A Photovoltaic Power Station Equivalent Method Based on Real-Time Digital Simulator

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Abstract. As a clean energy power generation technology, photovoltaic generation has the characteristics of low carbon, green and environmental protection. More and more countries pay close attention to it, more than one megawatt demonstration projects of grid photovoltaic power station has been commenced or built. In order to study interconnection characteristics of large-scale photovoltaic power station better, reduce the effects of photovoltaic power station to the grid, we need to set up photovoltaic power station simulation model. However, the model of photovoltaic power station is complex, the speed of system simulation become slow after establish. In this paper, a real-time digital simulator based on the photovoltaic power station equivalent method will be given, through the proposed hierarchical equivalence method can simplify the process of equivalent of photovoltaic power station, shortening the period of equivalent model, and can be carried out in the process of each layer of the equivalent model accuracy validation, improve the accuracy of the equivalent model.

1 Introduction

Due to the rapid consumption of traditional fossil fuels and worsening environmental pollution, there is growing concern over the development of new energy all over the world. PV generation, as a kind of clean energy generation technology, attract more and more countries' attention, Many governments have successively introduced favorable policies to support PV industry research, and established a number of large-scale PV power stations. With the rapid development of PV generation, large-scale PV generation system will become the future trend.

Since the 1970s, many developed countries have begun to be concerned about PV generation. Germany, Japan and the United States have established a lot of PV power stations, and invested a series of pilot projects. After 2000, the total installed capacity of PV power stations increased rapidly, especially in Japan in 2006 the cumulative PV installed capacity reaching 1760MW to become the world leader in the photovoltaic industry [1]-[3]. PV power station mainly consists of photovoltaic array, controller and inverter. Photovoltaic array is composed by the multi-block photovoltaic modules in series and parallel structure, converting solar energy into electricity. The inverter is a power conversion equipment of PV power station, converting DC to single-phase or three-phase alternating current. Because PV array is made of semiconductor, and controller and inverter are electronic devices, PV power station has no rotating parts, reliable operation, and low failure rate [4]-[6].

With the increase of the capacity and scale of the photovoltaic power station, the influence of the photovoltaic power station on the access point grid is gradually emerging. Because the PVPS is different from conventional energy generation, the access point is a great challenge to the security, stability and reliability of the power access point [7]. At present, most of large-scale grid-connected photovoltaic power station in China is still in the experimental stage and there is no united design specification and access standard, so the security and stability of power system can't be guaranteed.

In order to study the grid connection characteristic of large-scale PV power station, and reduce the impact of PV power station on the grid, the simulation model of photovoltaic power station is needed. A detailed PVPS model will greatly increase the complexity of the simulation, resulting in lowering the speed of system simulation, costing a lot of computing time and reducing the efficiency of the system simulation, so it is important to establish the equivalent model of large-scale PV power station.

The Real-Time Digital Simulator (RTDS) has two advantages: (1) RTDS can simulate in real time. (2) RTDS can be connected with the external device through the interface. Compared to the physical experiment, the real-time digital simulation is more convenient and has better expansibility and compatibility, and it is more close to the actual situation, providing more accurate simulation results [8]-[11]. This paper provides an equivalent modeling method for the photovoltaic power stations, to shorten the equivalent modeling time and simplify the process of the equivalent modeling. This method can be verified in each equivalence procedure, which improves the accuracy of the equivalent model.

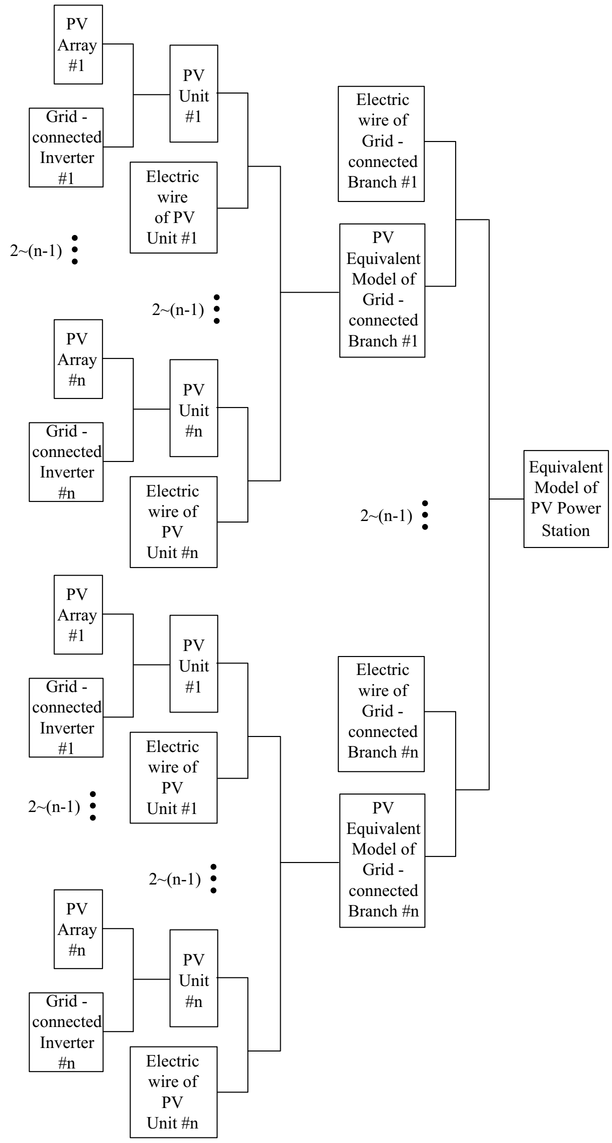


Figure 1. The flow chart of equivalent method based on RTDS.

2 Equivalent modeling of PVPS

2.1 Process of equivalent modeling

As shown in Figure 1, the equivalent method of PV power station based on real-time digital simulator is carried out as follows:

(1) Divide the PV power station into three layers: bottom layer, middle layer and top layer.

(2) Establish the generation model of PV array as bottom layer, including PV array model, grid-connected inverter model, and electric wire model. Obtain the equivalent model of bottom layer and verify its accuracy, including the parameters of above models.

(3) Establish the middle layer model made of PV arrays, including the generation model of PV array, and electric wire model between generation units. Obtain the equivalent model of middle layer and verify its accuracy.

(4) Establish the top layer model made of grid-connected branches, including the equivalent model of all branches and electric wire. To obtain the equivalent model of top layer, complete the equivalent model of entire PV power station and verify its accuracy are needed.

2.2. The parameter of equivalent modeling

Equivalence modeling of the PV power station is to aggregate the whole detail model of PV station as an integration. It is required that the Equivalence Model (EM) and the Detail Model (DM) show the same external characteristic in the utility connection points of the grid. As a result of that, the parameter should be set as follows:

(1) The voltage of EM and DM are equal at utility connection point of grid.

(2) The rated capacity of EM is equal to the sum capacity of each PV power generation units, as formula (1) shows:

$$S_{eq} = \sum_{i=1}^{n} S_i \tag{1}$$

In the formula, n is the number of PV power generators in the PV power generation station; S_{eq} is the rated capacity of EM; S_i is the rated capacity of generator i in the PV power station.

(3) The grid-connected active power of EM is equal to the sum grid-connected active power of each PV power generators.

$$P_{eq} = \sum_{i=1}^{n} P_i \tag{2}$$

In the formula, P_{eq} is the grid-connected active power of EM; P_{i} is the grid-connected active power of PV power generators i.

(4) The grid-connected reactive power of EM is equal to the sum grid-connected reactive power of each PV power generators.

$$Q_{eq} = \sum_{i=1}^{n} Q_i \tag{3}$$

In the formula, Q_{eq} is the grid-connected reactive power of EM; Q_{i} is the grid-connected reactive power of PV power generators i.

Generally speaking, the equivalence modeling of PV station is to integrate each models of PV generators in the PV station as a whole in order to make the two model show same external characteristic at the utility connection point of grid. In the EM, for guaranteeing the active and reactive output power of EM and DM are equal, the circuit parameter of EM should be integrated based on each DM. If the PV station is made up of n PV generators, the integrating formula of EM could be as follow:

➢ **The parameter of converter**

The parameter of converter mainly includes DC side capacitance and AC side filter inductance. Their calculation formula is:

$$\begin{cases} C_{dc\_eq} = C_{dc} \times n \\ L_{eq} = \dfrac{L}{n} \end{cases} \tag{4}$$

In the formula, $C_{\text{dc\_eq}}$ is DC side capacitance of EM; C_{dc} is DC side capacitance of each generators; L_{dc} is AC side filter inductance of EM; L is AC side filter inductance of each generator.

In the simulation, three phase π type equivalent circuit was used as model of electric wire, as it is shown in Figure 2. When stimulating, the parameter of electric wire is set under the premise that its active and reactive power loss are equal after doing equivalent transform.

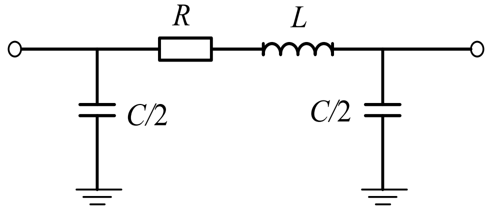


Figure 2. π type equivalent circuit.

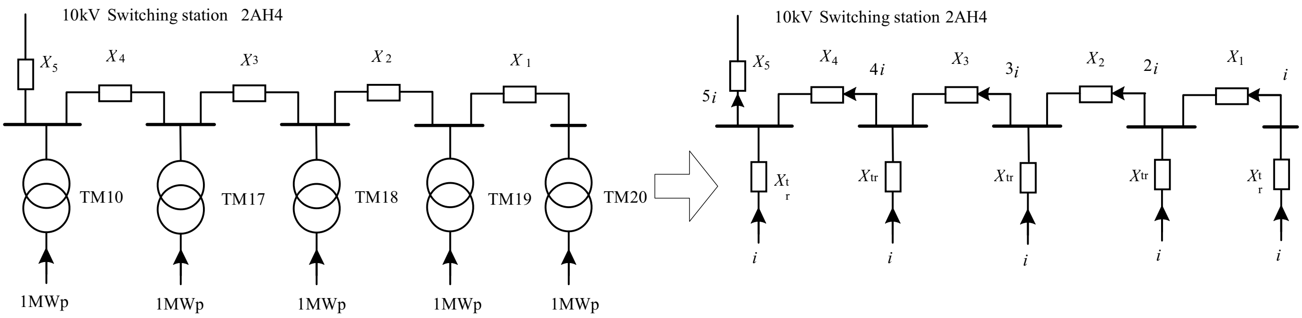


Figure 3. 4#line structure.

➢ **The parameter of transformer and electric wire**

The diagram of 4# electric wire is shown as Figure 3. As the structure shown in Figure 3, the power loss on electric wire and transformer are:

$$\begin{cases} Q_{tr} = 5i^2 X_{tr} \\ Q_{line} = i^2 X_1 + (2i)^2 X_2 + (3i)^2 X_3 \\ \qquad + (4i)^2 X_4 + (5i)^2 X_5 \end{cases} \tag{5}$$

Xtr is the impedance of transformer, X1, X2, X3, X4, X5 is the impedance of each wire. After taking equivalent measure, the line structure of Figure 3 turns into Figure 4, the power loss on electric wire and transformer become:

$$\begin{cases} Q_{tr\_eq} = (5i)^2 X_{tr\_eq} \\ Q_{line\_eq} = (5i)^2 X_{eq} \end{cases} \tag{6}$$

$X_{\text{tr\_eq}}$ is equivalent impedance of transformer, X_{eq} is equivalent impedance of wire.

According to formula (5) and (6):

$$\begin{cases} X_{tr\_eq} = \dfrac{X_{tr}}{5} \\ X_{eq} = \dfrac{X_1 + 2^2 X_2 + 3^2 X_3 + 4^2 X_4 + 5^2 X_5}{5^2} \end{cases} \tag{7}$$

As a result, when n PV generator connected as the structure shown in Figure 3, the parameter of transformer and electric wire are shown as listed:

➢ **Parameter of transformer**

$$\begin{cases} S_{T\_eq} = S_T \times n \\ X_{tr\_eq} = \dfrac{X_{tr}}{n} \end{cases} \tag{8}$$

$S_{\text{T\_eq}}$ is the rated capacity of transformer in EM, S_{T} is the rated capacity of transformer, $X_{\text{tr\_eq}}$ is the impedance of transformer in EM, X_{tr} is the impedance of transformer.

➢ **Parameter of electric wire**

$$X_{eq} = \frac{X_1 + 2^2 X_2 + 3^2 X_3 + \bullet\bullet\bullet + n^2 X_n}{n^2} \tag{9}$$

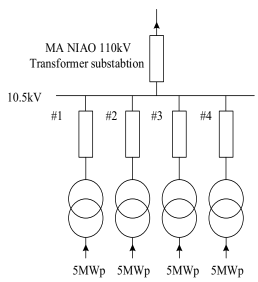
According to the formula of capacitance reactive power: $Q_c = \omega C U^2$, when the voltage remain constant, the reactive power is direct ratio to capacitance. As for electric wire, the voltage on wire is approximately constant, so the capacitance of wire is:

$$C_{eq} = C_1 + C_2 + \bullet\bullet\bullet + C_n \tag{10}$$

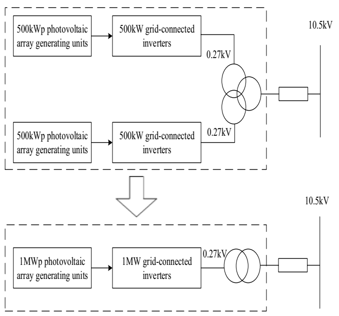
C_{eq} is capacitance of wire, C_1, C_2, C_{n} is capacitance of each wire.

3 RTDS modeling of photovoltaic power station

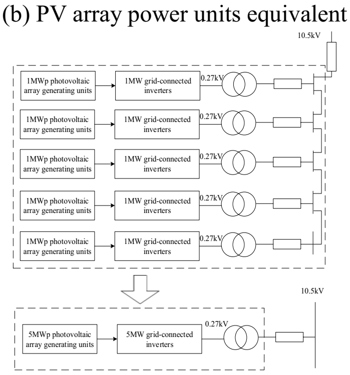
The Photovoltaic Power Station (PVPS), whose capacity is 20MW, is composed of 20 photovoltaic array generating units with a capacity of 1MW, each photovoltaic array generating unit consists of 2 subunits of 500kWp rated capacity, and a total of 40 grid-connected inverters with a capacity of 500kW are included. In the design of the PVPS, the photovoltaic arrays is integrated into power grid through 4 electric wires, each electric wire contains 5 photovoltaic array generating units with a capacity of 1MW, which is shown as Figure 4(a).



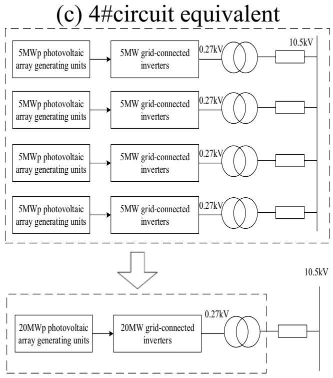
(a) PVPS electric circuit structure



(b) PV array power units equivalent



(c) 4#circuit equivalent



(d) PVPS equivalent

Figure 4. Equivalent model of PV.

The RTDS modeling process can be listed as followed, first of all, two grid-connected inverters with a capacity of 500kW are aggregated into a 1MW grid-connected inverter. Secondly, 5 photovoltaic array generating units of 1MWp in each electric wire are aggregated into a 5MWp photovoltaic array generating unit according to the electrical structure of PVPS. Finally the whole PVPS is aggregated into a 20MWp photovoltaic grid-connected power generation unit. The whole equivalent process are shown as Figure 4(b), (c), and (d).

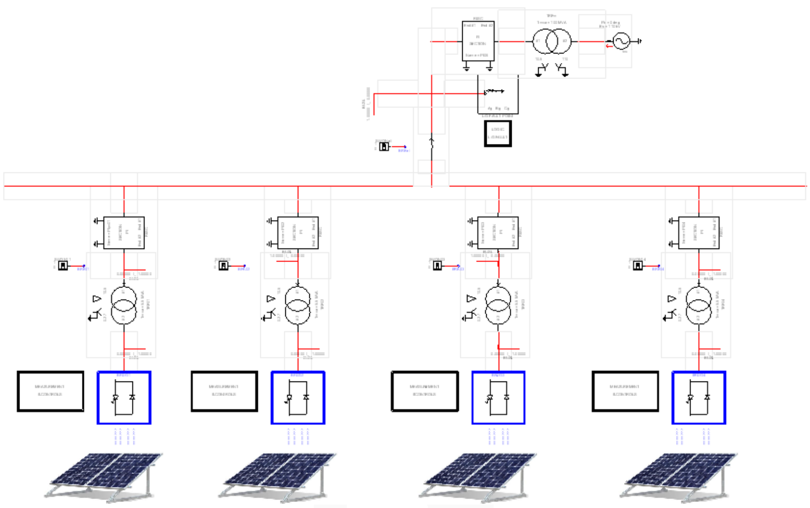
After the equivalent process above, the system parameters can be aggregated according the parameter aggregation formula. When the circuit parameters is obtained and put them into the equivalent model, the RTDS modeling of PVPS is completed.

4 RTDS simulation of the photovoltaic power station

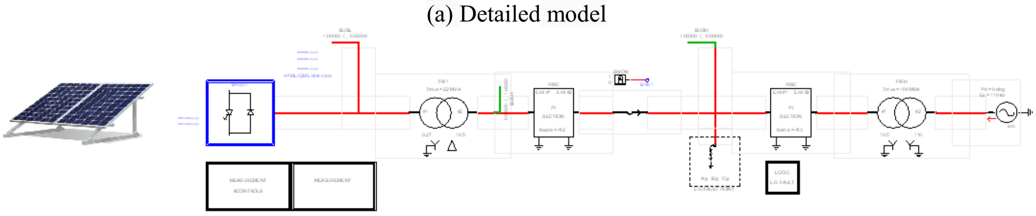
4.1 Simulation and modeling

According to the equivalent modeling method of the photovoltaic power station, the detailed model and the equivalent model of the photovoltaic power station are built in RTDS. In order to avoid the repetitive narration, only the detailed model and equivalent model shown in Figure 4(d) are discussed. The RTDS model corresponding to Figure 4(d) is as shown in Figure 5.

A detailed model is compared with the equivalent model to verify the correctness of the RTDS equivalent model. The following chapter will verify the accuracy of the equivalent model, based on the consistencies of the responses to external characteristics between the DM and EM when the light intensity changes and the three-phase short circuit happens in the external grid.



(a) Detailed model

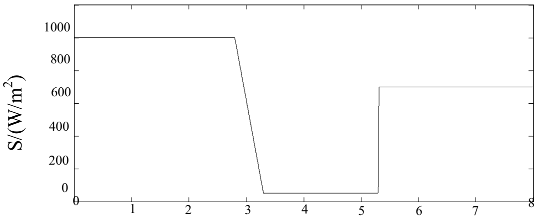


(b) Equivalent model

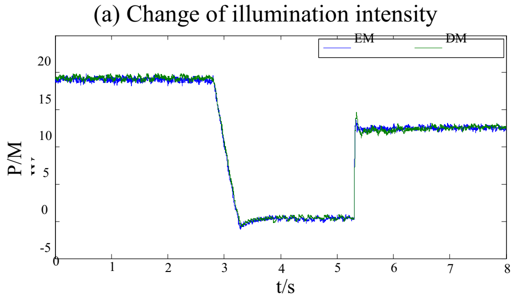
Figure 5. RTDS model of PVPS.

4.2 Simulation and comparison under varying light intensity

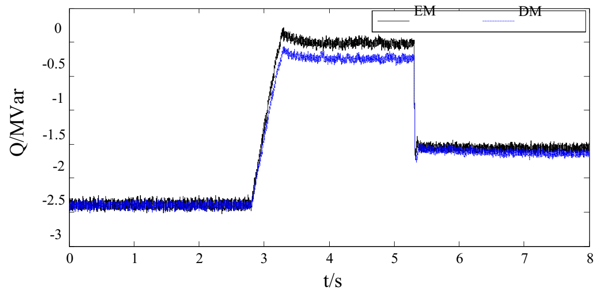
Figure 6 shows the simulation results under the varying light intensity. The curve of the light intensity is shown in the Figure 6(a). The initial illumination intensity is 1000W/m^2, and declines in a short time, and finally mutates to 700 W/m^2. The Figure 6(b) shows the curve of the grid-connected active power. The output active power of the photovoltaic power station changes with the changing illumination intensity, and the trend of active power is the same as that of the illumination intensity. Figure 6(c) shows the curve of the consumed reactive power. The consumption of the reactive power is caused by the reactive power loss of the lines and the transformers. Figure 6(d) shows the curve of the high voltage side current effective value. The voltage per-unit value of PCC is shown in Figure 6(e).



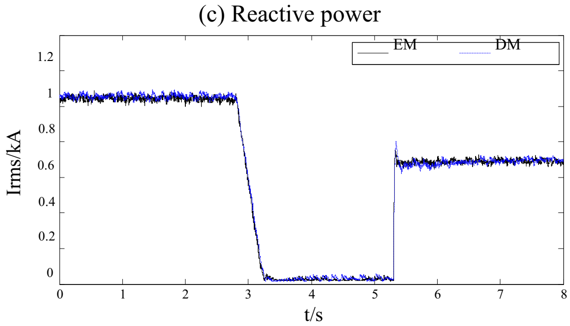
(a) Change of illumination intensity



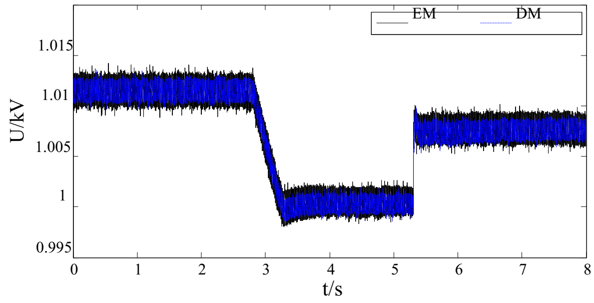
(b) Active power



(c) Reactive power



(d) Grid current valid values of PCC point



(e) Voltage per-unit value of PCC point

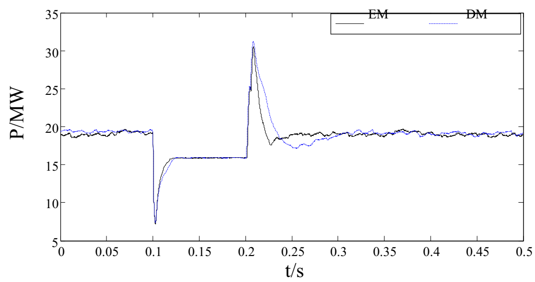
Figure 6. Simulation result of PVPS

In Figure 6, the trends of the voltage, current, active power, and reactive power are the same that of the light intensity. It means that the equivalent model and the detailed model have the similar external characteristics, which verifies the validity of the equivalent modeling of photovoltaic power station.

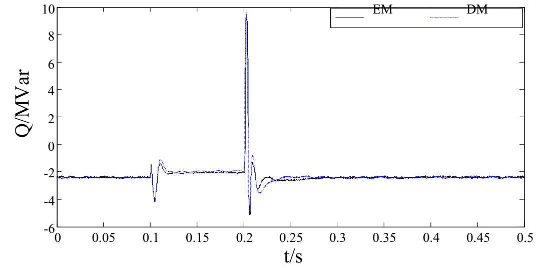
4.3 Simulation and comparison in three-phase line-to-ground fault

The simulation result of PVPS with the three-phase line-to-ground fault in the radiation of 1000W/m^2 is shown in Figure 7. Firstly, PVPS worked steadily while the three-phase line-to-ground fault happened in 0.1s with 0.1Ω grounding resistance and continued 0.1s. When the three-phase line-to-ground fault happened, the voltage of PCC decreased rapidly and the output power of PVPS decreased. The unbalance between the DC input power and the AC output power of grid-connected inverter, increased the DC voltage quickly. Power grid returned to be normal after 0.1s and the DC input power and the AC output power of grid-connected inverter became still balanced through the short adjustment of PVPS. During the process of short circuit, the output active power of PVPS was shown in Figure 7(a). The PV grid-connected inverter worked in the unity power factor and didn't have the ability of reactive power compensation. As shown in Figure 7(b), the reactive power consumption of system was mainly caused by the transformer and line loss and changed little.

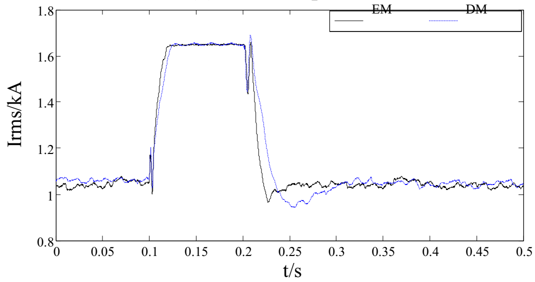
From the Figure 7(C), the grid-connected current about 1.6 times during the three-phase line-to-ground fault for the inherent I-V characteristics of photovoltaic. The change of the PCC voltage during the three-phase line-to-ground fault can be seen in Figure 7(d).



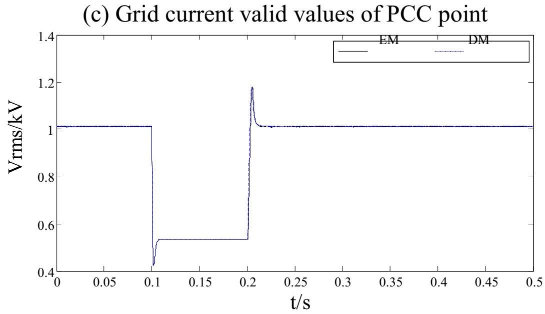
(a) Active power



(b) Reactive power



(c) Grid current valid values of PCC point



(d) Voltage per-unit value of PCC point

Figure 7. Simulation result of PVPS when three-phase line-to-ground fault

During the three-phase line-to-ground fault, the external characteristics response of the equivalent model and the detailed model are consistent. In other words, the response of the equivalent model in active power, reactive power, current and voltage are consistent with the detailed model, which proved the correctness of the equivalent model.

5 Conclusion

In this paper, the basic concepts of PVPS and RTDS have been presented at first and the mathematical model of PV array and grid-connected inverter have been established. Combined with the actual PVPS, the RTDS model of PV grid-connected inverter, the detailed model and the equivalent model of PVPS have also been established. At last, the correctness of the equivalent model of the PVPS is verified by comparing the detailed model and the equivalent model in different conditions.

Acknowledgment

This work was supported by the national high technology research and development program (863 Program, 2014AA052001); Guangdong Province science and technology plan project (2012B040303005); Electric Power Research Institute, CSG, science and technology project (SEPRI-K143003); China Southern Power Grid, CSG, science and technology project (K-KY2014-009).

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