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Comparative Study on Electromagnetic and Electromechanical Transient Model for Grid-connected Photovoltaic Power System

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ABSTRACT

With the development of new energy technology, there are increasing applications of grid-connected photovoltaic power generation system. However, there is little research on development of electromechanical model of large scale photovoltaic power station. The computational speed will be very slow if electromagnetic transient model is used for stability study because of its complexity. Therefore, study on electromechanical transient model of grid-connected photovoltaic power generation system is of great meaning. In this paper, electromagnetic transient model of photovoltaic power generation system is introduced first, and then a general electromechanical transient model is proposed. These two kinds of simulation model are set up in PSCAD. By comparing the simulation results of two models, the correctness and validity of the electromechanical transient model is verified. It provides reference model for efficient simulation and modeling of grid-connected photovoltaic power station in large-scale power systems.

Keywords: Photovoltaic Power; Electromagnetic Transient Model; Electromechanical Transient Model; Simulation Comparison

1. Introduction

With the development of new energy technology, there are more and more applications of grid-connected photovoltaic power generation system [1,2]. Transient model of both accuracy and efficiency is needed in power system dynamic analysis with photovoltaic power generation. In the previous study, two models usually used as photovoltaic power generation model, of which one is the power flow model, and the other is electro- magnetic transient model. The former uses photovoltaic system just as a simple power source without considering its dynamic process [3-5], while the latter is established according to specific photovoltaic system, and strictly reflects the maximum power point tracking(MPPT) and the inverter control [6-9]. The latter is very detailed and can meet the requirements of grid transient process analysis, but it also has many problems, such as: 1) the electromagnetic transient model is not universal because the internal structure and control method of photovoltaic system are different of different manufactures, so a lot of work is needed if we want to establish electromagnetic transient model for different manufacturers and types, 2) the electromagnetic transient model needs proprietary equipment internal parameters, which are difficult to obtain, 3) the electromagnetic transient model needs small compute step because of its complexity, resulting in long computation time, and 4) at present, large power grid analysis often requires business or engineering simulation software, so in order to improve the automation level and expand the scale of calculation, unified model is needed for different kinds of power, including photovoltaic. In conclusion, according to the demand of the electromechanical transient simulation of power system, a universal modeling method is needed while analyzing the common features of different kinds of photovoltaic power generation system.

In this paper, electromagnetic transient model of photovoltaic power generation system is introduced first according to the references, and then a general electromechanical transient model of grid-connected photovoltaic power system is proposed, and two simulation models are established in PSCAD/EMTDC. By comparing the simulation results of two models, the correctness and validity of the electromechanical transient model is verified, which provides reference model for simulation and modeling of large scale grid-connected photovoltaic power station.

2. The Electromagnetic Transient Model

Grid-connected photovoltaic system includes photovoltaic array, DC/DC, inverter, controller and MPPT control, as shown in **Figure 1**.

The photovoltaic array changes solar energy to DC electricity, which is connected to the power grid through DC/DC and inverter.

According to **Figure 1**, we can establish electromagnetic transient model of photovoltaic system, which is introduced in the following text.

2.1. The Photovoltaic Cell Model

There are mainly two types of photovoltaic cell simulation model used in related literature [10]: the physical model and the behavior model. The physical model is based on the physical equivalent circuit of the cell, in which some semiconductor parameters such as photocurrent and PN coefficient are needed [1], which have no direct relationship with the characteristics of the cell, and are hard to obtain, therefore, the behavior model is often used in studies [11].

In practice, photovoltaic manufactures provide four parameters of the cell: I_{sc}, U_{oc}, I_m and U_m under standard environment, according to which we have the following characteristic of the cell:

$$I = I_{sc}^{'}\{1 - C_1[e^{U/(C_2 U_{OC})} - 1]\} \quad (1)$$

$$C_1 = \left(1 - I'_m / I'_{sc}\right) e^{-U_m^{'}/(C_2 U_{OC})} \quad (2)$$

$$C_2 = (U_m^{'}/U_{oc}^{'} - 1)[\ln(1 - I_m^{'}/I_{sc}^{'})]^{-1} \quad (3)$$

where,

$$I_{sc}^{'} = I_{sc}\Delta I, I_m^{'} = I_m \Delta I, U_{oc}^{'} = U_{oc}\Delta U, U_m^{'} = U_m \Delta U$$

$$\Delta I = [1 + \alpha\left(T - T_{ref}\right)]S / S_{ref}$$

$$\Delta U = [1 - \gamma\left(T - T_{ref}\right)]\ln[e + \beta(S - S_{ref})]$$

And, S_{ref} = 1000W/m^2, T_{ref} = 25℃is the standard environment, I_{sc}', U_{oc}', I_m' and U_m' are the parameters under different environments, α and γ is the temperature compensation coefficient, and β is the illumination compensation coefficient.

Take STP062-12/Sc for example, its I-U and P-U curve are shown in **Figure 2** and **Figure 3** under different illumination and the same temperature 25℃, from which we can see that they are both non-linear. The P-U curve has a maximum point under the same illumination and temperature, which is the maximum power point of the cell, and it changes with the illumination, temperature or load state. In order to obtain the maximum power, maximum power point tracking control must be used, called as MPPT.

2.2. MPPT Control

The I-U curve shows that the internal resistant of photovoltaic cell is time-varying, and MPPT is a process of dynamic load matching, which is usually achieved by the DC/DC circuit. When the maximum power point changes with the environment, the matched external resistant can be obtained by changing the duty cycle of the DC/DC circuit, thus when the external resistant equals the internal resistant, the maximum power of the cell can be obtained. In practice system, the Boost circuit is usually used as the DC/DC circuit.

The structure of MPPT controller is shown in **Figure 4**. The MPPT controller gives the reference voltage of the cell though real-time detection of the actual cell voltage, then the difference between the two voltages go through a PI regulator, and gives the carrier signal, which compares with the triangle wave and then gets the PWM signal. This process is a closed loop control of the photovoltaic cell voltage, through which the actual voltage meets the maximum power point voltage quickly, and then the maximum power of the photovoltaic array is obtained.

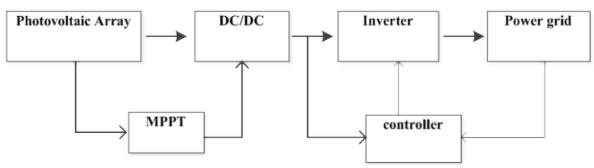

Figure 1. Structure of photovoltaic system.

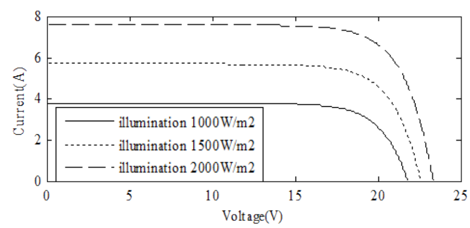

Figure 2. I-U curve.

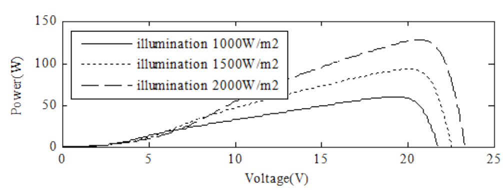

Figure 3. P-U curve.

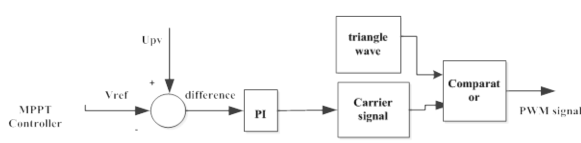

Figure 4. The structure of MPPT controller.

The core of the MPPT controller is MPPT arithmetic [12,13], such as perturbation and observation method, incremental conductance method and so on, which is not the focus of this paper, so we will not elaborate it here.

2.3. Grid-connected Inverter Control

The structure of three-phase grid-connected inverter is shown in **Figure 5**. The PQ decoupling control based on synchronous rotating frame is usually used, which includes inner current loop control and outer power loop control [14-16].

Under static abc frame, three-phase inverter can be modeled as follows:

$$\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{1}{L+R}\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} - \frac{1}{L+R}\begin{bmatrix} e_{ga} \\ e_{gb} \\ e_{gc} \end{bmatrix}. \tag{4}$$

where, i_a, i_b, i_c is the output current of the inverter, u_a, u_b, u_c is the output voltage of the inverter, e_{ga}, e_{gb}, e_{gc} is the grid voltage, L is the inductance and R is the equivalent resistant.

Equation (4) can be changed to synchronous rotating frame as:

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} 0 & \omega \\ -\omega & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{1}{L}\begin{bmatrix} u_d - e_{gd} - Ri_d \\ u_q - e_{gq} - Ri_q \end{bmatrix} \tag{5}$$

where, ω is the angular frequency of grid fundamental wave. If the grid voltage is ideal, the active and reactive power can be described as follows:

$$P = 3e_{gd}i_d / 2, Q = 3e_{gd}i_q / 2 \tag{6}$$

Equation (6) shows that PQ can be controlled independently. And equation (5) is the principle of current control [14,16].

3. The Electromechanical Transient Model

Now we have the electromagnetic transient model of one photovoltaic power system, while there are many sets of photovoltaic working together in an actual photovoltaic power station, which needs simulation at the same time. Because the power flow model is too simple to describe the dynamic process, and the electromagnetic transient model needs small simulation step and takes a long computation time because of its complexity, so none of them is suitable for dynamic process simulation of large scale photovoltaic system, therefore the study of an electromechanical transient model is of great meaning.

The following presents a general electromechanical transient model suitable for the simulation of large-scale power system. This model includes the photovoltaic array model, MPPT, DC/DC , the DC link, the inner and outer loop of inverter control. **Figure 6** shows the relationship of signal transfer between them.

The electromechanical transient model is based on mathematical calculations, with no electric elements and no high frequency switching device. Compared with the electromagnetic transient model, MPPT control, DC/DC and the inverter are replaced by pure mathematical models, while the photovoltaic cell model remains the same. These modules will be discussed later.

3.1. The MPPT Model

The main purpose of MPPT module is to achieve real-time tracking of the maximum power point voltage, through which the photovoltaic output voltage is a first order lag of the reference voltage. Although different controller has different pure lag time constant τ and first order time constant T, its effect can be described by the following equation:

$$V_{pv} = \frac{e^{-\tau s}}{1+Ts}V_{pvm} + \Delta V_{pvm} \tag{7}$$

where, V_{pv} is the real voltage of photovoltaic, V_{pvm} is the reference voltage, and ΔV_{pvm} is the tracking error.

3.2. DC/DC Module

Take Boost circuit for example, DC/DC mainly raises the voltage and transmits the power. In electromagnetic transient model, the Boost circuit helps achieve the MPPT, while not in electromechanical transient model. DC/DC module can be described by the following equation:

$$\begin{cases} P_{out} = f_1(P_{in}) = P_{in}\eta \\ V_{out} = f_2(V_{in}, D) = V_{in} / (1-D) \end{cases} \tag{8}$$

where, η is the efficiency of DC/DC, and D is the duty cycle.

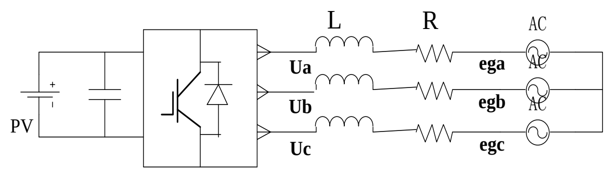

Figure 5. Structure of three-phase grid-connected inverter.

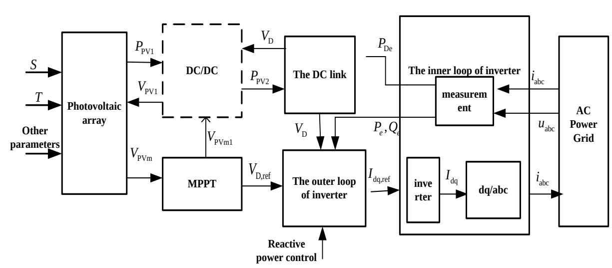

Figure 6. Signal transfer of electromechanical transient model.

3.3. The DC Link

The DC link connects the DC side and the AC side, and the DC bus voltage stability is a prerequisite to ensure the normal work of the inverter, which needs much attention while establishing the electromechanical transient model.

The DC link module can be described as follows:

$$\begin{cases} \dfrac{dE_C}{dt} = P_{\mathrm{PV2}} - P_{\mathrm{De}} \\ E_C = 1/2CV_D^2 \end{cases} \tag{9}$$

where, P_{PV2} is the DC side input power, P_{De} is the AC side input power, C is the capacitance of DC link, V_D is the voltage of the DC link, and E_C is the energy of the capacity.

3.4. The Outer Loop of Inverter Control

The outer loop of inverter control is power control, realizing the PQ decoupling control. The difference between the actual value and reference value of the DC link voltage, through a PI regulator, output the d axis current reference value, which forms the closed loop control of DC bus voltage. The difference between the actual value and reference value of the reactive power, through a PI regulator, output the q axis current reference value, which forms the closed loop control of the grid reactive power.

The transfer function of the outer loop is as follows:

$$\begin{cases} I_{d,\mathrm{ref}}^1 = \dfrac{B_{d2}s^2 + B_{d1}s + B_{d0}}{A_{d2}s^2 + A_{d1}s + A_{d0}}\left(V_{\mathrm{D,ref}} - V_{\mathrm{D}}\right) \\ I_{d,\mathrm{ref}} = \mathrm{Sat}\left(I_{d,\mathrm{ref}}^1, I_{d,\max}, I_{d,\min}\right) \end{cases} \tag{10}$$

$$\begin{cases} I_{q,\mathrm{ref}}^1 = \dfrac{B_{q2}s^2 + B_{q1}s + B_{q0}}{A_{q2}s^2 + A_{q1}s + A_{q0}}\left(Q_{\mathrm{ref}}^{'} - Q_{\mathrm{e}}\right) \\ I_{q,\mathrm{ref}} = \mathrm{Sat}\left(I_{q,\mathrm{ref}}^1, I_{q,\max}, I_{q,\min}\right) \end{cases} \tag{11}$$

where,

1) $\mathrm{Sat}\left(x, x_{\max}, x_{\min}\right)$ is saturation function, as follows:

$$\mathrm{Sat}\left(x, x_{\max}, x_{\min}\right) = \begin{cases} x_{\max} & x > x_{\max} \\ x_{\min} & x < x_{\min} \\ x & x_{\min} \le x \le x_{\max} \end{cases}$$

2) $I_{d,\max}$, $I_{d,\min}$, $I_{q,\max}$, $I_{q,\min}$ can be decided by the model parameters, or deduced only by $I_{\max}$, as follows:

$$\begin{cases} I_{d,\max} = I_{\max} \\ I_{d,\min} = -I_{\max} \end{cases} \begin{cases} I_{q,\max} = \sqrt{I_{\max}^2 - I_{d,\mathrm{ref}}} \\ I_{q,\min} = -I_{q,\max} \end{cases}.$$

3) A_{d2}, A_{d1}, A_{d0}, B_{d2}, B_{d1}, B_{d0}, A_{q2}, A_{q1}, A_{q0}, B_{q2}, B_{q1}, B_{q0} are control parameters.

3.5. The Inner Loop of Inverter Control

The inner loop of inverter control is current control, through which the actual current tracks the reference current, thus the active and reactive power meets the demands. The following gives the derivation of its transfer function.

Equation (5) can be written as follows:

$$\begin{cases} e_{gd} = u_d - \left(L\dfrac{di_d}{dt} + Ri_d\right) + L\omega i_q \\ e_{gq} = u_q - \left(L\dfrac{di_q}{dt} + Ri_q\right) - L\omega i_d \end{cases} \tag{12}$$

Through the Laplace transform, we have

$$\begin{bmatrix} e_{gd} \\ e_{gq} \end{bmatrix} - \begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} -\left(Ls+R\right) & \omega L \\ -\omega L & -\left(Ls+R\right) \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{13}$$

Through the PI regulator, the output voltage of inverter is:

$$\begin{cases} e_{gd,ref} = u_d + \left(K_{1p} + \dfrac{K_{1i}}{s}\right)\left(i_{d,ref} - i_d\right) + L\omega i_q \\ e_{gq} = u_q + \left(K_{2p} + \dfrac{K_{2i}}{s}\right)\left(i_{q,ref} - i_q\right) - L\omega i_d \end{cases} \tag{14}$$

In matrix form, as follows:

$$\begin{aligned} &\begin{bmatrix} e_{gd} \\ e_{gq} \end{bmatrix} - \begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} -PI_1(s) & \omega L \\ -\omega L & -PI_2(s) \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \\ &+ \begin{bmatrix} PI_1(s) & 0 \\ 0 & PI_2(s) \end{bmatrix} \begin{bmatrix} i_{d,ref} \\ i_{q,ref} \end{bmatrix} \end{aligned} \tag{15}$$

Compare Equation (13) and (15), we have:

$$\begin{aligned} &\begin{bmatrix} -\left(Ls+R\right)+PI_1(s) & 0 \\ 0 & -\left(Ls+R\right)+PI_2(s) \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \\ &= \begin{bmatrix} PI_1(s) & 0 \\ 0 & PI_2(s) \end{bmatrix} \begin{bmatrix} i_{d,ref} \\ i_{q,ref} \end{bmatrix} \end{aligned}$$

That is:

$$\begin{cases} i_d = \dfrac{PI_1(s)}{-\left(Ls+R\right)+PI_1(s)} i_{d,ref} \\ i_q = \dfrac{PI_2(s)}{-\left(Ls+R\right)+PI_2(s)} i_{q,ref} \end{cases} \tag{16}$$

In a general form:

$$\begin{cases} i_d = \dfrac{b_{d2}s^2 + b_{d1}s + b_{d0}}{a_{d2}s^2 + a_{d1}s + a_{d0}} i_{d,ref} \\ i_q = \dfrac{b_{q2}s^2 + b_{q1}s + b_{q0}}{a_{q2}s^2 + a_{q1}s + a_{q0}} i_{q,ref} \end{cases} \tag{17}$$

Equation (17) is the transfer function of the inner current loop, which includes dq/abc transformation, the phase-lock loop and so on. The AC power can be obtained by measurement and dq/abc transformation and the phase-lock loop is the same as that in the electromagnetic transient model.

4. Simulation Results

The electromagnetic transient model and electromechanical transient model are established in PSCAD/EMTDC. Take STP062-12/Sc poly-silicon for example, its parameters are as follows: $U_m = 17.4$ V, $I_m = 3.56$ A, $U_{oc} = 21.8$ V, $I_{sc} = 3.78$ A, $P_m = 62$ W. In the simulation model, we use 4 cells in series 3 cells in parallel in a module, and 10 modules in series 6 modules in parallel in an array, thus the maximum power of photovoltaic array is 44.6 kW in the standard environment. The MPPT control uses perturbation and observation method.

For both models, the simulation time is 10 s and step is 50 us. When system simulation achieves a steady state, raise the illumination intensity from 800 W/m^2 to 1500 W/m^2, and observe the active power and some other electrical quantities. The following are two conditions according to different reactive power reference.

1) The reactive power reference is 0, which means the power factor of the grid is 1.

It takes 13.5 s to finish the simulation for electromagnetic model, while just 4.3 s for electromechanical model. **Figure 7** to **Figure 12** show some curves when the reactive power reference is 0. **Figure 12** shows that the current and the voltage has the same phase, which means that the power factor of the grid is 1, meeting the control goal. From **Figure 7**, **Figure 9**, **Figure 10**, we can see that the photovoltaic power, the active and reactive power of the grid increase after the illumination density increases. In addition, **Figure 7** to **Figure 11** show that the simulations results of two models are almost the same,

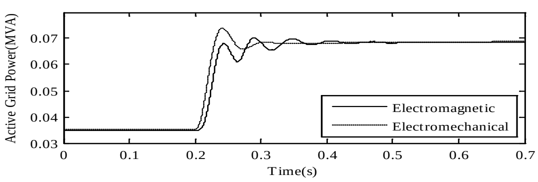

Figure 7. Active power of grid.

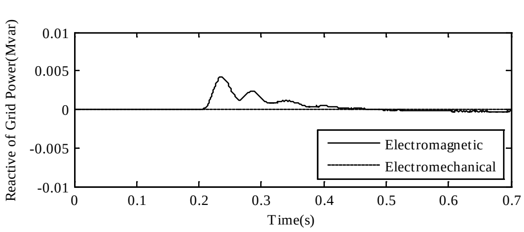

Figure 8. Reactive power of grid.

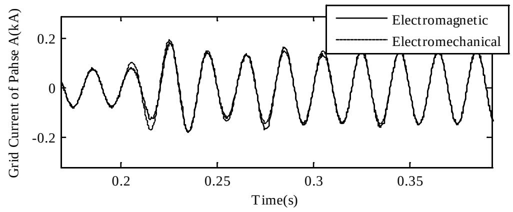

Figure 9. current of phase A.

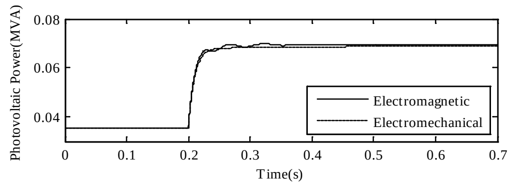

Figure 10. Photovoltaic power.

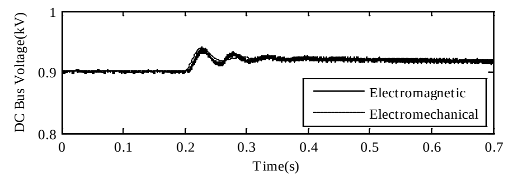

Figure 11. The DC bus voltage.

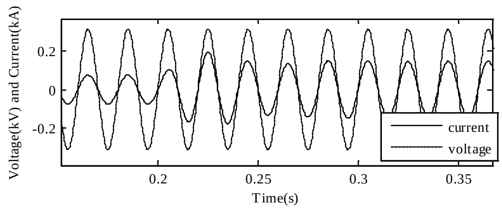

Figure 12. voltage and current of phase A.

which means that the electromechanical transient model is valid and reasonable.

2) The reactive power reference is 0.03 Mvar.

It takes 12.8 s to finish the simulation for electromagnetic model, while just 4.1 s for electromechanical model. The photovoltaic power, the active power of the grid and the DC bus voltage of condition 2) are similar to condition 1). **Figure 13** shows the reactive power of the grid, and **Figure 14** shows the current and voltage, between which the phase is not the same but has an angle, meaning that the grid power factor is not 1.

5. Conclusions

In this paper, a general electromechanical transient model of grid-connected photovoltaic power generator is proposed, and both electromagnetic and electromechanical transient models are established in PSCAD. By comparing simulation results of the grid active and reactive power, the grid current, the photovoltaic power and the DC bus voltage of two models, the correctness and validity

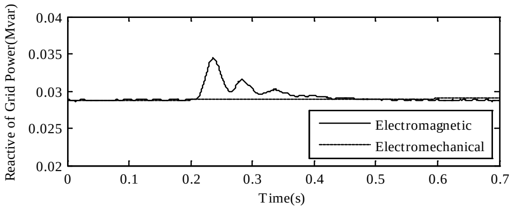

Figure 13. reactive power of the grid.

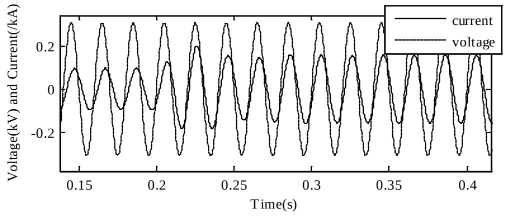

Figure 14. voltage and current of phase A.

of the electromechanical transient model is verified, which provides reference model for simulation and modeling of large scale grid-connected photovoltaic power station.

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