Calculation of Voltage Stability Margin Considering Volt/Var Control Types of Photovoltaic Power Plants

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Abstract. With the increasing penetration of photovoltaic power plants, research on the voltage stability of power systems under different control types has become a significance issue. Firstly, this paper analyzes the Volt/Var control type of photovoltaic power plant, establishes the extended power flow equation considering the control types of photovoltaic power plant, and proposes the corresponding solution algorithm. Through the analysis of the adjusted IEEE 39-bussystem, the effectiveness of the proposed method is verified. If the photovoltaic power plant with the same capacity replaces the traditional generator, no matter what control type the photovoltaic power plant adopts, the voltage stability margin of the power system will decrease. At last, the influence of different control types of the photovoltaic power plant on the voltage stability of the power system is analyzed.

Keywords: Volt/Var control type · Voltage stability · Photovoltaic power plant · Continuous power flow

1 Introduction

Power system voltage stability is defined as the ability of power system voltage to maintain or recover to the normal range without causing voltage collapse after the power system is subjected to small or large disturbances.

Since the continuous power flow (CPF) method was proposed in the 1990s, it has developed into a mature static voltage stability analysis technology [1–3], but how to calculate the continuous power flow more accurately and efficiently is still the focus of academic circles, especially how to better solve the ill-conditioned problem of the Jacobian matrix at the critical point [4]. So far, scholars have proposed many continuous power flow solving methods, which are mainly divided into indirect methods and direct methods.

The indirect method is widely used, and it solves the ill-conditioned problem of the Jacobi matrix at the critical boundary by adding parameters. Reference [5] first used the

continuation method to extend the matrix, and then solved it. In [6], a piecewise linear model is used to approximate the injected power, but the calculation process is more complicated. The authors of [7] proposed a part geometric parameterization approach. The singularity of the Jacobi matrix at the critical point is avoided by adding a linear equation, but after expansion, the non-singular points in the original system may become singular, resulting in the failure of the calculation of the non-critical points. Literature [8] studies the influence of the permeability of doubly fed wind turbine on power system voltage stability margin through continuous power flow method. For purpose of studying the static voltage stability of the AC/DC transmission system with wind power, the probabilistic continuous power flow analytical approach proposed in literature [9] considers the frequency characteristics of generators, loads and the DC control types. Reference [10] established a discrete joint probability distribution considering the correlation of wind and solar output based on the Copula function and nonparametric and density estimation, and performed continuous power flow calculations for different states to obtain the discrete probability distribution of bus voltage, system voltage stability margin and critical voltage. The existing literature rarely considers the effect of the control type of the photovoltaic power plant on the voltage stability.

The remaining work of this paper is as follows. Section 2 proposes continuous power flow calculation considering Volt/Var control type of photovoltaic power plant. Section 3 shows case study. Section 4 summarizes the work of this paper.

2   Continuous Power Flow Calculation Considering Volt/Var Control Type of Photovoltaic Power Plant

2.1   Parametric Power Flow Equation Considering Volt/Var Control Type of Photovoltaic Power Plant

Continuous power flow method is a basic method for tracking the trajectory of the equilibrium point solution of nonlinear dynamic systems. It is of great significance to the study of power system voltage stability. Continuous power flow mainly includes load type, branch type and fault type models. The continuous power flow method includes four main steps: prediction process, correction process, parameterization strategy and step size control method. We can first select the prediction method, parameterization strategy and correction method separately, and finally consider the other three steps in selecting the step size control strategy.

When the photovoltaic power plant adopts the constant power factor control type, its active and reactive power meet the constraints

$$
\begin{aligned}
P_{PV} &= P_{mppt} \\
Q_{PV} &= P_{PV} \cdot \tan \varphi
\end{aligned}
\tag{1}
$$

where P_{PV} is the active power of the photovoltaic power plant, P_{mppt} is the maximum active power when photovoltaic power plant adopts maximum power tracking control, Q_{PV} is the reactive power of the photovoltaic power plant, φ is the constant power factor angle.

When the photovoltaic power plant adopts the constant voltage control type, its power and voltage meet the constraints

$$P_{PV} = P_{mppt}$$
$$V_{PV} = V_{set}$$
(2)

where V_{PV} is the set voltage of the photovoltaic power plant.

When the photovoltaic power plant adopts the constant reactive power control type, its active and reactive power meet the constraints

$$P_{PV} = P_{mppt}$$
$$Q_{PV} = Q_{set}$$
(3)

where Q_{PV} is the set reactive power of the photovoltaic power plant.

The power flow equation considering load growth can be expressed as:

$$\mathbf{S}_G + \Delta\mathbf{S}_G(\lambda) + \mathbf{S}_{PV} + \Delta\mathbf{S}_{PV}(\lambda) - \mathbf{S}_L - \lambda\mathbf{b} = \mathbf{f}(\mathbf{x})$$
(4)

where $\mathbf{S}_{PV} = \left[\mathbf{P}_{PV}^T \ \mathbf{Q}_{PV}^T\right]^T$ is the injected power of the photovoltaic power plant, $\mathbf{S}_G = \left[\mathbf{P}_G^T \ \mathbf{Q}_G^T\right]^T$ is the injected power of the generator in the ground state, $\mathbf{S}_L = \left[\mathbf{P}_L^T \ \mathbf{Q}_L^T\right]^T$ is the ground state power of node load, $\mathbf{b} = \left[\mathbf{b}_P^T \ \mathbf{b}_Q^T\right]^T$ is the load growth type, which is composed of the load growth scale factors of all nodes in the whole system. $\Delta\mathbf{S}_{PV}(\lambda) = \left[\Delta\mathbf{P}_{PV}(\lambda)^T \ \Delta\mathbf{Q}_{PV}(\lambda)^T\right]^T$ is dispatching type of the photovoltaic power plant, which is in constant voltage control type. $\Delta\mathbf{S}_G(\lambda) = \left[\Delta\mathbf{P}_G(\lambda)^T \ \Delta\mathbf{Q}_G(\lambda)^T\right]^T$ is the generator dispatching type, λ is the load growth factor, indicating the total load growth level of the whole system, λb represents the load increment of each node in the whole system. $\mathbf{x} = \left[\boldsymbol{\theta}^T \ \mathbf{V}^T\right]^T$ is the steady state voltage vector of the system, $\boldsymbol{\theta}$ is the angle vector of node voltage. $\mathbf{V}$ is the node voltage amplitude vector. $\mathbf{f}(\mathbf{x}) = \left[\mathbf{f}^P(\mathbf{x})^T \ \mathbf{f}^Q(\mathbf{x})^T\right]^T$ is the node injection power function of the conventional power flow equation, $\mathbf{f}^P(\mathbf{x})$ is the injected active power function of PV and PQ nodes, $\mathbf{f}^Q(\mathbf{x})$ is the injected reactive power function of PQ node.

2.2 Continuous Power Flow Calculation

As in Fig. 1, the voltage stability margin calculation considering the control type of the photovoltaic power plant can give the voltage stability margin under the specific control type of the photovoltaic power plant through continuous power flow calculation under the conditions of different control types of the photovoltaic power plant, specifically including the following steps:

1) Input traditional unit data, grid data, load related data and photovoltaic power plant data.
2) Detect the control type of the photovoltaic power plant, update its access node type, its voltage value and reactive power input.

3) Set the load growth type, the traditional generator output growth type, and set the change type of active power, reactive power and voltage according to the control type of the photovoltaic power plant.

4) Number of initialization iterations. Calculate the power flow at the initial operation point.

5) The dominant node is determined, and then the extended power flow equation including voltage stability margin parameters is established with the dominant node voltage as a continuous variable.

6) The adaptive step size method is used to determine the prediction step size.

7) The parameterized power flow equation is predicted by the mixed prediction method, and the extended power flow equation is corrected and calculated by the Newton approach with the estimated value as the initial value.

8) According to the corrected power flow calculation results, the state value at the next operation point and the node set with structural transformation are obtained, and whether the node set with structural transformation is an empty set is judged? If yes, turn 10); otherwise, turn 9).

9) For the traditional generators and photovoltaic power plants in the node set of structural transformation, detect the degree of reactive power exceeding the limit in the PV node type, change its corresponding node type, set its reactive power to its allowable maximum value, and convert the node type to PQ type, turn to 5).

10) Detect whether the voltage stability critical point is detected, and if so, end; Otherwise, turn to 5).

3 Case Study

The adjusted IEEE 39-bus system in Fig. 2 is used to verify the effectiveness of the proposed method, and further compare the voltage stability margin of the power system under different Volt/Var control types of the photovoltaic power plant. The generator node 32, 33, 36 in example are replaced by photovoltaic power plants with the same capacity. Other parameters in the system are consistent with the original IEEE 39-bus system's parameters.

Set four scenarios:

(1) Original IEEE 39-bus system.
(2) Generator 32, 33, 36 are replaced by photovoltaic power plants with the same capacity, which adopt constant power factor control type.
(3) Generator 32, 33, 36 are replaced by photovoltaic power plants with the same capacity, which adopt constant voltage control type.
(4) Generator 32, 33, 36 are replaced by photovoltaic power plants with the same capacity, which adopt constant reactive power control type. Q_{set} is set to Q_{max}, which is the max reactive power of photovoltaic power plants.
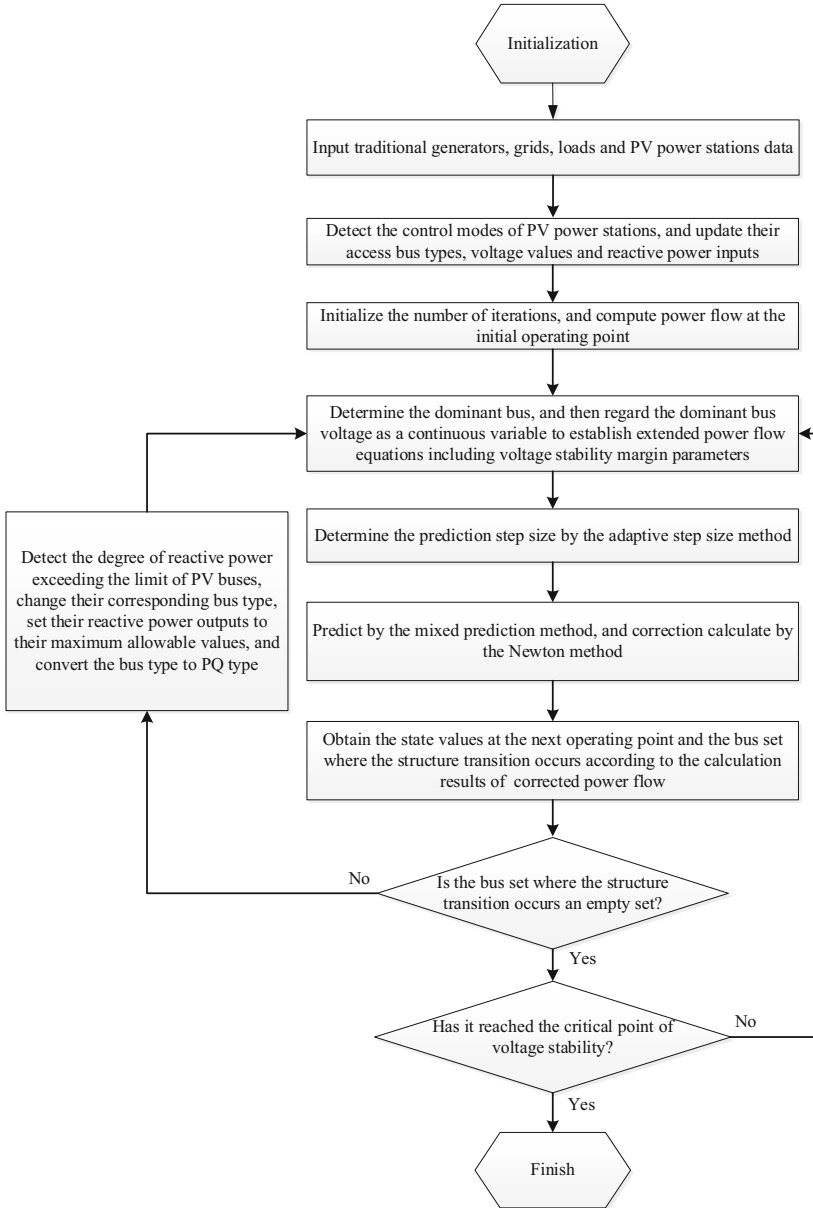
Fig. 1. Continuous power flow diagram considering control types of photovoltaic power plant

The calculation results of scenario 1–4 are shown in Fig. 3–6. It can be proved by comparing Fig. 3 and Fig. 4, 5 and 6 that when the traditional generator is replaced by the photovoltaic power plant with the same capacity, the voltage stability margin will drop no matter what control method is adopted. The voltage support capacity of the
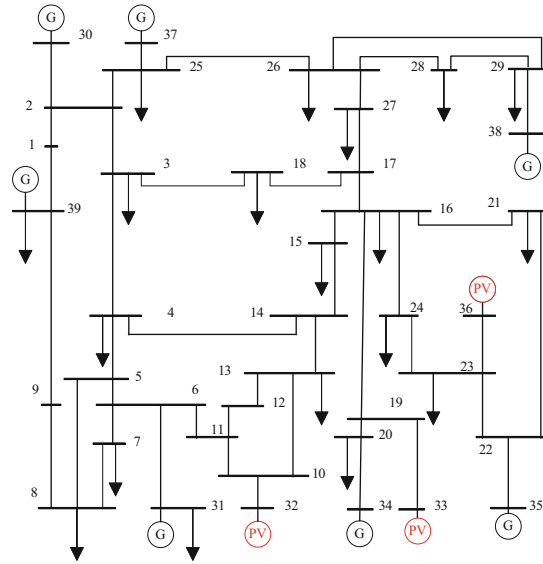
Fig. 2. Adjusted IEEE 39-bus system

photovoltaic power plant with the same capacity is weaker than that of the traditional generator. With the augment of photovoltaic power plants, the power system needs to configure more reactive power compensation equipment to maintain voltage stability.

As shown in Fig. 5, the voltage stability margin of the power system is 1.11 when the photovoltaic power plant adopts the constant voltage control type. The voltage stability margin of the power system is largest. Compared with Fig. 3, it can be concluded that the voltage stability margin of the power system under this control type is closest to the power system connected to the conventional generator.

As shown in Fig. 4, the voltage stability margin of the system is 0.8 when the photovoltaic power plant adopts the constant power factor control type. Compared with Fig. 3, The voltage stability margin of the power system decreases most under this control type.

As shown in Fig. 6, the voltage stability margin of the power system is 0.86 when the photovoltaic power plant adopts the constant reactive power control type. Compared with Fig. 4, it can be concluded that the voltage stability margin of the power system under this control type is higher than that under the constant power factor control type. Although the voltage of the access point cannot be maintained constant under this control type, the reactive power capacity of the photovoltaic power plant can be fully utilized.
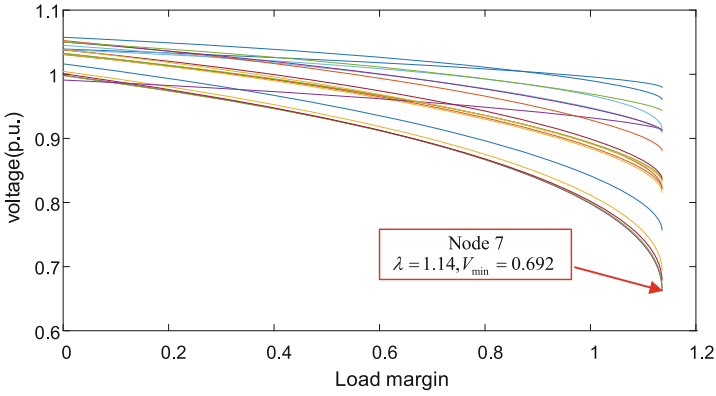
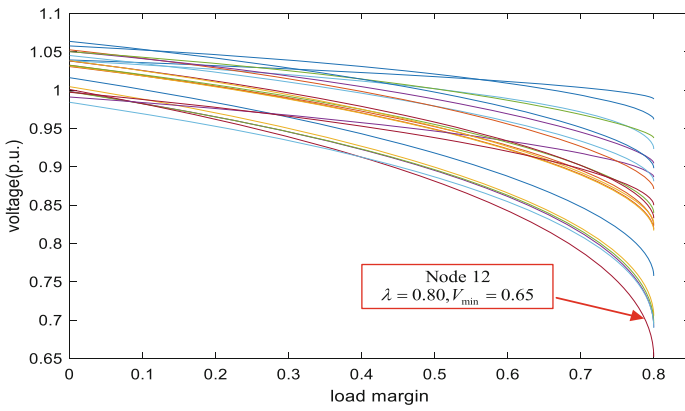**Fig. 3.** Continuous power flow calculation results in scenario 1

Fig. 4. Continuous power flow calculation results in scenario 2
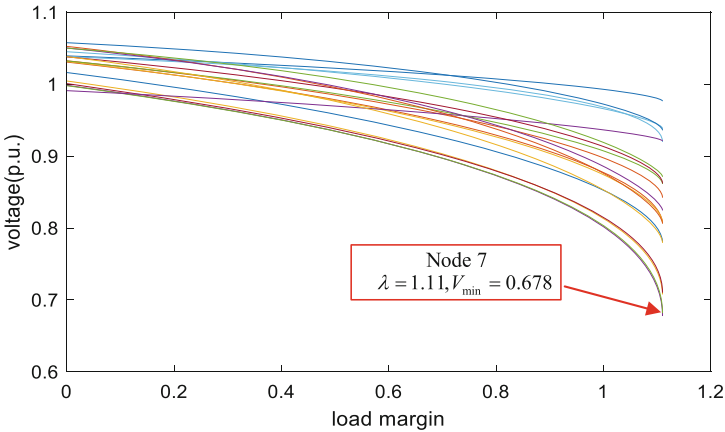

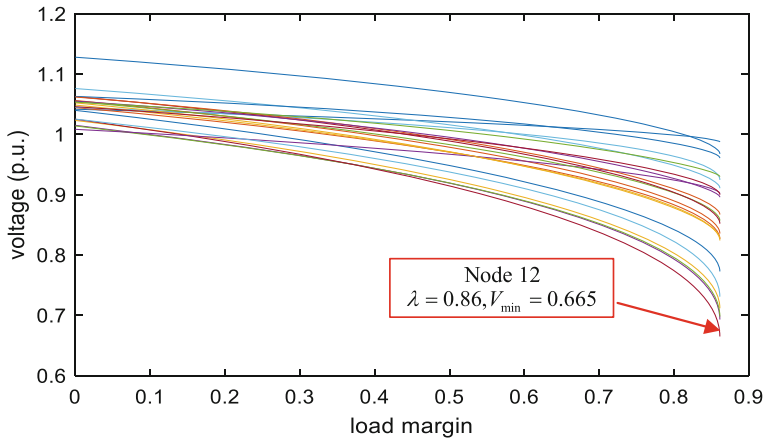**Fig. 5.** Continuous power flow calculation results in scenario 3

Fig. 6. Continuous power flow calculation results in scenario 4

4 Conclusion

With the increasing access ratio of photovoltaic power plants, it is of great significance to research the voltage stability of power systems under different control types. By analyzing the Volt/Var control type of the photovoltaic power plant, the extended power flow equation considering the control type of the photovoltaic power plant is established, and the corresponding solution algorithm is proposed. This paper draws the following conclusions:

If the photovoltaic power plant with the same capacity replaces the traditional generator, no matter what control type the photovoltaic power plant adopts, the voltage stability margin of the power system will decrease.

The constant voltage control type adopted by the photovoltaic power plant is the most favorable for the voltage stability margin of the power system. Under the constant power factor control type, the voltage stability margin is the lowest, and more reactive power compensation equipment needs to be added. With the increase of photovoltaic power plants connected to the power system, it is necessary to require the photovoltaic power plants to adopt the constant voltage control type to provide voltage support for the power system when the voltage stability margin of the power system is insufficient.

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