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Power Quality Pre-evaluation Method of PV Power Station Considering Its Output Elements

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Power Quality Pre-evaluation Method of PV Power Station Considering Its Output Elements

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Abstract. At present, the studies of power quality pre-evaluation of PV power station mainly focus on the internal mechanism modeling of PV power generation units, which makes the modeling and calculation process complex. Aiming at the situation mentioned above, this paper presents a power quality pre-evaluation method of PV power station considering its output elements. First of all, the paper establishes an equivalent model of PV power generation unit by taking the light intensity and temperature as the input, and the steady output current and voltage as output. Secondly, a power source model and a harmonic source model are paralleled to establish an equivalent model of single PV power generation unit in the working conditions. Then, the equivalent model of a grid-connected PV power station in Guangdong Province is built on the PSCAD/EMTDC. Finally the paper makes a detailed power quality pre-evaluation of the PV power station and verifies the practicality of this method.

1. Introduction

The power quality problems caused by PV power stations are becoming more and more obvious within a large number of grid-connected PV units are put into use [1]. Therefore, a power quality pre-evaluation is necessary before a PV power station is connected to the grid. It is of great value to study how to analyze the power quality problems generated by grid-connected PV power stations effectively and simply.

The current researches mainly focus on the detailed modeling of the internal structure of a single PV power generation unit: In [2-4], PV cells, boost circuit, inverter circuit, MPPT and phase-locked loop are modeled respectively. A dynamic model of PV power station based on differential equations and algebraic equations are proposed in [5-6]. In [7]. An improved sliding mode is proposed to track the maximum power point of PV arrays under partial shading by using a piecewise function. In [8], an equivalent model of PV power generation unit considering parameter aggregation is proposed, whose dominant dynamic characteristics are consistent with that of the original unit when being disturbed. It can be seen that many calculation steps and control strategies are taken into account during the current researches, leading to a complex modeling process and calculation, which are not suitable for the power quality pre-evaluation of a PV power station which contains a large number of PV power generation units.

The voltage, output current, active power and reactive power of PV power station are the focus to the power supply. Therefore, this paper proposes a power quality pre-evaluation method of PV power station considering its output elements. Firstly, the relationship between the output and input elements

of PV power generation unit is studied, and the equivalent power model of PV power generation unit is established. Secondly, harmonic components are used to characterize the harmonic characteristics of PV power generation unit, and a single PV power generation unit in the working conditions is matched by a paralleled model of a power source and a harmonic source. Finally, a PV power station is taken as the study case, whose power quality evaluation model is established in the PSCAD/EMTDC, and its power quality pre-evaluation is carried out to verify the practicability and effectiveness of the proposed method.

2. Equivalent model of PV power generation unit

2.1. Analysis of output elements of PV power generation unit

The output elements of PV power generation unit mainly include the active power, reactive power, voltage and output current. The light intensity and battery temperature are usually taken into account when calculating these elements in the current researches. In this paper, a model is established to simulate the voltage-current characteristics of PV power generation unit by using the technical parameters provided by the manufacturer (V_m, I_m) only.

When a PV power generation unit works at the maximum power point, its voltage and output current can be written as:

$$V_m^{'} = V_m \cdot \ln(e + b\Delta S) \cdot (1 - c\Delta T) \tag{1}$$

$$I_m^{'} = I_m \cdot \frac{S}{S_{ref}}(1 + \lambda\Delta T) \tag{2}$$

Where $\Delta S = S - S_{ref}$, $\Delta T = T - T_{ref}$, S and T are light intensity and battery temperature, respectively. S_{ref} and T_{ref} are the reference value of light intensity and battery temperature respectively. V_m and I_m are the Maximum output current and voltage of PV power generation unit, whose values are provided by the manufacturer. λ, b and c are constant compensation coefficients, whose typical recommended values are $\lambda = 0.0025(℃)^{-1}$, $b = 0.0005(\text{W/m}^2)$, $c = 0.00288(℃)^{-1}$. e refers to the base of natural logarithms.

A PV power generation unit relies on MPPT to ensure maximum output power continuously. So the maximum output power at any light intensity and battery temperature can be obtained based on (1) and (2):

$$P_m^{'} = \frac{P_0 S}{S_{ref}}(1 - c\Delta T)(1 + \lambda\Delta T)\ln(e + b\Delta S) \tag{3}$$

Where $P_0 = V_m I_m$.

2.2. Analysis of grid-connected PV power generation unit

A distribution network with a PV power generation unit is shown in Fig.1, where Z_S and Z_{PV} refer to the equivalent impedance of the power grid and filter circuit of PV power generation unit respectively. Z_{L1} and Z_{L2} are the line impedance of the front and rear line of PCC. E_S is the equipotential potential of the power grid.
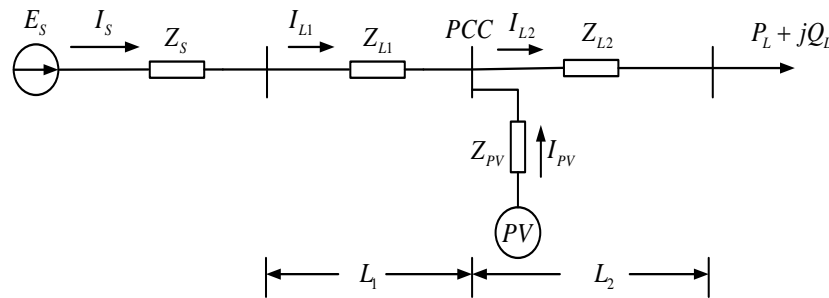
Figure 1. A distribution network with a PV power generation unit

After the PV power generation unit is connected to the grid, its total power is equal to the sum of output power, loss of line and components:

$$P_m^{'} = \frac{3}{2}I_{PV}^2 R_{PV} + \frac{3}{2}I_{PV}U_{PCC} + \Delta P \qquad (4)$$

Where I_{PV} and R_{PV} refers to the output current and equivalent resistance of filter circuit of PV power generation unit. U_{PCC} is the voltage amplitude at PCC. ΔP is the loss of components, whose value is small that can be ignored. The steady-state voltage (U_{PV}) and output current (I_{PV}) of PV power generation unit can be obtained according to (3)-(4):

$$\dot{U}_{PV} = \dot{U}_{PCC} + \dot{I}_{PV}Z_{PV} \qquad (5)$$

$$I_{PV} = \frac{-U_{PCC} + \sqrt{U_{PCC}^2 + \frac{8}{3}R_{PV}P_m^{'}}}{2R_{PV}} \qquad (6)$$

Where the phases of the U_{PV} and I_{PV} are all based on that of U_{PCC}.

According to the analysis above, when a PV power generation unit is working at a steady-state, its output current is determined by light intensity and battery temperature together. The equivalent model is shown in Fig 2: Taking light intensity and temperature as the input elements, the powers of a PV power generation unit in different conditions can be calculated according to (3), and the voltage and steady output current are obtained according to (5) and (6). This equivalent model has a high precision and can simulate the impact of PV power generation unit on the grid accurately.
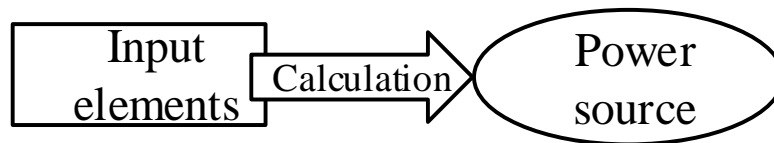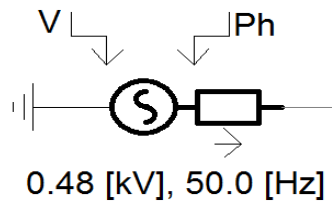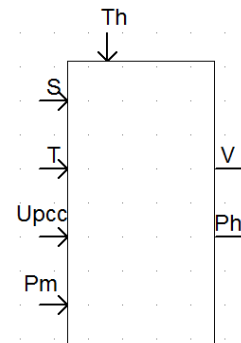

Figure 2. Structure of the equivalent model of a PV generation unit

3. Model and analysis of PV power station based on PSCAD/EMTDC

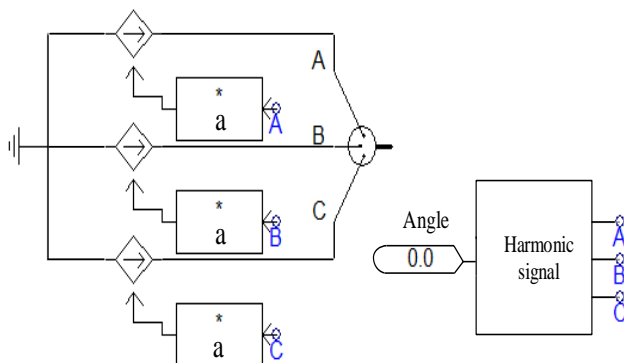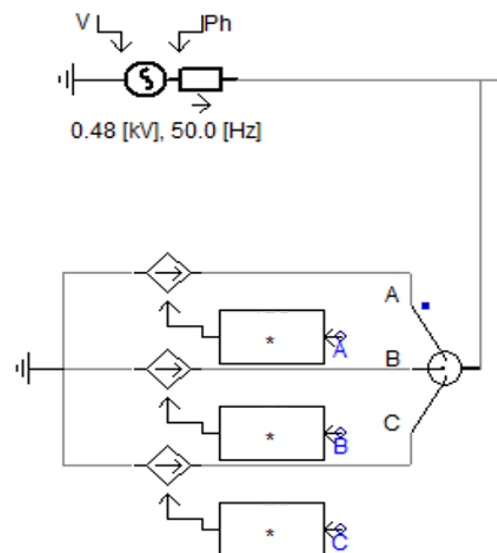*3.1. Model of single PV power generation unit*

3.1.1. Power source equivalent model. According to the analysis above, a power source model can be used to simulate the output characteristics of a single PV power generation unit in the ideal condition, as shown in Fig 3.

Figure 3. Equivalent power source model of a PV

Figure 4. Calculation module of a PV

Where V and Ph are voltage amplitude and phase of a PV power generation unit under the steady-state respectively. The internal model of a PV power generation unit is established so as to obtain V and Ph, as shown in Fig. 4.

Where S is the light intensity, T is the battery temperature, P_m is the rated power of PV power generations in a certain area, S, T, U_{PCC} and P_m are all input elements. V and Ph are output elements. V and Ph can be obtained by programming in the model to achieve the operations from (1)~ (6).

3.1.2. Harmonic equivalent model. A harmonic current generating component is set up in PSCAD, which can produce 2nd to 25th harmonic signals. The harmonic component is based on the harmonic parameters provided by the manufacturer of PV power generation units. The harmonic current of a PV power generation unit in various working conditions can be simulated based on these harmonic parameters. The harmonic equivalent model is shown in Fig. 5. Where a refers to the number of the paralleled PV generation units which are connected to the grid. The a can be adjusted to simulate the output characteristics of multiple PV power generation units.

Figure 5. Equivalent harmonic source model.
PV.

Figure 6. Complete equivalent model of single

3.1.3. Complete equivalent model of PV power generation unit. The model of a PV power generation unit can be got by paralleling a power equivalent model and a harmonic equivalent model. The model

can simulate the power and harmonic characteristics of a PV power generation unit at PCC, as shown in Fig.6.

3.2. Power quality evaluation model for a PV power station
The equivalent model of a PV power generation unit is applied to the modeling and analysis of power quality pre-evaluation of a PV power station in Guangdong province in order to verify its effectiveness.

The PV power station consists of 39 power generation units which are arranged in 5 plots. All the power generation units are connected to the 35kV bus through 39 transformers, and are connected to a newly built 110kV booster station (check point) by 5 collector lines (length 5km). They finally got to the bus of 110kV substation (PCC) through an 110kV overhead line. The installed capacity of this PV power station is about 50kW.

The power quality evaluation model of this PV power station can be built in PSCAD/EMTDC when all the details are confirmed, as shown in Fig.7.
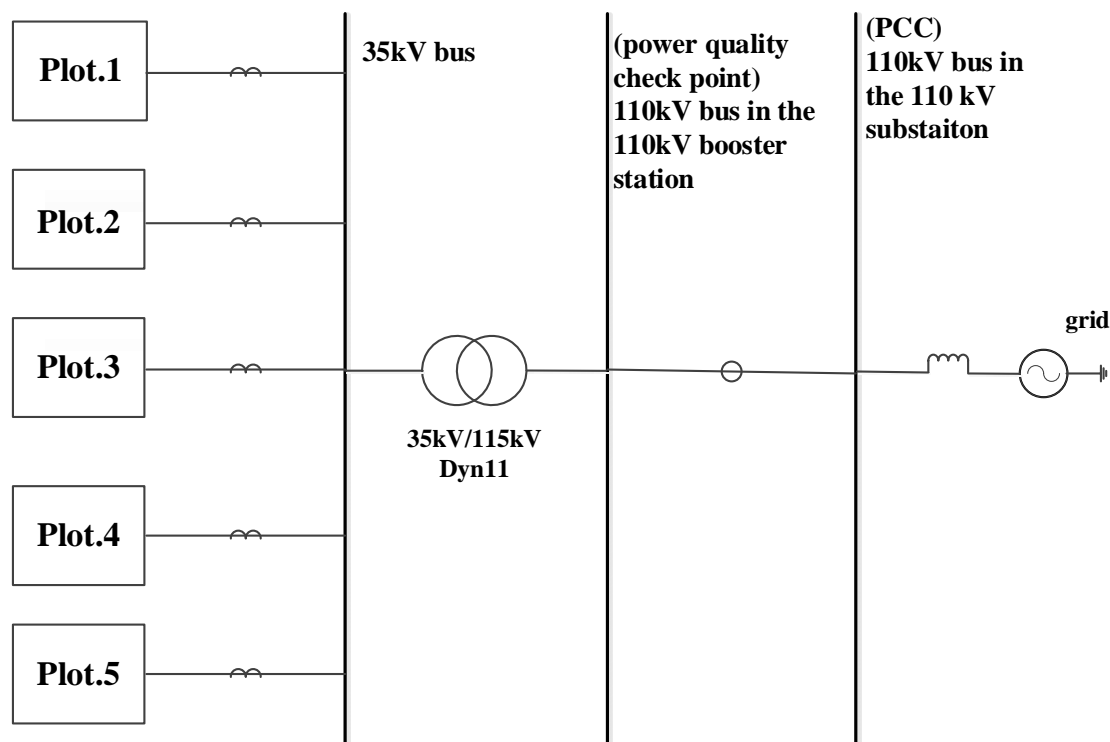

Figure 7. Equivalence diagram of the simulation model of the PV power station

4. Power quality pre-evaluation for the PV power station
According to the power quality indexes mentioned in the national standard, the power quality problems caused by the power station are evaluated in four aspects: voltage deviation, voltage fluctuation and flicker, harmonics, and the three-phase voltage unbalance.

4.1. Voltage deviation
In a PV power station, power loss will arise as lines and transformers need to absorb the reactive power, which results in voltage deviation in the grid.

In this paper The voltage deviation of "110kV bus in the substation (PCC) " and "110kV bus in the booster station (the power quality check point)", are obtained respectively when the output power of the PV power station is 100%, 70%, 50% and 30% of the rated value, as shown in Table 1.
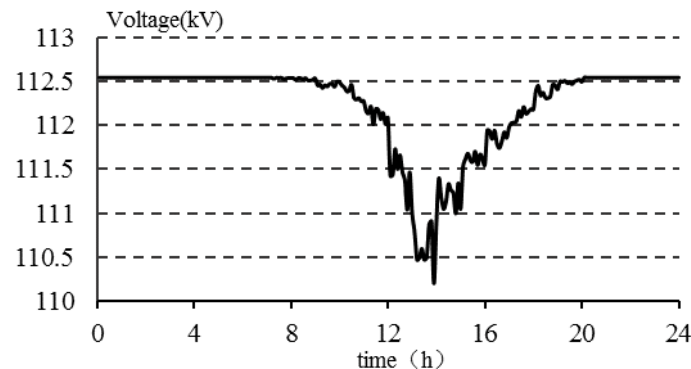
Table 1. Voltage deviation caused by the PV power station.

Output of PV power station	Power factor	Voltage deviation (%)	
		110kV bus in the substation (PCC)	110kV bus in the booster station (check point)
100% of the rated power	0.95 (lagging)	3.53	3.85
	0.95 (leading)	-4.33	-4.48
70% of the rated power	0.95 (lagging）	3.49	3.72
	0.95 (leading)	-1.32	-1.38
50% of the rated power	0.95 (lagging）	3.25	3.42
	0.95 (leading)	0.05	0.02
30% of the rated power	0.95(lagging)	2.88	2.98
	0.95(leading)	1.07	1.06

It can be seen that when the output power of PV power station is 100%, 70%, 50%, and 30% of the rated value, the maximum positive value of voltage deviation in the check point is 3.85% and the maximum negative value is -4.48%. The sum of positive and negative voltage deviations should not be more than 10% of the rated voltage. Therefore, the voltage deviation caused by the PV power station just conforms to the national standard.

4.2. Voltage fluctuation and flicker

4.2.1 Voltage fluctuation. The main factors that affect the power of the PV power generation units are light intensity and the battery temperature. Therefore, the output elements of the PV power station are simulated based on the typical light intensity and the battery temperature which are collected from the PV power station installation location during summer. And the voltage variation curves of the 110kV bus in the booster station in one day are calculated. As shown in Fig.8.

Figure 8. Voltage curve of the 110kV bus in the booster station in one day.

The voltage fluctuation d is expressed as the percentage of the difference of two extreme voltage values in the fluctuation curve with its rated voltage, as shown in (7).

$$d = \frac{U_{max} - U_{min}}{U_N} \times 100\% \tag{7}$$

According to Fig.8, the maximum voltage fluctuation of the 110kV side in the booster station appears around 14:00 with the value of $d = 1.0\%$, which meets the limitation (2.5%) of the national standard.

4.2.2. Voltage flicker. According to the definition of flicker by the IEC standard, the voltage flicker is measured by the international general flicker which is proposed by UIE. The model is built in Matlab,

and the fluctuation curve of in Figure 8 is used as the input. The voltage flicker of the PV power station is measured as 0.21 by the model, which is less than the limit of 0.699.

Therefore, the voltage fluctuation and flicker caused by the PV power station conform to the national standard.

4.3. Harmonic

The inverter is always in work after the PV power generation unit has been put into operation, which will cause harmonic problems to the grid. In this section, the harmonic injection of the PV power station is simulated in PSCAD according to the harmonic test report provided by the inverter manufacturer.

4.3.1. Harmonic voltage. Taking the A phase as an example, the harmonic voltage contained in the A phase of the 110kV bus in the booster station is calculated, as shown in Table 2. The simulation results show that the total harmonic distortion of the 110kV bus side of the booster station is 0.27%, which is in line with the national standard (2%).

Table 2. Harmonic voltage content of phase A of 110kV bus in the booster station

Harmonic voltage times	2	3	4	5	6	7	8	9
limit value	0.8	1.6	0.8	1.6	0.8	1.6	0.8	1.6
INDUSA	0.02	0.00	0.02	0.05	0.00	0.08	0.01	0.00
Harmonic voltage times	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
limit value	0.8	1.6	0.8	1.6	0.8	1.6	0.8	1.6
INDUSA	0.01	0.07	0.00	0.00	0.07	0.00	0.01	0.00

4.3.2. Harmonic current. The harmonic current simulation spectrum is shown in Figure 9. It is obvious that the main harmonic currents caused by PV unit are 2nd, 5th, 7th and 11th, with the value of 0.51A, 0.42A, 0.51A and 0.31A respectively. All the current values do not exceed the limit of national standard.
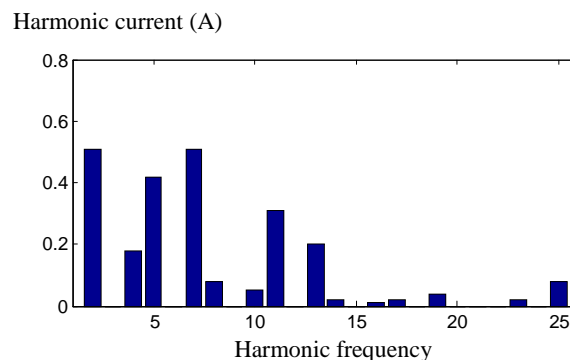

Figure 9. Harmonic current spectrum

4.4. Three-Phase Voltage Unbalance

National standard stipulates that the unbalance of three-phase voltage at the PCC caused by PV should be less than 2%, and the short time permissible value should be no more than 4%. The calculation of three-phase voltage unbalance is shown in (8):

$$\varepsilon_U = \frac{U_2}{U_1} \times 100\% \tag{8}$$

Where U_2 and U_1 refers to the negative and positive sequence component of voltage.

When the power factor of the inverter is 1, the voltage of 110kV bus in the booster station is extracted

to calculate three-phase voltage unbalance. The result is $4.88 \times 10^{-5}\%$, which meets the national standard and will not cause power quality problems.

5. Conclusion

(1)In this paper, an equivalent model of a PV power generation unit based on its output elements is proposed. Light intensity and the battery temperature are taken as the input elements, and the steady output current is obtained. Without iterative calculation in the complex simulation process, this model simplifies the modeling process of PV power generation unit.

(2) The model of a PV power generation unit can be got by paralleling a power equivalent model and a harmonic model, which can simulate the power and harmonic characteristics of a PV power generation unit at PCC. The number can be adjusted to simulate the output characteristics of multiple PV power generation units. The modeling process is simple and suitable for PV power stations which contains a large number of PV power generation units.

(3) This paper makes a detailed power quality pre-evaluation of a large PV power station, including voltage deviation, voltage fluctuation and flicker, harmonic and three-phase voltage unbalance, which verifies the practicability and effectiveness of the proposed model and pre-evaluation method.

Acknowledgments

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