Design of voltage stability monitoring simulation system for PV grid-connected system

Sheng Li¹, Zhiyang Cao, Jian Cui, Jiawei Yu and Wenqi Bao

School of Electric Power Engineering, Nanjing Institute of Technology, Nanjing 211167, China

¹E-mail: lisheng_njit@126.com

Abstract. Voltage stability monitoring simulation system for photovoltaic (PV) grid-connected system is designed, taking the classic three-node power system model with a PV power station for example. The voltage instability theory and application researches for the monitoring simulation system are carried, and the frame, communication protocol and software functions of the voltage stability monitoring system are discussed. The monitoring simulation system can realize two-computer communication and joint debugging, which can not only monitor the basic operational aspects, but also be used to view the voltage equilibrium point curves and voltage response curves as the operating point is affected by various disturbances. And the system load margin index calculation, load shedding and other voltage stability remote control methods are provided to maintain or improve voltage stability. The monitoring simulation system provides a reference scheme for the application of voltage stability theory in practical engineering.

1. Introduction

As the economy develops at high speed, a high degree of dependence on electric power and aggravation of the urban haze phenomenon day by day results in that the application of photovoltaic (PV) power technology develops rapidly. However, due to the characteristics of randomness, volatility and intermittence, PV power generation will bring several adverse influences to the work of grid-connected, and one of them is voltage instability for the PV grid-connected power system [1-3].

Power system is a typical high-dimensional nonlinear system, and there are some bifurcation phenomena such as saddle-node bifurcation (SNB) and Hopf bifurcation (HB) in the system, which are harmful to the voltage stability of the power system [4, 5]. Once the power system has a disturbance occurred at the SNB point or HB point, load voltage monotony instability or oscillation instability will happen in the system.

Literatures [6, 7] indicated that SNB and HB still exist in PV grid-connected system, just as their existence in the traditional power grid. Meanwhile, the uncertainty of power output can result in the bifurcation point position’s changes, thus increasing the complexity of the evaluation process for voltage stability in the grid-connected system. There exists fundamental engineering value in strengthening the voltage stability of the PV grid-connected system, and developing online monitoring software of a grid-connected system can improve its voltage stability effectively.

This paper introduces the design scheme of the voltage stability monitoring simulation system, taking a classic three-node system with a PV power station integration as a typical example. The influences of various disturbance conditions on voltage stability and functions of online monitoring
software will be discussed, aiming to provide a reference for voltage stability monitoring in the PV grid-connected system.

2. Voltage stability of PV grid-connected power system

2.1. System model and voltage stability analysis

A three-node power system with a PV power station is used as the study case shown in Figure 1. The classic three-node system is a typical study case for voltage stability, and it is usually used to analyze various aspects of voltage stability existing in it.

2.1.1. Small-turbulence voltage stability. Now we take load power fluctuation as the disturbance condition. Make constant power load keep its power factor as invariant value, that is, \( Q_1 = kP_1 \). \( P_1 \) and \( Q_1 \) are the active power and reactive power of the constant power load, respectively, \( k \) is a constant. We take \( P_1 \) as a bifurcation parameter with an initial value 1 pu, and set \( k=0.2 \) and PV active output \( P_{pv} \) as 1 pu.

The bifurcation calculating results (namely \( P-U \) curve or \( \lambda-U \) curve) are showed in Figure 2. \( \lambda \) is the load parameter, \( \lambda = P_1/P_{10} \), where \( P_1 \) represents the current active power value and \( P_{10} \) is the initial value of \( P_1 \). LP point is the SNB point of PV grid-connected system, and at the point, the corresponding maximal load parameter \( \lambda_{max} = P_{1LP}/P_{10} = 2.81 \) pu, where \( P_{1LP} \) is the active load power at SNB point. As the system running at the SNB point, a slight disturbance to \( P_1 \) or \( P_{pv} \) can influence the system’s voltage stability, leading to a rapid breakdown of load bus voltage \( U_{Bus2} \) [6].

Considering PV power output’s changes, we can set four situations named as 0.06 pu (distributed scale), 0.2 pu (relatively large-scale), 1 pu (large-scale) and 0 pu (without PV power) to analyze voltage stability of the PV grid-connected system shown in Figure 1. It is noteworthy that there still exists SNB point in the distributed PV grid-connected power system.

To which extent, the grid-connected system’s voltage stability reaches can be indicated by the voltage stability index (VSI). One of the frequently-used VSI is the load-margin index, and it is expressed as:

\[
I_{LM} = 1 - \frac{P_1}{P_{1LP}} = 1 - \frac{\lambda}{\lambda_{max}}
\]

(1)

Where, \( P_1 \) and \( \lambda \) are the current load active power and load parameter, respectively.

![Figure 1. The classic three-node power system with PV.](image-url)
2.1.2. Transient voltage stability. When Line 1 has a short-circuit fault at its middle point, t-U curves (time t to voltage U curves) with the different fault clear time $t_{\text{clear}}$ are shown in Figure 3. It can be seen that if $t_{\text{clear}}$ is 0.03 s, $U_{\text{Bus}2}$ can recover about 0.89 pu but $U_{\text{Bus}3}$ falls to 0, the system loses its equivalent generator. If $t_{\text{clear}}$ is 0.02 s, $U_{\text{Bus}2}$ and $U_{\text{Bus}3}$ can all recover to the normal range, but the voltage amplitudes have constant tiny fluctuations. PV’s dynamic results in the fluctuation phenomenon and it is uneasy to be eliminated.

![Figure 2. $\lambda$-$U$ equilibrium point curve (k=0.2).](image)

![Figure 3. t-V curves when short-circuit fault happens at the middle point of Line 1.](image)
2.2. Disturbances setting and control measures
We can set many kinds of disturbances to the system shown in Figure 1, including:
1) Setting slight fluctuation of load power at SNB point;
2) Setting slight fluctuation of PV active output at SNB point;
3) Setting fluctuation of load power by a big margin at none-bifurcation point;
4) Setting fluctuation of PV active output by a big margin at none-bifurcation point;
5) Setting faults at the transmission line or bus, etc.
Control measures to improve the system’s voltage stability include, but are not limited to:
1) Quickly clearing the fault by relay protection device when there is a short circuit at the line or bus.
2) Quickly recovering to the pre-failure state by auto reclosing in a short time when a line breaking.
3) Implementing bifurcation control by bifurcation controller aiming to the angular velocity or power angle of the generator.
4) Inputting mechanical switching capacitor (MSC) when the system is going through a fault.
5) Inputting dynamic reactive power compensation equipment (STATCOM or SVC) when the system is going through a fault [8].
6) Load shedding according to VSI [9].
7) Classification control for PV active output (10% step size) in some special circumstances.
All disturbances and control measures above should be capable of being displayed in the voltage stability monitoring simulation system.

3. Frames of voltage stability monitoring simulation system
There are two basic frames of voltage stability monitoring simulation system for PV grid-connected power system. As shown in Figure 4(a), two PCs are used to communicate, one of which is used to build a PV grid-connected simulation system, known as plant end or station end. The other is used to simulate the main station end, which includes the voltage stability monitoring software. As shown in Figure 4(b), PC is used as the station end, and MCU (Microcontroller Unit) is used to build voltage stability local monitoring center, simulating various auto-control devices.

![Figure 4 frames of voltage stability monitoring simulation system](image)

The data resources of the station end can be acquired using two kinds of simulation software:
1) Using MATCONT, which is the numerical bifurcation software to set up ordinary differential equations (ODEs) of the PV grid-connected system, known as a way to use mathematical models.
2) Using power system analysis toolbox PSAT to build the Simulink simulation model of the PV grid-connected system.

The reason to use MATCONT to build simulation model is that this software is capable of searching bifurcations and applying the continuation method, being able to find out the SNB point of the system. PSAT is used to build a simulation model because it contains functions of continuation.
power flow calculation and eigenvalue calculation, also being able to find out SNB point of the system. Meanwhile, both of them can execute the time-domain simulation. MATCONT is able to display process of load shedding, and PSAT is able to display short circuits and other faults, and the process of fault clearing.

Interfaces of the station end and main station end are developed by Visual C++ (VC++), VB also easily catering to need. The interface should be able to dynamically display operating parameters of the system, refreshing data every 5 seconds. Data displayed on the main station end come from tele-metering and tele-signaling to the station end.

At the station end, VC++ is used to realize off-line simulation through calling MATCONT or PSAT calculation data stored in the MYSQL database, and ODBC (Open Database Connectivity) technology is used to operate on the database. It is also feasible to use VC++ to make a connection with the MATLAB engineering model, realizing real-time transferring and controlling of data, which helps to make on-line simulation. However, because of the relatively long running time of PSAT or MATCONT, the running results need patience.

In Figure 4, the communication protocol applied between station end and main station end or local monitoring center is a modified Modbus protocol, which is able to reach communicating effect through integrating various effective message basically. The main rules of Modbus protocol are:

a. When receiving a communication message, the first thing to do is checking format faults, then returning an exception response if faults exist. If the message is right, we are then dealing with the message command, returning the right message.

b. If the message is not received because of communication interruption or transmission fault, the command should not be allowed to execute.

c. If message is not accurately received, and the command cannot be executed in the current condition, then returning message of cancellation.

4. Functions of voltage stability monitoring simulation system

4.1. Frame A

In Frame A, the voltage stability monitoring software of main station end contains following basic functions:

1) Operator login.
The operator has to login in the system before starting tele-metering, tele-signaling and tele-control, examining SOE, etc., otherwise all of which above cannot be executed.

2) Tele-metering.
The station end sends tele-metering command, updating main station end’s data displaying in the monitoring interface.

3) Tele-signaling.
Station end sends tele-signaling command, and main station end receives it. If it does not match the monitoring interface, the statuses of breakers will be refreshed in the monitoring interface.

4) Tele-control.
Operator sends remote control command for a breaker at main station end, he could receive tele-control executing prompt box after station end responds the message, and execution of which is decided by operator.

5) Remote signal transposition.
When station end makes remote signal transposition and sends the message, operator should refresh the monitoring interface after confirming it.

6) Sequence of Event (SOE).
SOE saves operating date, time, device identification, operating type, acting state, which is convenience for operator to examine.

7) Voice broadcast.
Making voice broadcast when the operator executing tele-control command, reminding the operator to cautiously operate. Station end will also make voice broadcast when happening remote signal transposition, helping to make a judgement, which aims to ensure the safety and stability of the power grid.

8) Viewing communication message.
Through the communication message window (including sending window and receiving window), the operator can check all communication messages sent to the main station end and communication messages received by the station end.

9) Viewing system voltage operation curves.
Voltage operation curves include load active power - voltage equilibrium curve (P-U curve), PV active power - voltage equilibrium curve (P_{pv}-U curve), and voltage response curves (t-U curves) at different disturbances, etc.

10) Voltage stability index calculation.
Voltage stability monitoring software sets the function of calculating VSI (such as load margin index $I_{LM}$). After making the bifurcation calculation of the PV grid-connected system shown in Figure 1, we can confirm the critical value of $I_{LM}$ for load shedding. Voltage stability monitoring software should store $P_{SNB}$ values calculated in different $P_{pv}$, which helps to calculate $I_{LM}$ index value.

11) Voltage stability remote control.
Main station end can realize remote switching of bifurcation controller, MSC, STATCOM / SVC and so on. It also can execute load shedding and remote setting of relay protection set value, improving the system voltage stability at various disturbances.

4.2. Frame B
In Frame B, the MCU is used as local monitoring center to simulate various auto-control devices for improving voltage stability, such as relay protection device, bifurcation controller, load shedding device, STATCOM / SVC switching and so on. Figure 5 is the dual computer communication picture between simulant load shedding device based on MCU and the PC simulated the station end.

![Figure 5. The dual computer communication of Frame B.](image)

5. Conclusions
This paper uses a three-node system with PV power station (including distributed, relatively large scale, and large scale) as an example to introduce the design frames of voltage stability monitoring simulation system, which provide a visualization platform (Frame A) or an operational platform (Frame B) to monitor and control voltage stability of PV grid-connected system. The designed voltage
stability monitoring simulation system reflects the requirements of the smart grid on dispatching function in aspects of standardization, integration, and intelligentization. It also provides an engineering application reference for voltage stability monitoring of the PV grid-connected system.

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