through transformers. Where, Subscript H is high voltage bus, $\dot{U}_H$ is the voltage of the high voltage bus, L is low voltage bus, $\dot{U}_L$ is the voltage of the low voltage bus. M is the equivalent motor in the low voltage bus, $\dot{I}_{Lm}$ is the current of the equivalent motor, the motor current. Z_L is the equivalent impedance of static load in low voltage bus, Z_D is the impedance of transformers and lines, $\dot{I}_{Line}$ is the current of line [21].

It can be seen from that the relationship between current and voltage is shown here:

$$\dot{U}_H = Z_D \dot{I}_{Line} + \dot{U}_L \quad (5)$$

$$\dot{I}_{Line} = \dot{I}_{Lm} + \frac{\dot{U}_L}{Z_L} \quad (6)$$

From (5) and (6), $\dot{I}_{Line}$ is eliminated, the voltage of low voltage bus can be presents as the function of the voltage of the high voltage bus, shown here:

$$\dot{U}_L = \frac{Z_L}{Z_D + Z_L} \dot{U}_H - \frac{Z_D Z_L}{Z_D + Z_L} \dot{I}_{Lm} \quad (7)$$

Using the voltage equation of low voltage bus, the transient equation of motor in low voltage bus can be transformed into high voltage bus as shown:

$$\dot{U}_H = \frac{Z_D + Z_L}{Z_L}\dot{E}_L' + \left[\frac{Z_D Z_L}{Z_D + Z_L} + r_s + jX'\right]\frac{Z_D + Z_L}{Z_L}\dot{I}_{Lm} \quad (8)$$

From Equation (8), it can be seen that the voltage is relation with the motor parameter and the current of the low voltage bus. The voltage of high voltage bus is:

$$\dot{U}_H = \dot{E}_H' + (r_{sH} + jX_H')\,\dot{I}_H \quad (9)$$

Comparing Equation (8) and Equation (9), it can be seen the relationship of equation motor parameters and state variables between each side of transformers. The parameters and state variables between low and high voltage bus can be written as:

$$\dot{E}_H' = \frac{Z_D + Z_L}{Z_L}\dot{E}_L' \quad (10)$$

$$\dot{I}_{Hm} = \frac{Z_D + Z_L}{Z_L}\dot{I}_{Lm} \quad (11)$$

$$\frac{Z_D\, Z_L}{Z_D + Z_L} = m_1 + jm_2,\ r_{sH} = r_s + m_1,\quad X_H' = X' + m_2 \quad (12)$$

Where $\dot{E}_H'$ is the transient voltage, X_H' is the transient reactance.

Using Equation (10), (11), (12) the transient voltage equation of equivalent motor in low voltage bus can be written as:

$$\frac{Z_L}{Z_D + Z_L}\frac{d\dot{E}_H'}{dt} = \frac{Z_L}{Z_D + Z_L}\left\{\frac{1}{T_0'}[-\dot{E}_H' + j(X_L - X_H' - m_2)\,\dot{I}_H] + js_L\omega_{sL}\dot{E}_H'\right\} \quad (13)$$

The transient voltage equation of high voltage bus is:

$$\frac{d\dot{E}_H'}{dt} = \frac{1}{T_{0H}'}[-\dot{E}_H' + j(X_H - X_H')\,\dot{I}_H] + js_H\omega_{sH}\dot{E}_H' \quad (14)$$

From Equation (13) and (14), we can get the follow conclusion that:

$$X_{sH} = X_s + m_2,\ r_{rH} = r_r,\ X_{rH} = X_r \quad (15)$$

and the torque can be written as:

$$T_{jH} = \left(\frac{Z_D + Z_L}{Z_L}\right)^2 T_{jL} \quad (16)$$

So the equivalent motor torque equation can be written as:

$$\frac{d\omega_{rH}}{dt} = \frac{1}{T_{jH}}(T_{EH} - T_{MH}) \quad (17)$$

As a result, the equivalent motor model in high voltage bus contains (9), (14) and (17). The parameters of equivalent motor in high voltage bus can be calculated based on the Equation (12), (15).

3.1.2. Static Load Equivalent Simplification

Form Equation (11), the voltage and current of Figure 2 can be written:

$$\frac{Z_D+Z_L}{Z_L}(\dot{I}_{Line}-\dot{I}_H)=(\frac{Z_L}{Z_D+Z_L}-\frac{Z_D+Z_L}{Z_L})\dot{I}_H+\frac{\dot{U}_H}{Z_L} \quad (18)$$

The Equation (18) is divided by $\frac{Z_D+Z_L}{Z_L}\dot{U}_H$, we can get the admittance equation:

$$Y_H=\frac{(\dot{I}_{Line}-\dot{I}_H)}{\dot{U}_H}=\frac{1}{Z_D+Z_L}-\frac{Z_D(Z_D+2Z_L)}{(Z_D+Z_L)^2}\frac{\dot{I}_H}{\dot{U}_H} \quad (19)$$

From Equation (19), admittance will change in the process of parameter transform. When if $Z_D >> Z_L$, the impedance of high voltage bus can be written $Z_{LH}=Z_D+Z_L$. it can be seen that the static load impedance can be written as the plus of line impedance and load impedance in low voltage bus.

3.2. Gas Turbine Equivalent Simplification

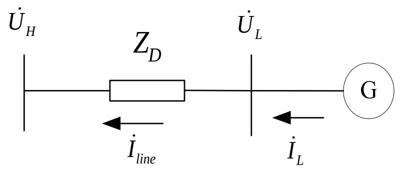

Figure 3. Gas Turbine Generator in Power System

The connection of the gas turbine synchronous generator in power system is shown in Figure 3. The voltage equation can be written as:

$$\dot{U}_L=\dot{U}_H+\dot{I}_{line}Z_D \quad (20)$$

Equation (20) can be split into dq components.

$$\begin{aligned} u_{dL}&=u_{dH}+i_{dline}R_D-i_{qline}X_D \\ u_{qL}&=u_{qH}+i_{qline}R_D+i_{dline}X_D \end{aligned} \quad (21)$$

Where $Z_D=R_D+jX_D$, $\dot{I}_{line}=i_{dline}+ji_{qline}$, $\dot{U}_H=u_{dH}+ju_{qH}$, $\dot{U}_L=u_{dL}+ju_{qL}$

The current in high voltage bus is equal to the current in the low voltage bus, the voltage of gas turbine generator can be rewritten as:

$$\begin{aligned} u_{dH}&=E''_d-(r_s+R_D)i_d+(X''_q+X_D)i_q \\ u_{qH}&=E''_q-(r_s+R_D)i_q-(X''_d+X_D)i_d \end{aligned} \quad (22)$$

Define:

$$r_{sH}=r_s+R_D,\ X''_{dH}=X''_d+X_D,\ X''_{qH}=X''_q+X_D,\ E''_{dH}=E''_d,\ E''_{qH}=E''_q \quad (23)$$

Equation (22) can be rewritten as:

$$\begin{aligned} u_{dH}&=E''_{dH}-r_{sH}i_{dH}+X''_{qH}i_{qH} \\ u_{qH}&=E''_{qH}-r_{sH}i_{qH}-X''_{dH}i_{dH} \end{aligned} \quad (24)$$

Define:

$$X_{dH} = X_d + X_D,\ \ X'_{dH} = X'_d + X_D,\ \ X_{lsH} = X_{ls} + X_D,\ \ X_{qH} = X_q + X_D,\ \ X'_{qH} = X'_q + X_D \tag{25}$$

We will get the gas turbine model equation in high voltage bus.

$$\begin{cases} T'_{qH0}\dfrac{dE'_{dH}}{dt} = -E'_{dH} - \dfrac{X_{qH} - X'_{qH}}{X'_{qH} - X''_{qH}}(E'_{dH} - E''_{dH}) \\ T''_{qH0}\dfrac{dE''_{dH}}{dt} = E'_{dH} - E''_{dH} + (X'_{qH} - X''_{qH})i_{qH} + \dfrac{X''_{qH} - X_{lsH}}{X'_{qH} - X_{lsH}}T''_{qH0}\dfrac{dE'_{dH}}{dt} \\ T'_{qH0}\dfrac{dE'_{dH}}{dt} = -E'_{dH} - \dfrac{X_{qH} - X'_{qH}}{X'_{qH} - X''_{qH}}(E'_{dH} - E''_{dH}) \\ T''_{qH0}\dfrac{dE''_{dH}}{dt} = E'_{dH} - E''_{dH} + (X'_{qH} - X''_{qH})i_{qH} + \dfrac{X''_{qH} - X_{lsH}}{X'_{qH} - X_{lsH}}T''_{qH0}\dfrac{dE'_{dH}}{dt} \end{cases} \tag{26}$$

Based on Equation (25), the parameters of gas turbine can be calculated form low voltage bus to high voltage bus.

3.3. Wind Turbine Equivalent Simplification

Wind turbine generator is asynchronous generator, and the model equations are similar with the asynchronous motor. So the equivalent simplification of wind turbine is similar with the motor shown above.

3.4. Photovoltaic Equivalent Simplification

Photovoltaic is an important distributed generation connected into micro-grid through inverter. The dynamic of photovoltaic is determined by the control strategy of inverter in the micro-grid operation. The control strategy of distributed generation is different in both of the micro-grid operation mode. Photovoltaic inverter is PQ control strategy when micro-grid grid connected operation. So the photovoltaic will give a constant power when micro-grid grid connected operation, which can be seen as a static power. The dynamic of photovoltaic can be described by a static power which can be combined with the static load.

4. Simulation Analysis

4.1. Micro-grid System

A three phase micro-grid is built to test the proposed method in this paper. The micro-grid consists of three types of distributed generation (wind generation, photovoltaic, gas turbine), two load (equivalent motor and static load), which is shown in Figure 4. The distributed generation and load connects each other through lines and transformers, and the micro-grid connects to the distributed network through PCC. In the micro-grid, the rated power of gas turbine is 8MW, and wind generation is 1MW, so they connect to micro-grid without through inverter, but the photovoltaic connect into the micro-grid through inverter.

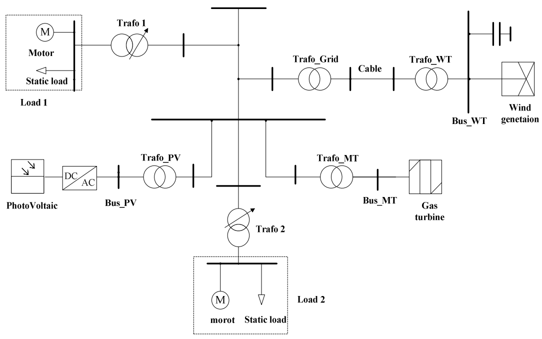

Figure 4. Micro-grid System

4.2. Micro-grid Equivalent Simplification

4.2.1. Network Simplification

With the method proposed above, the micro-grid network is simplified as shown in Figure 5. It can be seen that the distributed components (Load 1, Load 2, wind generation, Photovoltaic, Gas turbine synchronous generator) parallel in the PCC after network simplification. The line impedance is calculated by the Equation (4).

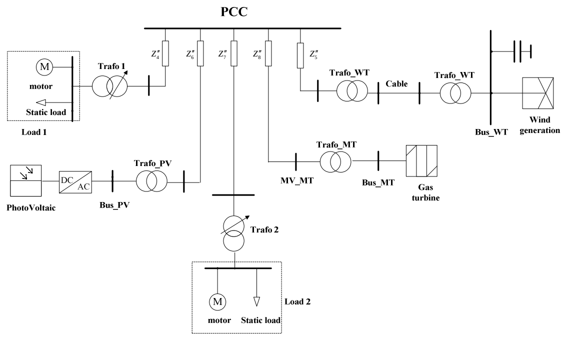

Figure 5. Micro-grid Network Equivalent Model

4.2.2. Distributed Components Equivalent Simplification

According to the methods for the simplification of composite load (motor load and static load), photovoltaic system, Gas turbine synchronous generator and wind generation system. From Figure 6, it can be seen that the distributed components is parallel in the PCC without the line impedance which is eliminated by the equivalent of distributed components.

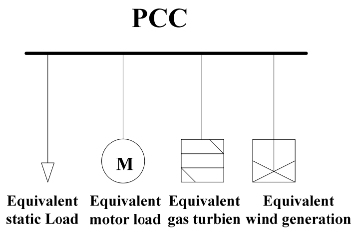

Figure 6. Micro-grid Equivalent Model

Table 1 gives the parameters equivalence of composite load, Table 2 gives the parameters equivalence of gas turbine synchronous generator, Table 3 gives the parameters equivalence of wind generation.

Table 1 Parameters of Composite Load

Parameters	/ p.u	X_s / pu	X_μ / pu	/ pu	X_r / pu	T_j /s
Load1	0.0005	0.025	2.390	0.202	0.0347	0.6279
Load2	0.0013	0.0334	2.390	0.202	0.0347	0.6343
Equivalent Load	0.0007	0.0265	2.390	0.202	0.0347	0.6297

Table 2. Parameters of Gas Turbine Synchronous Generator

Parameters	/pu	X_d /pu	X_q /pu	X'_d /pu	X''_d /pu	X'_q /pu	X''_q /pu	T'_{d0} /s	T'_{q0} /s	T''_{d0} /s	T''_{q0} /s
Before Equivalent	0	1.5	1.5	0.256	0.07	0.3	0.07	0.017	0	0.013	0.0057
After Equivalent	0.0038	1.561	1.561	0.317	0.131	0.361	0.131	0.017	0	0.013	0.0057

Table 3. Parameters of Wind Generation

Parameters	/ pu	X_s / pu	X_μ / pu	/ pu	X_r / pu	T_j / s
Before Equivalent	0.0100	0.1000	0.1000	3.000	0.0100	1.188
After Equivalent	0.0224	0.1202	0.1000	3.000	0.0100	1.181

4.3. Simulation Analysis

The distributed components parallel in the PCC bus, which will connect to the distribution network. Simulations are performed between the detailed model and equivalent model of micro-grid to verify the micro-grid equivalent model and the simplification method. Micro-grid is connected to the distributed network through a 110K/20K transformer, all the simulations performers under grid connected operation of micro-grid.

A three phases and single phase grounded fault in distributed network are performed to test the equivalent model of micro-grid. The three phase grounded fault last 0.06 seconds, and the single phase grounded fault last 0.14 seconds, respectively. The exchange power between micro-grid and distributed network is chosen for reflecting the difference of the detailed model and equivalent model of micro-grid.

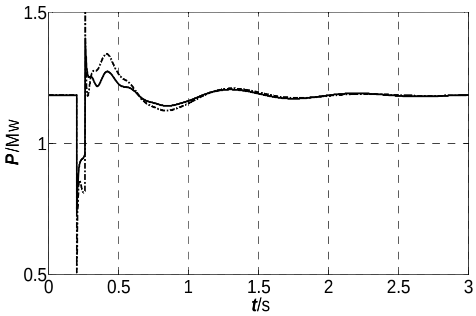

Figure 7. The Active Power of Single Phase Grounded Fault

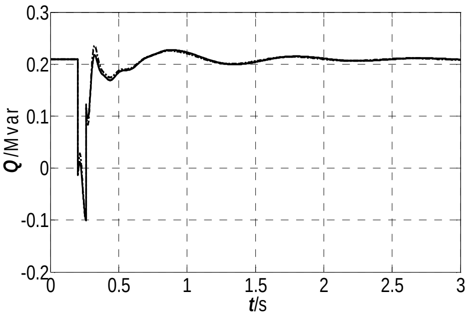

Figure 8. The Reactive Power of Single Phase Grounded Fault

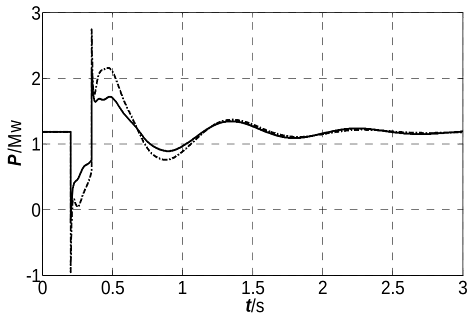

Figure 9. The Active Power of Three Phase Grounded Fault

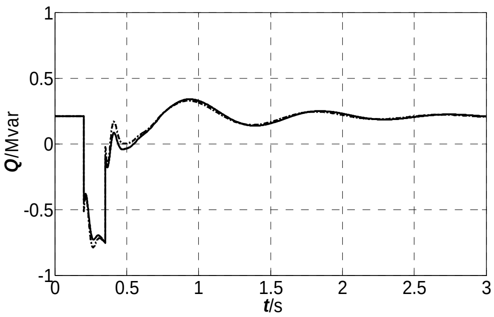

Figure 10. The Reactive Power of Three Phase Grounded Fault

—— Detailed model — — Equivalent model

From Figure 7 and Figure 10, it can be seen that the exchange power between micro-grid equivalent model and distributed network is close to the micro-grid detailed model and distributed network, which means that the dynamic of equivalent model of micro-grid is similar with the dynamic of the detailed model. From the detailed model of micro-grid shown in Figure 4 to the equivalent model shown in Figure 6, it can be seen that the equivalent process pull the distributed components more closer and parallel in the PCC, which will strengthen the interaction of different distributed components. The distributed components connected each other through transformers and lines, and the dynamic of distributed component effect the dynamic of micro-grid feebly, but in the equivalent model of micro-grid, the distributed components next to each other, which will effect the dynamic of the micro-grid directly. From Figure 7 and Figure 9, it can be seen that there is an abrupt change of the power at the fault occur and clear time, and the micro-grid can reduce the impact of distributed generation effectively, and reducing the threat of the high penetration of distributed generations.

5. Conclusion

Micro-grid is new paradigm of electric power systems contains load, distributed generation and storage system, which can increase the utilization of distributed generation and improve the Supply reliability of power system. A micro-grid is built in the simulation software DIgSILENT to analysis and verify the equivalent simplification method. Micro-grid equivalent simplification is an effective method for the study of the interaction between micro-grid and distributed network.

The paper proposes a micro-grid equivalent simplification method for micro-grid network, composite load, gas turbine synchronous generation, wind generation. The distributed components parallel in the PCC bus after equivalent simplification. The simulations show that the equivalent simplification method is effective and the dynamic of equivalent model of micro-grid is similar with the detailed model.

Acknowledgments

This paper was sponsored by The Fundamental Research Funds for the Central Universities (10B101-08) and the Open Fund of Jiangsu Key Laboratory of Power Transmission & Distribution Equipment Technology (2011JSSPD11). The authors are also grateful to College of Internet of Thins Engineering at Hohai University, China.

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