Development of fast simulation models of photovoltaic generation system based on MATLAB

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Abstract. Based on the mathematical model of photovoltaic power generation system, the simulation model based on MATLAB/Simulink is given. Traditional simulation models have the drawbacks of rapidity and poor robustness. In this paper, two equivalent simplified models based on inverters are established—the equivalent switch model and the average model. In this paper, the above three models are compared comprehensively from different aspects such as simulation speed, simulation precision and robustness, and the applicable occasions of each method are proposed.

1. Introduction
As a clean and renewable energy source, solar energy is receiving increasing attention in energy strategies around the world. Among them, the research and application of large-scale solar photovoltaic power generation technology is particularly prominent, and has made a series of important progress, laying a good technical foundation for large-scale photovoltaic grid-connected power generation. As the penetration rate of photovoltaic power generation continues to increase, its importance to traditional power grids continues to increase, affecting the overall security and stability of power systems, economic dispatching, and peaking and frequency modulation [1-3]. Computer simulation method is a powerful way to study the characteristics of photovoltaic power generation system, and it is of great significance for the study of the impact of large-scale photovoltaic access on power system operation [4].

The existing research on photovoltaic power generation simulation mainly focuses on the simulation model of single component [5-7] and the simulation model of system level [8-11]. For the simulation of photovoltaic power generation system, in order to accurately reflect the system characteristics, the simulation model should have the following conditions: 1) It can accurately reflect the influence of environmental factors (mainly illuminance and ambient temperature) on the system; 2) can accurately reflect the photovoltaic system Control strategy; 3) can correctly respond to disturbances from the power system [9].

Based on the existing research, this paper fully considers the detailed characteristics of each important link in the photovoltaic power generation system, and establishes a detailed simulation model of the whole system for steady state and transient analysis in MATLAB/Simulink platform. A simplified equivalent switch model and average model are established for the inverter model. The above models are compared in terms of simulation speed, simulation precision and robustness. The applicable occasions of each method are proposed.
2. Structure of photovoltaic grid-connected system

The photovoltaic power generation system mainly includes photovoltaic battery components, energy storage capacitors, inverters, controllers and filters, and is connected to the power system through the step-up transformer and the transmission line[10], as shown in Figure 1.

Among them, \( C_{dc} \) is a DC filter capacitor. \( U_{dc} \) is a DC capacitor voltage. \( U_k \) is the AC side output voltage. \( U_g \) and \( \delta_g \) are the voltage and phase of node \( g \). \( L_f \) is the output filter inductor. \( I_g \) is the output current, and \( X_T \) is the reactance converted to the high voltage side of the transformer. \( R_{line} \) is the transmission line resistance. \( X_{line} \) is the transmission line reactance. \( R_{grid} \) is the Thevenin equivalent resistance. \( X_{grid} \) is the Thevenin equivalent reactance. \( b \) is the infinite bus, and its voltage phasor is \( 1 \angle 0^\circ \).

3. Photovoltaic system inverter and controller model

3.1. Inverter and controller

In the photovoltaic power generation system, the topology of the voltage-type three-phase PWM inverter controlled by SPWM [11] is shown in Figure 2. In this system, the d-axis of the \( dq \) coordinate system is selected to be positioned on the voltage vector \( U_g \) of the node \( g \). So, \( U_{dg}=0 \).

The three-phase photovoltaic inverter generally adopts the feedforward decoupling control strategy [12], which realizes the decoupling of the current inner loop, and adds the voltage outer loop, which constitutes the classic PWM inverter double closed loop control, as shown in Figure 3. In order to achieve unit power factor grid-connected power generation, the q-axis current command value is controlled to be 0. According to this, the control block diagram of the photovoltaic inverter can be obtained, shown in Figure 3.

\( K_{P1}, K_{P2}, K_{P3} \) are the proportional coefficients of the voltage outer loop and the current inner loop controller. \( K_{I1}, K_{I2}, K_{I3} \) are integral time constants of the voltage outer loop and current inner loop controller, and the unit is \( s^{-1} \).
3.2. DC side capacitance equation
If the switching loss of the inverter is ignored, the power balance of the photovoltaic cell is equal to the sum of the increased power of the DC filter capacitor and the AC power output of the inverter. Taking the reference direction shown in Figure 1, the equation of state for the DC filter capacitor is:

\[ \frac{dU_{dc}}{dt} = I \left( \frac{U_{dc}}{I_{dc}} - \frac{u_{dc}}{I_{dc}} \right) = I - \frac{P_{out}}{U_{dc}} \]

I is the output current of the photovoltaic cell component, and Pout is the active power output to the grid.

4. Accurate simulation model and simplification of photovoltaic power generation system

4.1. Accurate simulation model of photovoltaic power generation system
Taking the example shown in Figure 1 as an example, an accurate simulation model of the photovoltaic power generation system is built and simulated.

When the input illumination changes, the maximum power point voltage of the photovoltaic cell changes accordingly. At this time, the command value of the voltage outer loop in the inverter control loop is reset to the maximum power voltage under the new illumination condition. The three-phase voltage/current and DC-side voltage of the inverter's grid-connected point reach a new steady state after the transient regulation process, and the system remains stable during this process.

At the same time, it can be seen that the accurate simulation model based on the real physical model completely reflects the characteristics of the system under steady-state operation (including the three-phase voltage/current harmonics of the grid-connected point generated by the inverter switching action, and the DC-side capacitance. The fluctuation of the voltage around the steady state value, etc.). Therefore, the accurate simulation model can simulate the transient performance and steady-state characteristics of the photovoltaic power generation system under different working conditions, and the results are in line with the real situation. At the same time, the main disadvantage of the simulation model is that the simulation operation is large and the simulation speed is extremely slow.

Since the inverter is the core component of the photovoltaic power generation system and the most complicated and time-consuming part of the simulation calculation, it is considered to simplify the part by using the equivalent model.

4.2. Equivalent simplified model of inverter
In the MATLAB/Simulink simulation platform, the three-phase bridge circuit has two equivalent simplified models: the switching-function based VSC and the average model based VSC.

In the equivalent switching model, a three-phase bridge circuit consisting of an IGBT and its parallel power diodes is replaced by an equivalent power supply. The equivalent source is internally composed of a voltage source on the AC side and a DC current source, which preserves the equivalent switching effect, ignoring the loss of the IGBT and the diode, and the output AC power is equal to the input DC power. Compared with the bridge circuit in the accurate model, the equivalent switch model
can accurately reflect the action of the switch tube, and reduce the amount of simulation operation and speed up the simulation. The disadvantage is that the loss in the inverter is neglected and the simulation accuracy is slightly reduced.

The average model of the inverter uses the three-phase voltage command signal as the reference signal input, eliminating the need for the PWM waveform generation of the control circuit. The simplified model is internally composed of an equivalent voltage source, and the output ignores the loss and all harmonic components of the inverter. Therefore, the simplified model can only represent the fundamental voltage characteristics of the inverter, and the accuracy is worse than the previous two models, but the simulation speed is faster, the sensitivity to the simulation step is significantly weakened, and the robustness of the simulation system is significantly enhanced.

The equivalent model is simplified from the simulation solution method. The internal power supply equivalent mechanism used is different from the traditional circuit method and will not be described in depth here.

5. Comparison of three simulation models

5.1. Comparison of simulation accuracy

The accuracy of the simulation results is one of the most important parameters in the simulation results, and is also a key indicator to measure the effectiveness of the simulation. The simulation of the three models of the photovoltaic system is carried out. The illuminance and temperature input are $S=1000\text{W/m}^2$, $T=25^\circ\text{C}$, and the simulation step is $2\mu\text{s}$.

Under steady-state operation, the fundamental component errors of the two simplified models are small and can accurately reflect the fundamental wave. When considering the influence of harmonic components, the equivalent switch model is closer to the exact model, which can better reflect the harmonic characteristics of the inverter bridge circuit.

The transient characteristics of the system can be compared and analyzed by the DC-side voltage $udc$ of the inverter. In the simulation case, the illuminance and temperature inputs are $S=750\text{W/m}^2$, $T=25^\circ\text{C}$; at $t=0.5\text{s}$, the illuminance input is abruptly changed to $1000\text{W/m}^2$.

In the transient process, the variation characteristic of the DC side voltage of the switch model is close to the exact model, and the maximum error is only $1.17\%$, which can well describe the transient process of the system; the maximum error of the average model is $5.62\%$, transient time It is $0.05\text{s}$ less than the exact model and has poor performance for system transient characteristics.

5.2. Simulation step robustness comparison

The simulation step size of the simulation system in fixed step mode (or the error range in variable step mode) is an important parameter affecting the simulation results. The selection of the simulation step directly affects the key links such as the PWM generation in the exact model and the equivalent switch model, thus directly affecting the correctness of the simulation results.

The accurate model is selected for simulation. It can be known that when the simulation step size is increased, the system solution accuracy is lowered, resulting in poor accuracy of the output result.

Both the accurate model and the equivalent switch model are sensitive to the simulation step size, so reasonable selection of simulation parameters is very important. In contrast, since the average model does not include the generation of the PWM signal, the current simulation results do not contain harmonic components, so the accuracy of the simulation results is weakly affected by the simulation step size, and a relatively large simulation step size can be selected to improve Simulation speed.

6. Conclusions

In this paper, an accurate simulation model of photovoltaic power generation system based on MATLAB/Simulink simulation platform is established. Based on the model, three equivalent simplified models are obtained, namely switch model, average model and phasor model. The simulation results are as follows:
1) The accurate simulation model can comprehensively and accurately reflect the steady state and transient characteristics of the system. Its shortcomings are slow simulation speed and high sensitivity to simulation parameters. It is suitable for the study of precise transient characteristics of photovoltaic power generation based on computer platform.

2) The equivalent switch model can describe the system characteristics more accurately, and the simulation speed is improved, which is suitable for HiL hardware real-time simulation system.

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