Complete Models of Transmission-connected Photovoltaic Plant Using Modularity Principle for Power System Small Signal Stability Study

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This paper adopts the modularity principle to completely model the transmission-connected photovoltaic plant. With more and more power electronics being integrated into the power system, modeling based on the modularity principle will increase the generality of the model of each module, for example, allowing the power electronic module for the PV plant to be used in other elements such as the wind plant. Moreover, we still lack complete PV plant models that express all components of the PV plant, such as changing irradiance, common control modes, and even the signal transmission model. The objective of this paper is to solve these problems. An overall structure using the modularity principle to model the PV plant is provided. Then each module is described, which is followed by the algorithm that how all modules work in conjunction. Finally, applications of the provided models in the power system small signal stability study are presented, where the characteristics of the PV plant can be closely simulated. A 2-area 4-machine system is used to test the applications of the models.

Keywords: large transmission-connected PV plant, modularized modeling, complete small signal model, small signal stability

1. Introduction

In order to prevent energy crisis and the detrimental environment effect, the penetration of photovoltaic plants is rising quickly to build a low-carbon, high-efficiency energy system (5). Besides, supporting as the substitutable energy at present and even being the main energy in the future, the large photovoltaic plants are also affecting the small signal stability of large connected power systems (2)–(4). Thus it is necessary to model the transmission-connected photovoltaic plants.

The power system is enjoying huge developments like, renewable energy resources, energy storage system, MT-HVDC, HVAC, etc. The power system is becoming more and more power electronics dominated. Given that these elements contain similar power electronics, element-oriented modeling is a waste of time due to repeated modeling (5)–(6). As a result, the modularized modeling method can be adopted to get rid of this problem. Using this method, the modules used in PV plant models can also serve for other power system elements.

The electric cyber-physical system is helpful to build a smart grid by using cyber-system-based intelligence to maintain correct, and to detect and react to faults and attacks (7)–(8). Under this circumstance, some control signals may come from the cyber system. As a result, network induced problems may occur such as the time delay, the packet losing and so on (9)–(10). So, in order to meet the needs of the future smart grid, the module of the signal transmission is necessary while modeling the PV plant.

As the main form of the most abundant clean energy—solar energy (11), though a large-scale PV plant can generate more than 20 MW (12), there are still no standard PV plant models (13). With the excellent efforts of the Western Electric Coordinating Council (WECC), generic PV system models are developed based on the Type 4 wind turbine generator (WTG) model (14)–(17). The proposed PV system models describe the PV system as an inverter-based equivalent generator with three active power control modes and eight reactive power control modes. Some simplifications are made for the above models. The models contain the dynamics related to the AC side of the inverter and the PV arrays and boost are ignored—this is from a grid perspective looking at the electric response and neglecting any of the effects of the energy source. In addition, the inner loop current control of the PV inverter is simplified.

This paper intends to use modularized method to build complete small signal models for transmission-connected PV plants which contain control signal transmission module.

The provided models completely describe the PV plant. Both one-stage and two-stage PV plant are considered. And components at both DC-side and AC-side of the PV inverter are expressed. At DC-side, the PV array, the DC/DC boost and its control modes (for two-stage PV system only), and the DC link are modeled. At the AC side, the filter, the phase lock loop (PLL), the inverter and its control are considered. The inverter control contains the current control loop and the voltage control loop adopting different control modes. Besides, a signal transmission module is optional for any control reference in any control mode.

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Because of modularity, the one-stage and two-stage PV plant models can share models of the same modules. Moreover, these modules can also been used in models of other elements in power system.

As complete small signal PV models, the linearization model and state matrix of the whole power system are available by integrating the PV models into traditional modal analysis program. Then based on the results of the power system modal analysis, we can make many researches including but are not limited to the followings. Firstly, the impact of every part of the PV plant can be revealed due to the complete PV models. This is useful since all parts of PV plants affect the small signal stability and the part affect most attracts attention. Secondly, randomness of the PV output, as the most special characteristic of PV plants, can be studied in the analysis, assessment and control of power system stability. Because the provided maximum power point tracking (MPPT) control mode reflects the fluctuant PV output as affected by stochastic irradiance and temperature.

This paper is organized in the following manner. Section 2 details overall structure adopting modularity, with contents in each module available in Section 3. In Section 4, some applications of the PV models are shown. Section 5 tests contents of this paper and Section 6 concludes the whole paper.

2. Overall Modularized Structure

2.1 PV Plant Structure The main task of building the small signal models of PV plants is to model the equivalent PV power generation process by because the collector system is available. As for the PV power generation process, there are two possible circuits, namely the one-stage PV plant and the two-stage PV plant shown in Fig. 1. The difference is whether the PV plant contains the boost or not. And the other parts of the two circuits are the same and share the same control methods. So, the modularity is very helpful to reduce the modeling efforts.

2.2 Overall Modularized PV Plant Structure The overall structure adopting modularity is given in Fig. 2 with the connections among different modules. This structure uses as many same modules as possible to describe the one-stage and two stage PV plants. Inputs of Fig. 2 are only necessary external factors. One is the the weather factor at the PV plants denoted as “Wea”, and the other is control reference value for a better power system performance denoted as “Ref”. Once these inputs are known, the PV plant model based on Fig. 2 can simulated independently.

3. Realization of the Overall Structure

The goal of the overall structure realization is to obtain the state matrixes used in the small signal stability studies. So the overall structure should be realized by using mathematical algebraic differential equations which obey the rules of the modal analysis program and the transient stability simulation program.

In the following, the algebraic differential model of each module is illustrated and followed by the method that makes all modules run coordinately.

When describing modules, they are arranged according to their categories. Firstly modules for large hardware-based circuits are given, such as the PV arrays. Secondly, modules for possible control methods in PV plants are shown such as the boost control.

As for each module, its physical or logical structure is contained in the green box inside which parameters are known. According to the physical or logical structure, one can derive its algebraic differential model where algebraic and state variables can be initialized and updated as long as input variables are given. As state variables are shared among all modules, input variables are only algebraic variables from the other modules.

3.1 Modules for Circuits

1) PV Array Module

The PV arrays module adopts the engineering analytical model shown in Fig. 3 to get rid of complexity. This model reasonably assume that four parameters are known, namely the short-circuit current (I_{SCref}), the open-circuit voltage (U_{OCref}), the maximum power point current (I_{MPref}), and the maximum power point voltage (U_{MPref}) of PV modules in standard test conditions (irradiance 1 kW/m² and temperature 25°C). Thus only two variables (the air irradiance S and air temperature T_{air}) are needed to obtain the current-voltage relationship of PV arrays in non-standard test conditions expressed as

\[
I_{PV}/n_p = I_{SC} \left[ 1 - C_1 \left( e^{U_{PV}/n_i/C_2 U_{OC}} - 1 \right) \right] \ldots (1)
\]

where \(I_{PV}\) and \(U_{PV}\) are the current and voltage of the PV array, \(n_p\) and \(n_i\) are the numbers of PV modules in parallel and in series in PV arrays, \(C_1, C_2, I_{SC}\) and \(U_{OC}\) are parameters.
that can be computed by using (12) that is needed to solve the two stage variables. As

differentiation of PV plants (denoted as UPV) and connects the boost in the two-stage PV
ferential model. As DC link connects PV arrays in the one-stage PV plant, the voltage of the PV array is also the DC
voltage of the inverter (denoted as UPV). The flag “SFlag” is used to handle this interface. It will switch to “S1” for the one-stage PV plant and “S2” for the two-stage PV plant.

This module simulates the current-voltage characteristics of the PV array that varies with S and Tair, and provides the maximum power point UPV of PV arrays and IPV.

2) Boost Module

The boost circuit structure is shown in Fig. 4. It can be models by two differential equations for there are two energy storage components CPV and LB. Three input variables are needed to solve the two stage variables UPV and IPV, namely IPV, the duty ratio of the boost D, and the DC voltage of the inverter UPDC.

3) DC Link Module

The DC link module structure is shown in Fig. 5. Similarly, one differential equation is needed to build its algebraic differential model. As DC link connects PV arrays in the one-stage PV plant and connects the boost in the two-stage PV plant, IPN equals D’IPB in the two-stage PV plant and equals IPV in the one-stage PV plant. The flag “SFlag” is also used to handle this interface with the same settings. The power balance relationship is important in connecting models in the DC and AC sides of the inverter.

4) Inverter Module

As small signal models, the fast process of the inverter can be ignored. And the output voltage of the inverter can be assumed to be the same as the input voltage reference as shown in Fig. 6.

5) Filter Module

The structure of the filter module is shown in Fig. 7. And its model is usually built in the dq frame by two differential equations, where ω is the power frequency and the dq frame is provided by the phase-locked loop module.

6) Signal Transmission Module

The structure of the signal transmission module is shown in Fig. 8. This module can be used to represent the non-ideal problems in the communication system including time delay, packet loss, multiple-packet transmission, networked jitter, packets disorder and so on. The signals as a frame as shown in Fig. 9. Also it will obtain the frequency of the voltage at the point of connection (VPV) by matching the phase and frequency of Vg and the q axis.

3.2 Modules for Control

1) Phase-Locked Loop Module

The phase locked loop module (Fig. 10) can build the dq frame as shown in Fig. 9. Also it will obtain the frequency ωPLL and the angle θPLL of the voltage at the point of connection of PV plants (denoted as VPV) by matching the phase and frequency of Vp and the q axis.

The phase-locked loop module structure is shown in Fig. 10. The control block diagram like Fig. 10 can be expressed by the algebraic differential equations, where the number of differential equations equals the number of differential blocks. And the algebraic equations can be derived by the algebraic operation of the control block diagram. For
example, Fig. 9 can be equally described by two differential equations and one algebraic equation as shown in Fig. 10.

Note that in this section, modules for control only consist of control block diagrams which can be easily described by algebraic differential equations equally. So the algebraic differential models in this section will not be shown hereafter to make paper concise.

2) Boost Control Module

The boost control module structure is shown in Fig. 11 and only used in two-stage PV plant. Two control modes are included, namely the maximum power point tracking and the constant active power control. They are switched by using different flags. “BFlag” will switch to “BF1” for maximum power tracking control and to “BF2” for constant power tracking control.

3) Inverter Control

A) Current Control Loop Module

The inverter control contains a current control module and a voltage control module. The current control loop module structure is shown in Fig. 12. It is used to compute the inverter output voltage references $u_q$ and $u_d$ which can generate the PWM pulse.

B) Voltage Control Loop Module

The voltage control loop module structure is shown in Fig. 13. It produces the current reference $i_q^*$ and $i_d^*$ for the current control loop module. This module offers two active power control modes and nine reactive power control modes for both one-stage and two-stage PV plants by using different flags (Table 1 and 2). In Table 2, “Q” means the reactive power, “PF” means the power factor, “V” means the voltage, and “/” means and.

3.3 Collaborative Simulation of All Modules

1) Form the Overall Structure for PV plants

As input and output variables of each module are listed, we can easily connect these modules to form the overall structure as shown in Fig. 14 which models the one-stage and two-stage PV plants at the same time. All modules except the
Table 1. Flags for current references in $q$ frame

<table>
<thead>
<tr>
<th>Control Modes</th>
<th>Categories</th>
<th>$i$ of $P$</th>
<th>$i$ of Udc</th>
<th>$i$ of $Ppv$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power</td>
<td>One-Stage</td>
<td>On</td>
<td>Off</td>
<td>On</td>
</tr>
<tr>
<td>Tracking Control</td>
<td>Two-Stage</td>
<td>Off</td>
<td>On</td>
<td>Off</td>
</tr>
<tr>
<td>Power Control</td>
<td>One-Stage</td>
<td>On</td>
<td>Off</td>
<td>On</td>
</tr>
</tbody>
</table>

Table 2. Flags for current references in $d$ frame for both one-stage and two-stage PV plant

<table>
<thead>
<tr>
<th>No</th>
<th>Control Mode</th>
<th>Flag 1</th>
<th>Flag 2</th>
<th>Flag 3</th>
<th>Flag 4</th>
<th>Flag 5</th>
<th>Flag 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Local Q</td>
<td>--</td>
<td>F22</td>
<td>F31</td>
<td>F41</td>
<td>--</td>
<td>F61</td>
</tr>
<tr>
<td>2</td>
<td>Local PF</td>
<td>--</td>
<td>F22</td>
<td>F32</td>
<td>F41</td>
<td>--</td>
<td>F61</td>
</tr>
<tr>
<td>3</td>
<td>Local Q+Local V</td>
<td>--</td>
<td>F22</td>
<td>F32</td>
<td>F42</td>
<td>F51</td>
<td>F62</td>
</tr>
<tr>
<td>4</td>
<td>Local PF+Local V</td>
<td>--</td>
<td>F22</td>
<td>F32</td>
<td>F42</td>
<td>F51</td>
<td>F62</td>
</tr>
<tr>
<td>5</td>
<td>Local Q</td>
<td>--</td>
<td>--</td>
<td>F22</td>
<td>F42</td>
<td>F51</td>
<td>F62</td>
</tr>
<tr>
<td>6</td>
<td>Plant Level Q/V</td>
<td>F11</td>
<td>F21</td>
<td>F31</td>
<td>F41</td>
<td>--</td>
<td>F61</td>
</tr>
<tr>
<td>7</td>
<td>Plant Level Q</td>
<td>F21</td>
<td>F21</td>
<td>F31</td>
<td>F42</td>
<td>F51</td>
<td>F62</td>
</tr>
<tr>
<td>8</td>
<td>Plant Level V</td>
<td>F11</td>
<td>F21</td>
<td>F31</td>
<td>F41</td>
<td>--</td>
<td>F61</td>
</tr>
<tr>
<td>9</td>
<td>Plant Level Q</td>
<td>F12</td>
<td>F21</td>
<td>F31</td>
<td>F41</td>
<td>--</td>
<td>F61</td>
</tr>
</tbody>
</table>

Fig. 14. The overall structure formed by the provided modules

Fig. 15. The flow chart of updating modules used in PV plants

4. Applications

The modularized complete PV plant small signal models have been illustrated totally. By using the modal analysis and transient simulation programs, applications of the provided PV plant models include but are not limited to the three applications in the small signal stability study listed below.

4.1 Modal Analysis

The state, input and output matrices $A$, $B$, $C$ of the power system with PV plant integrated can be obtained by using the modal analysis and transient simulation programs in Section 3.3 as expressed by

\[ \dot{x}(t) = Ax(t) + Bu(t) \]

\[ y(t) = Cx(t) \]

Then the modal analysis can be carried out. In addition, if the modal analysis is applied to power systems with different PV plant parameters, the impact of the PV plant parameters will be revealed to be beneficial or detrimental.

4.2 Stability Assessment

The stability assessment of the power system is important due to the plenty uncertain parameters such as the PV irradiance. The basic method is the Monte Carlo simulation. By a large number of the modal analysis on the system (2), the probability of stability will be obtained.

4.3 Stability Control

Many methods such as PSS are available to ensure the stability of the power system. In this paper, a robust control method is adopted as an example to test the potential ability of the PV plant to stabilize the power system.

There exists Theorem 1 for the system (2) with a $\tau$-second delayed state feedback controller

\[ u(t) = Kx(t - \tau) \]

Then Theorem 1 can be applied to

\[ \dot{x}(t) = Ax(t) + Bu(t) \]

\[ y(t) = Cx(t) \]

Then the modal analysis can be carried out. In addition, if the modal analysis is applied to power systems with different PV plant parameters, the impact of the PV plant parameters will be revealed to be beneficial or detrimental.
Because of the existence of the nonlinear element $-dP Z^{-1} P$, (4) is nonconvex. It can be solved by formulating as a cone complementarity problem expressed by

$$\begin{equation}
\min \ tr(UZ + PV + TS) \\
subject to \\
\begin{bmatrix}
AP + PA + Y^T+Q - BL - Y + W^T - dY - dPA^T \\
- Q - W - W^T - dW - dL^T B^T \\
* - dPZ^{-1} P \\
* - dT 0 \\
* - dZ
\end{bmatrix} < 0
\end{equation}
$$

(4)

If the input $u(t)$ in the system (2) will be added to the reactive current reference of the PV plant, a PV supplementary damping controller will be obtained by solving (5) given by Theorem 1.

5. Case Studies

In this section, the correctness of the provided PV models is verified. Then the application of the PV models is shown in the power system small-signal stability analysis and assessment.

The provided modularized PV plant models are integrated into the modal analysis and transient simulation in MATLAB on a PC with an Intel Core i5-4590 CPU, 3.3-GHz processor, 8 GB of RAM. A modified two-area four-machine system (Fig. 16) is adopted as the test system with a PV system at Bus 6 modeled by the provided method.

5.1 Verifying the Computer Program

The program has been verified to be right by the consistency between the modal analysis and the transient analysis. We will take the PV system adopting the maximum power point tracking mode and the local unity power factor mode as an example to explain the process of verification.

In Fig. 16, the irradiance for the PV system is set as 1015 W/m², and Load 7 and Load 9 are 967 MW and 1767 MW, respectively. The result of the modal analysis is shown in Table 3. Then the transient analysis is implemented. A small disturb is designed for this analysis. The voltage reference of the excitation system in G2 is modified from 1.0 to 1.05 from 1.0 s to 1.2 s. As a transient response, Fig. 17 shows the rotor angle of G1 with reference to the rotor angle of G4 in a time range of 8 seconds. Then the Prony identification method is applied to this curve and the identified dominated modes are shown in Table 4. The comparison of Tables 3 and 4 will draw the conclusion that the modal analysis and the transient analysis produce the consistent result so that the program of modal analysis and transient analysis is correct.

5.2 Applications of the Provided PV Plant Models

This section will show three applications of provided PV system models, namely, the analysis, the assessment and the control of the small-signal stability for the PV-integrated power system.

We will firstly show the application in PV-considered small-signal stability analysis. In addition to the ability of obtaining the oscillation modes of a PV-integrated power system (verified by results in Table 3), the root loci of the critical modes as affected by parameters of the PV models are also available. For example, Fig. 18 shows the root loci of Mode 3 as affected by the increasing irradiance where the PV system in Fig. 16 adopts the MPPT mode and Local PF mode (unity power factor). It can be seen that the root loci will clearly show the impact of the PV parameter.

Secondly, we will show the application in the stability assessment of PV-considered power system. Three random variables (Table 5) are considered in the test system (Fig. 16), namely, the fluctuant PV generation at Bus 6, the random Load 7 (1st load), and the random Load 9 (2nd load). The reactive power of Load 7 and 9 varies with active power to keep the power factor constant. Correlations can be assumed stationary and set according to their geographical positions.

The cumulative distribution function (CDF) of the critical damping ratio (Mode 3) is solved by Monte Carlo simulation (MCS) and shown in Fig. 19. Thus the probability of the

$$\begin{array}{|c|c|c|c|}
\hline
\text{No.} & \text{Frequency (Hz)} & \text{Damping} & \text{ Dominated generators} \\
\hline
1 & 1.0508 & 0.1393 & G1 \leftrightarrow G2 \\
2 & 1.1013 & 0.1145 & G3 \leftrightarrow G4 \\
3 & 0.6082 & -0.0003 & G1, G2 \leftrightarrow G3, G4 \\
\hline
\end{array}$$

Fig. 16. The two-area four-machine system with a PV plant

Fig. 17. The rotor speed of G1 with reference to that of G4

Table 4. The identified dominated modes

<table>
<thead>
<tr>
<th>No.</th>
<th>Frequency (Hz)</th>
<th>Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0507077</td>
<td>0.140815</td>
</tr>
<tr>
<td>2</td>
<td>1.113395</td>
<td>0.105340</td>
</tr>
<tr>
<td>3</td>
<td>0.606962</td>
<td>-0.000207</td>
</tr>
</tbody>
</table>
6. Conclusions

An overall structure using modularity principle to model the PV plant is provided. The contents of each module are then illustrated, along with how all modules work coordinately. Moreover, the applications of the provided models are also studied. The provided PV plant models have many merits.

1) The modularity principle adopted can save time and efforts by simplifying the modeling task (the module is plug-and-play) and will expand the scope of applications of the modules.

2) The provide PV plant models is a full and detailed model which even contains the signal transmission module.

3) The provided PV plant model can be applied in modal analysis, the stability assessment, and the design of PV supplementary damping controller with the signal transmission module considered.

small-signal instability is 53%.

Thirdly, the application in small signal stability control is verified. The unstable 4-machine 2-area power system in Section 5.1 is adopted as the test system here. Theorem 1 is verified. The unstable 4-machine 2-area power system in small-signal instability is 53%.

Table 5. Distributions of three random variables

<table>
<thead>
<tr>
<th>Irradiance (W/m²)</th>
<th>Distribution</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beta</td>
<td>1015</td>
<td>220</td>
</tr>
<tr>
<td>Load 7 (MW)</td>
<td>Normal</td>
<td>967</td>
<td>96.7</td>
</tr>
<tr>
<td>Load 9 (MW)</td>
<td>Normal</td>
<td>1767</td>
<td>176.7</td>
</tr>
</tbody>
</table>

Fig. 18. The root loci of Mode 3 as affected by irradiance

Fig. 19. The CDF of the damping ratio of Mode 3

Fig. 20. The rotor speed of G1 with reference to that of G4

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