Modeling and electromagnetic transient simulation of photovoltaic generators in large-scale photovoltaic power generation systems

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Abstract. On account of the large amount of electromagnetic transient simulation of single photovoltaic power generation units, it is difficult to simulate a large-scale photovoltaic power generation system with multiple photovoltaic power generation units by power system simulation software. A method of single photovoltaic power generation unit model simplification is proposed in this paper, which can be applied in a large-scale photovoltaic power generation system. In order to improve simulation efficiency to study the output characteristics of photovoltaic power generation units more efficiently, the converter model and the control loop in the electromagnetic transient model are simplified and reduced respectively. There is no need to change the algorithm of simulation software, and the requirement to the computer performance is lower because of the reduction in the amount of computational data. The simplified simulation models are built by PSCAD simulation software, which are applied in the electromagnetic transient simulation of the large-scale photovoltaic power generation system. The simulations are carried out under constant light intensity and temperature condition, variable light intensity and temperature condition and single-phase ground fault condition. The output characteristics of the simplified model under different working conditions are compared in detail. The simulation results show that the dynamic response curves of simplified model and the electromagnetic transient model for a single device are consistent. Within the allowable precision range, the simulation speed can be improved and the time consumption can be shortened by using simplified model. The larger the number of photovoltaic power generation unit modules is, the more obvious the simulation speed improvement is. So the simplified model can be applied to the simulation research of the large-scale photovoltaic power generation systems where the output characteristics of photovoltaic power generators needs to be observed.

1. Introduction

As a kind of renewable energy generation, photovoltaic power generation has been highly valued [1–4]. At present, the research on simulation model of photovoltaic power generation device includes mathematical model of photovoltaic array, MPPT (Maximum Power Point Tracking) and control strategy of inverter, etc. [5, 6] Although the traditional electromagnetic transient simulation can comprehensively observe the response characteristics of the system, it is only suitable for small-scale system research due to the complexity of the calculation process and the limitation of computer
performance. For the simulation analysis of large photovoltaic power generation system, it is necessary to establish a more efficient and accurate simulation model.

At present, there are three main methods to solve the simulation efficiency problem of large power system: 1) Electromagnetic and electromechanical transient hybrid simulation technology; 2) Parallel computing technology; 3) Equivalent simplification of mathematical model.

In [7, 8], electromagnetic and electromechanical transient hybrid simulation technology was applied to improve the efficiency of simulation. However, due to the complexity of parameter calculation and the high requirement of computing resources, it is not suitable for large-scale interface modeling. In [9], the hybrid simulation technology of electromagnetic and electromechanical power systems is described in detail, which provided more particulars needed to analyze the dynamic characteristics of the system, and the scale of the simulated power system is not limited. Electromagnetic transient simulation mainly analyzes the transient process response at a microsecond level, where the system nonlinear is taken into consideration. Electromechanical transient simulation mainly analyzes the transient process response at a second level and only the system characteristics in the vicinity of power frequency is considered. Electromagnetic and electromechanical transient hybrid simulation not only meets the requirements of detailed modeling for some parts of system, but also expands the simulation scale. However, due to the different simulation step sizes, the designs of data exchange, interface sequence and equivalent circuits on both sides are complex.

In [10], the dynamic phasor method is applied to the modeling of HVDC (High Voltage Direct Current Transmission) systems and FACTS (Flexible AC Transmission Systems) equipment to analyze the transient stability of FACTS devices in systems and dynamic phasor models and other AC system components in the electromechanical model. Parallel computing technology can improve the simulation speed of large-scale system, but it needs to improve the traditional electromagnetic transient algorithm and model, and introduce new computing equipment.

In [11, 12], a simplified model of photovoltaic modules is presented by using equivalent simplification of mathematical model. However, it lacked the simplification research of circuit and control system. In [13], a simplified model of microgrid based on solar PV was analyzed in detail, which took into account both the DC and AC side dynamic characteristics of the inverter, and also the uncertainty of PV power generation was considered. In [14], it proposed a simplified mathematical model of a photovoltaic power generation system that can be used in various power system studies. The model is simplified by take into account the controllers used in the grid-connected photovoltaic power generation system. [15] proposed a switching time-scale electromagnetic transient simulation model, which has high accuracy, but is not suitable for large-scale photovoltaic system simulation due to the large amount of simulation data. In [16], the PV (photovoltaic) array and MPPT links were simplified into the maximum output calculation model, which is composed of control module, controlled voltage source and filter circuit. The control quantity is obtained by decoupling control of active and reactive power. However, the model contained current loop, so it belonged to the millisecond time-scale electromagnetic transient simulation, which can be further improved into a larger time scale one. In [17, 18], the control system of photovoltaic power generation unit is simplified, and the power expression is obtained for power system analysis. This method can be used for electromagnetic transient simulation on the time scale of about 20 milliseconds. However, the variation of the parameters of the photovoltaic power generation device itself can not be observed by the mathematical expression of the power model in the paper, which needs further improvement. In [19, 20], the model of photovoltaic power generation system is simplified as a voltage source for power system analysis. The control system in the model is ignored to make the model very simple, whose time scale belongs to the electromechanical transient model. But there is a lack of research on system failures in [19, 20], which need a further improvement. The equivalent simplification of the mathematical model reduces the data of simulation and the dependence on the computer performance without any change of the original program algorithm to improve the efficiency. The corresponding equivalent model can be established according to different research requirements, which can be
applied to the simulation analysis of large power system. Therefore, the modeling in this paper is based on this method.

The electromagnetic transient simulation model of photovoltaic power generation system proposed in this paper is based on 10 milliseconds to 20 milliseconds time scale, where the photovoltaic cell module is retained, and the control loop and converter are simplified. It can not only maintain the effectiveness of the control system but also observe the output parameters of the photovoltaic power generation device, so as to improve the simulation speed and ensure the accuracy of the results. Therefore, it is suitable for the study of large-scale photovoltaic power generation system which needs to observe the output characteristics of photovoltaic power generation device.

2. Method
As a DC power supply, photovoltaic array is usually connected to the power grid after converting direct current to alternating current through power electronic devices. In the electromagnetic transient model of photovoltaic power generation device, the dynamic process of the converter is frequent, which increases the calculation amount of simulation. The simulation step length of switching time-scale electromagnetic transient model is generally about 20 to 200 milliseconds, which not only focuses on the nonlinear components and the motion characteristics of power electronic devices, but also considers the transient response process of the system. The simulation step length of the electromechanical transient model is generally more than 20 milliseconds, and only the RMS of the system fundamental wave vector is concerned, so the simulation scale is relatively large. For the study of the external characteristics of the photovoltaic power generation system, it is not necessary to pay attention to the dynamic characteristics of the internal components of the converter. Therefore, for the study of electromagnetic transient simulation of large-scale power system, which mainly focuses on the system characteristics of its power-frequency range, changing the time response scale of the model will greatly improve the simulation efficiency.

Figure 1. Structure of single-stage PV generation system.
2.1. Simplification of single-stage photovoltaic power generation device

In the single-stage photovoltaic power generation device, the output DC power of the photovoltaic array is directly converted into AC power through the inverter to realize grid connection. Its structure is shown in Figure 1. At this time, the inverter not only needs to achieve maximum power point tracking, but also needs to complete the goal of grid connection control. The control system adopts the double-loop control method, namely dc voltage/reactive power outer loop and current inner loop.

Due to the symmetry of the two current inner loops, $i_q$ is taken as an example. Considering the delay of the current inner loop signal sampling and the small inertia characteristics of the PWM control, the structure of the decoupled $i_q$ current inner loop is shown in the Figure 2.

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The small time constants $0.5T_S$ and $T_S$ are combined to obtain a simplified current inner loop structure. Since the response speed of the current inner loop is faster than that of the outer current loop, and the time scale of the inner current loop is much smaller than that of the outer current loop, the dynamic process of the inner current loop in the control system will be ignored when simplifying the model, and the output value of the inner current loop will be equal to the input value. The simplified structure and control system are shown in Figure 3.
The DC reference voltage $U_{dcref}$, which corresponds to the maximum power point of the PV array output, is obtained by the output current $I_p$, and the output voltage $U_{dc}$ of photovoltaic array and the MPPT algorithm module. The reference voltage $U_{dcref}$ and the reference reactive power $Q_{ref}$ are respectively compared with the actual DC voltage $U_{dc}$ and the reactive power $Q_{grid}$, and the current inner loop reference signals $i_{dref}$ and $i_{qref}$ are output through the PI regulator. Since the inner loop is simplified, the actual value of the inner loop current $i_d$ and $i_q$ are considered to be equal to the reference value, which acts as the command signal $i_{source}$ of the controlled current source after inverse transformation of the coordinates. The inverter-side converter is simplified to a controlled current source, whose command signal $i_{c_s}$ is obtained through multiplying the id value by the proportional coefficient $K$. Therefore, when the ambient conditions such as illumination intensity and temperature change, it can achieve zero-static error tracking adjustment.

2.2. Simplification of double-stage photovoltaic power generation device

In the double-stage photovoltaic power generation device, the photovoltaic array is first connected to a DC/DC chopper to change voltage amplitude, which is usually boost chopper circuit in real systems. Then the DC power is converted into AC power through the inverter to realize grid connection. The typical structure of the device is shown in Figure 4, mainly including photovoltaic array, filter capacitor, boost chopper circuit, inverter and ac power grid.

In the structure of the boost chopper circuit, the inductance $L$ and the capacitance $C$ are large. When the circuit reaches steady state, the duty cycle is $D$ ($0 < D < 1$), and the average value of the inductor voltage and the capacitor current is 0 in one switching cycle. The following formula can be obtained as shown in (2).

\[
\begin{align*}
\bar{u}_L &= DU_p + (1 - D)(U_p - U_{dc}) = 0 \\
i_c &= DI_{dc} + (1 - D)(I_{dc} - I_p) = 0
\end{align*}
\]

Where, $\bar{u}_L$ is average voltage across the inductor $L$, and $i_c$ is average current of capacitor $C$. The steady state model of the boost chopper obtained by Equation (2) is:

\[
\begin{align*}
U_{dc} &= \frac{1}{1 - D} U_p \\
I_{dc} &= (1 - D) I_p
\end{align*}
\]

![Figure 4](image1.png)  
**Figure 4.** Structure of double-stage PV generation system.

![Figure 5](image2.png)  
**Figure 5.** Structure of simplified model for double-stage PV generation system.
The chopper and inverter of the double-stage photovoltaic power generation device have independent control objectives. By adjusting the duty cycle $D$ of the chopper, the maximum power point of the photovoltaic array can be tracked. The inverter control is similar to single-stage PV generation system to realize grid-connection. Similarly, the converter module is replaced by controlled sources to simplify the system; boost chopper circuit is equivalent to a controlled voltage source and a controlled current source, and the inverter is equivalent to a controlled current source. The DC reference voltage $U_{\text{pv ref}}$ corresponding to the maximum power point of the photovoltaic array is obtained by the MPPT module, which get a first-order lagged to generate the command signal $U_{\text{pv s}}$ of the controlled voltage source. The DC side reference current $I_{\text{dc ref}}$ is obtained through multiplying PV array output current $I_{\text{pv}}$ by scale factor $1-D$, which get a first-order lagged to generate the command signal $I_{\text{dc s}}$ of the controlled current source. The above processes simulate the boost chopper circuit's conversion of voltage and current amplitudes on both sides. The DC reference voltage $U_{\text{dc ref}}$ of the inverter is another given constant, and the other controlled source control methods are the same as the simplified model of the single-stage photovoltaic power generation device, so as to achieve zero-static error tracking regulation when the external conditions change. The simplified model structure and control system are shown in Figure 5.

3. Results

In order to verify the correctness of the simplified model of a single photovoltaic power generation unit, a simplified model and detailed model of a single single-stage and double-stage photovoltaic power generation unit were built on the PSCAD platform.

The following are the model parameter settings. The grid voltage is 380 V (line voltage RMS). The rated power of a single photovoltaic power generation device is 26 kW. The line inductance is 0.2 mH. The DC stabilized capacitor value in a single-stage photovoltaic power generation device is 1000 μF. The photovoltaic array output terminal capacitance and the inverter side capacitance value in the double-stage photovoltaic power generation device are both 1000 μF. The inductance in the boost chopper circuit is 10 mH.

3.1. Output characteristics analysis under normal conditions

3.1.1. Comparison of output characteristics of single device model under constant light intensity and temperature conditions. The simulation steps are set to 20 μs and 100 μs respectively, the simulation duration is 30 s, the constant light intensity is set to 600 W·m$^{-2}$, and the constant temperature is set to 50 °C. The time-consuming and precision comparison results of the model are shown in Table 1 and Table 2, respectively.

| Table 1. Model simulation time-consuming comparison results. |
|---------------------------------------------------------------|
| Model type | Single-stage | Double-stage |
|-------------|--------------|--------------|
| Quantity    | 1            | 1            | 5            | 1            | 1            | 5            | 1            | 5            |
| Simulation step size / μs | 20 | 100 | 20 | 100 | 20 | 100 | 20 | 100 |
| Switch model time-consuming / s | 171 | 71 | 699 | 263 | 209 | 89 | 839 | 306 |
| Simplified model time-consuming / s | 36 | 18 | 134 | 39 | 35 | 18 | 113 | 34 |
| Time-consuming ratio | 4.8 | 3.9 | 5.2 | 6.7 | 6.0 | 4.9 | 7.4 | 9.0 |

As shown in Table 1, under the same simulation step, the on-off process of the power electronic device is neglected in the simplified model, so the simulation time-consuming is significantly shortened compared with the detailed model, and the simulation efficiency improvement is more significant when the number of photovoltaic power generation models increases. Therefore, when studying large-scale photovoltaic power generation systems, the simplified model of this paper can improve simulation efficiency and shorten simulation time.

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Since there is no power electronics equipment in the simplified model, which is replaced by ideal controlled power sources, the switching losses are ignored and the output harmonic components are reduced. But as shown in Table 2, the output error of the simplified model in this paper does not exceed 5%, which is acceptable. Therefore, PV array output current control by controlled sources is effective. The simplified models of a single photovoltaic power generation device in this paper significantly improve the simulation efficiency and shorten the time-consuming within the allowable range of accuracy.

### Table 2. Accuracy comparison of different simulation models.

| Model type | Single-stage | Double-stage |
|------------|--------------|--------------|
| Illuminance / W·m⁻² | 800 | 800 | 600 | 600 | 800 | 800 | 600 | 600 |
| Temperature / °C | 50 | 25 | 50 | 25 | 50 | 25 | 50 | 25 |
| PV array current of switch model / A | 67.08 | 66.20 | 50.31 | 49.60 | 67.01 | 66.00 | 50.32 | 49.43 |
| PV array current of simplified model / A | 67.30 | 66.00 | 50.34 | 49.53 | 67.07 | 66.01 | 50.35 | 49.53 |
| Error / % | 0.33 | 0.30 | 0.06 | 0.14 | 0.09 | 0.02 | 0.06 | 0.20 |

### 3.1.2. Comparison of output characteristics of single device model under fluctuating light intensity and temperature conditions.

At \( t=20 \) s, the light intensity (R) increased from 600 W·m⁻² to 660 W·m⁻² at a constant rate of 20 W·m⁻² per second in 3 s, and the temperature (T) increased from 50 °C to 56 °C at a constant rate of 2 °C per second in 3 s. The comparison results of the detailed model and simplified model dynamic characteristics of a single single-stage and double-stage photovoltaic power generation unit based on the PSCAD platform are shown in Figure 6.

As shown in Figure 6, at \( t=20 \) s, for a single single-stage photovoltaic power generation device, the current of the detailed model increased from 50.3 A to 55.6 A in 7 s, and the current of the simplified model increased from 50.3 A to 55.5 A in 7 s. For a single double-stage photovoltaic power generation device, the current of the detailed model increased from 50.3 A to 55.4 A in 5 s, and the current of the simplified model increased from 50.3 A to 55.6 A in 5 s. At \( t=21 \) s, because the illuminance and temperature stopped rising, the rate of current rise also changed. As shown in Figure 6, the dynamic process trends of the currents of the two models are the same. When the system reached a steady state, they also maintained good accuracy. Therefore, when the external light intensity and temperature conditions change, the simplified models of the two kinds of devices can achieve the maximum power point tracking, and can also maintain good consistency with the output characteristics of the detailed model.

![Figure 6. Comparison of dynamic characteristics for PV generation system.](image)

### 3.2. Simulation analysis of fault conditions

In order to verify the effectiveness of the simplified model of a single unit under fault conditions, the two types of photovoltaic power generation unit models are operated under the condition of single-phase ground fault at the grid side. The constant light intensity is 600 W·m⁻² and the constant
temperature is 50 °C. The comparison results of the detailed model and simplified model characteristics under fault conditions of a single single-stage and double-stage photovoltaic power generation unit based on the PSCAD platform are shown in Figures 7, 8 and Table 3.

![Figure 7. Characteristic under single-phase ground fault condition (single-stage).](image1)

![Figure 8. Characteristic under double-phase ground fault condition (double-stage).](image2)

| Table 3. Comparison of accuracy under fault condition. |
|-------------------------------------------------------|
| **Single-phase grounding short-circuit** | Steady-state short-circuit current | Short circuit maximum current |
| Single-stage | Detailed model | 48.65A | 53.53A |
| | Simplified model | 49.86A | 50.92A |
| | Error / % | 2.49 | 4.88 |
| Double-stage | Detailed model | 45.77A | 51.36A |
| | Simplified model | 47.54A | 48.98A |
| | Error / % | 3.87 | 4.63 |

As shown in Figures 7 and 8, under the single-phase ground fault condition, the short-circuit current trend of the detailed model is the same as that of the simplified model. After the fault occurred, the current of phase a increased. The detailed model current fluctuation lasted until around 15.7s to reach a new steady state, and the simplified model current fluctuation lasted until around 15.2s to reach a new steady state.

The reason for the error is mainly due to the simplification of control loop in the simplified model and the replacement of the power electronics equipment, which reduces the model order, the fluctuation process and device loss. The error of the simulation data between the detailed model and the simplified model is within 5%, which meets the accuracy requirements.

3.3. Large-scale photovoltaic power generation system simulation

In large-scale photovoltaic power generation systems, there are a large number of different types of photovoltaic power generation equipment. Based on the simplified model proposed in this paper, the simulation research of large-scale photovoltaic power generation system is realized.

3.3.1. Simulation of multiple units photovoltaic power generation system under normal working conditions. The simulation of large-scale photovoltaic grid-connected power generation system,
includes 50 simplified models of single-stage and double-stage photovoltaic power generation units for simulation analysis.

![Figure 9. Comparison of dynamic characteristics for multiple PV generator simplified models.](image)

![Figure 10. Output characteristics of multiple devices simplified model under fault condition.](image)

Since the data of the same amount of detailed model is too large to run on the PSCAD, the sum of the 50 times of the output value corresponding to the single detailed model under the same working condition is the expected value of the system output current. The simulation steps are 20 μs and 100 μs respectively, the simulation duration is 30 s, the constant light intensity is 600 W·m⁻², and the constant temperature is 50 °C. The simulation time-consuming and accuracy comparison results are shown in Table 4 and Figure 9.

| Model type and quantity | Simulation step size /μs | Time-consuming / s |
|------------------------|-------------------------|--------------------|
| 50 single-stage units and 50 double-stage units | 20 | 1849 |
| | 100 | 428 |

As shown in Table 4, under the conditions of a simulation step size of 20 μs and a simulation duration of 30 s, the time-consuming (1849 s) of simulation for 100 hybrid simplified models is only 2.2 times that of the simulation for five double-stage detailed models under the same conditions (839 s).

When the simulation step is changed to 100μs, the time-consuming (428 s) of simulation for 100 hybrid simplified models is only 1.4 times that of simulation for five double-stage detailed models under the same conditions (306 s). As shown in Figure 9, t=20 s, the output current increased from 5.0 353 kA (expected value: 5.0315 kA, error: 0.08%) to 5.5577 kA (expected value: 5.5565 kA, error: 0.02%) in 7 s. It shows that when the external conditions change, the simplified model of the multiple devices can also maintain good consistency with the dynamic output characteristics of the detailed model. The error between the actual value and the expected value of the simulation result does not exceed 5%. It can be seen that the simplified model still has good accuracy in analyzing the output characteristics of large-scale photovoltaic power generation systems.

3.3.2. Simulation of multiple units photovoltaic power generation system under fault conditions. By the same as normal working condition analysis method, the sum of the 50 times of the short-circuit current value corresponding to the single detailed model under the same fault condition is the expected
value of the total short-circuit current. The simulation results of the hybrid multi-unit model under the condition of single-phase ground fault at the grid side are shown in Figure 10 and Table 5.

| Table 5. Comparison of accuracy under fault condition of multiple devices. |
| --- | --- | --- | --- |
| Single-phase grounding short-circuit | Steady state short circuit current | Short circuit maximum current |
| Expected value of detailed model | 4.721kA | 5.245 kA |
| Actual value of simplified model | 4.879 kA | 4.998 kA |
| Error / % | 3.35 | 4.71 |

As shown in Figure 10, when a single device model is applied to a large system containing multiple devices, the voltage output waveform is consistent with a single device, and the current output waveform magnitude of hybrid multi-unit model can also maintain good consistency with that of a single device model. It shows in Table 5 that under the single-phase ground fault condition, the error between the actual value of the simplified model and the expected value of the detailed model is within 5%. Therefore, the simplified models proposed in this paper, which are applied in a large-scale system including multiple devices, can also maintain good consistency with the detailed models.

4. Conclusions
For the simulation efficiency of multiple photovoltaic power generation units in large-scale photovoltaic power generation systems, this paper proposes a simplified method for simulation model of photovoltaic power generation unit. Through the simplified model proposed in this paper and its simulation verification, the following conclusions can be obtained:

1) In the simplified model of a single single-stage and double-stage photovoltaic power generation unit, the photovoltaic cell module is retained, where the converter model and control system are simplified. The controllable current source and voltage source model are applied to replace the converter of the detailed model. Therefore, the time scale of the electromagnetic transient simulation model is transformed to about 10 milliseconds to 20 milliseconds.

2) The modeling method proposed in this paper does not need to change the software algorithm, and the simplification reduces the model calculation data and the dependence on the performance of the computer.

3) The simplified simulation models proposed in this paper not only shorten the simulation time-consuming, improve the simulation efficiency, but also maintains good consistency with the simulation results of the detailed models under normal and fault conditions respectively, which can be applied to a large-scale photovoltaic power generation system including multiple devices.

4) There are controllable current sources and voltage sources in the model, so the proposed simplified models can be applied to the simulation study of large-scale photovoltaic power generation systems whose output parameters need to be observed.

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