A Study on Synchronous Stability Analysis of Power System with a Large Amount of PVs


Abstract – To solve the energy and environmental issues, it is planned that a large amount of photovoltaics (PVs) are introduced in Japan. However, because the characteristic of PV output is different from that of conventional generators, it is possible that the synchronous stability changes due to a large amount of PVs. Additionally, supposing that some generators are stopped when PV output becomes large, decrease of inertia constant and change of power flow are also important factors for synchronous stability. Hence, in this paper, the synchronous stability of power system with a large amount of PVs is studied considering both the voltage characteristic of PV output and the change of system operation such as unit commitment. Specifically, the stability is evaluated from a viewpoint of critical clearing time (CCT) based on both the accelerating and decelerating energy in P-δ curve. IEEJ-WEST10 model system is utilized as a simulation model.

Keywords: Synchronous stability, Critical clearing time, Photovoltaics, P-δ curve, Voltage characteristic

1. Introduction

To solve the energy and environmental issues, it is planned that a large amount of photovoltaics (PVs) are introduced in Japan. Specifically, the targeted value of PV introduction is 28 GW in 2020 and 53 GW in 2030. However, the characteristic of PV is different from that of conventional generator as follows.

- PV output depends on the weather condition.
- PVs are decentrally-introduced to demand side area.
- PV is connected to power system using inverter.

Therefore, it is possible that the synchronous stability of power system changes due to above characteristics when a large amount of PVs are introduced as above. Additionally, it is desirable to stop some thermal generators in order to reduce CO2 emission when PV output becomes large. At this time, both the equivalent transformer reactance and equivalent synchronous reactance of multiple generators at the same node increase. Moreover, the inertia constant of whole system is reduced because the PV has no inertia force. Hence, the synchronous stability must be carefully analyzed considering various factors.

Although there are some studies so far regarding the synchronous stability of power system with a large number of wind turbine generators [1][2][3], there are few studies regarding power system with a large number of PVs [4][5]. For example, the authors have shown the following impact may be given by a large number of PVs in Ref.[5].

- Synchronous stability is improved because power flows on transmission lines are reduced in the case that PVs are distributed with uniformity. However, it is possible that the stability decreases due to the decrease of inertia constant.
- Synchronous stability may decrease in the case that the PV output is not distributed with uniformity.

However, in those previous papers, the electric characteristic of PV is not considered. Thus, in this paper, the synchronous stability of power systems with a large number of PVs are studied considering the voltage characteristic of PV output from a viewpoint of both theoretical and analytical sides based on critical clearing time (CCT).

The rest of this paper is organized as follows. In section 2, the synchronous stability of power system is discussed using P-δ curve supposing that a large number of PVs are
A Study on Synchronous Stability Analysis of Power System with a Large Amount of PVs

202

introduced. Next, in section 3, the simulation model and simulation results are shown. Finally, in section 4, the conclusion will be provided.

2. Synchronous Stability based on \( P-\delta \) Curve

2.1 The improvement of synchronous stability due to the power flow decrease

![Diagram 1: Change of operating point due to the change of power flow.](image)

In the case that the total capacity of PVs increases, the power flow on transmission line decreases because a part of demand is supplied by them. Therefore, the synchronizing power becomes larger and steady state stability is improved as shown in Fig. 1 supposing that it is possible to discuss the stability analysis using \( P-\delta \) curve. The figure shows the example in which the operating point changes from \( a \) to \( b \) by decreasing the sending power from generator due to the increase of PV output. At this time, transient stability is also improved because the accelerating power at fault increases and the decelerating power after the fault clear decreases, as shown in Fig. 2.

2.2 Voltage characteristic of PV

PV has no inertia force because it is connected to power system using inverter. Thus it is possible to maintain PV output constantly by the inverter control in the case the amount of insolation does not change. Therefore, the voltage characteristic of PV should be modeled as “constant power characteristic”. On the other hand, in the case that inverter capacity is not sufficient, voltage characteristic of PV output becomes “constant current characteristic” because the PV output is not maintained due to the upper limit of current constraint. Hence, in this section, the synchronous stability is discussed supposing both voltage characteristics.

First, the difference between load and PV output at a node is defined as its “apparent load” in this paper. The voltage characteristic of apparent load depends on voltage characteristics of both load and PV output. In this paper, we have an assumption that the voltage characteristic of load is “constant current characteristic”. Fig. 3 shows the change of apparent load due to the voltage change of its node. Where, the meaning of each variable is as follows.

- \( V_r \): reference voltage
- \( P_L \): load
- \( P_{PV} \): PV output
- \( P_{La} \): apparent load at reference voltage
- \( \alpha_L, \alpha_{PV} \): voltage characteristic index of load and PV output

Fig. 1. Change of operating point due to the change of power flow.

![Diagram 2: Relationship between accelerating and decelerating energy.](image)

As shown in the same figure, both the load and PV output become larger when the voltage increases supposing the PV output is constant current characteristic. On the other hand, supposing the PV output is constant power characteristic, PV output does not change although the load increases when the voltage increases. As a result, the apparent load becomes larger in the case of constant power characteristic compared with the case of constant current characteristic.
In general, the displacement angle of the generator increases due to the accelerating energy during a fault. In the case that the apparent load becomes larger at that time, the synchronous stability is improved because the decelerating energy increases due to the increase of electrical output of the generator. Oppositely, in the case that the apparent load decreases, the synchronous stability gets worse because the decelerating energy decreases due to the decrease of electrical output of the generator.

As above, the change of the synchronous stability at the same fault depends on the timing of the voltage change at the load node. When the excitation control works effectively, the voltage at the load node is increased when the displacement angle increases. At this time, the synchronous stability is superior in the case of constant power characteristic due to the large apparent load. Thus the stability change caused by the voltage characteristic of PV should be studied considering the work of excitation control.
in the model system. Specifically, inertia constant decreases while both synchronous reactance and transformer reactance increase. Because it is clear that the synchronous stability decreases due to the increase of the synchronous reactance and transformer reactance, only the impact of the decrease of inertia constant is discussed below.

3. Simulation Results

3.1 Simulation model

Fig. 6 shows the IEEJ-WEST10 system model[6] based on Japanese 60Hz real system. In this section, we utilize this system model by adding PVs to load nodes. The PV capacity of each node is in proportional to the load capacity at its connection node. The total PV capacity is set to 0, 5, 10, 15, 20, 25, 30 [GW]. As for the voltage characteristic of PV output, both the constant current and constant power characteristics are considered. The PV capacity at each node is described as Eq. 1. And the output of each generator is adjusted according to following Eq. 2 and 3 in order not to change the power flow on transmission line largely.

\[
PV_i = \frac{L_i}{L_T} \times PV_T
\]  
(1)

\[
P_i = P_{IS} - (PV_i + PV_{i,j}) \quad (j=3\sim6)
\]  
(2)

\[
P_i = P_{IS} - \left( PV_i + \frac{P_{IS}}{P_{IS} + P_{2S}} PV_2 \right)
\]  
(3)

where,

\( PV_i \): PV capacity at node \( i \)

\( PV_T \): total PV capacity of whole system

\( L_i \): load capacity at node \( i \)

\( L_T \): total load capacity of whole system

\( P_i \): output of generator \( i \)

\( P_{IS} \): output of generator \( i \) without PV

\( P_T \): total output of all generators

In this simulation model, a large number of generators are aggregated to single generator at each node as shown in Fig. 7. In the case that some generators are stopped when PV output increases, generators in operation at a same node are aggregated as shown in Fig. 8. As a result, the inertia constant and reactance of equivalent single machine at the same node are described as Eq. 4 and 5.

\[
M_i = M_0 \times \frac{P_i}{P_{IS}}
\]  
(4)

\[
X_i = X_0 \times \frac{P_{IS}}{P_i}
\]  
(5)

\( M_i \): equivalent inertia constant of generators at node \( i \)

\( M_0 \): rated value of equivalent inertia constant of generators at node \( i \)

\( X_i \): equivalent synchronous reactance and transformer reactance of generators at node \( i \)

\( X_0 \): rated value of equivalent synchronous reactance and transformer reactance of generators at node \( i \)

Following two simulation cases are treated. In both cases, the fault occurs at the transmission line 2-3 (near the bus 2:
3LG) and reclose is not treated. In both cases, transient stability analysis is executed repeatedly with increasing clearing time before it becomes unstable. As above, CCT is calculated as to both constant current and constant power characteristics.

[Case 1] Active power control without unit commitment
Supposing that only the active power of generators are adjusted in order to satisfy the demand and supply balance in each area, inertia constant, synchronous reactance, and transformer reactance do not change.

[Case 2] Active power control with unit commitment
Supposing that some generators are stopped in order to satisfy the demand and supply balance, the inertia constant, synchronous reactance, and transformer reactance are set according to Eq. 4 and 5.

3.2 Simulation results

Fig. 8. Change of CCT.

Fig. 8 (a) and (b) show the simulation results of Case 1 and 2, respectively. Horizontal and vertical axes represent PV capacity and CCT in both figures. As shown in Fig. 8 (a), CCT increases significantly as PV capacity increases in Case 1 because the power flow on transmission line becomes smaller. Especially, CCT becomes larger in the case of constant current characteristic. On the other hand, in Case 2, CCT increases slightly in the case of constant current characteristic as PV capacity increases. Oppositely, in the case of constant power characteristic, CCT decreases slightly as PV capacity increases. From these results, we can estimate that the CCT reduction caused by generator stop is more significant than the CCT increase by the power flow reduction.

In both cases, CCT is smaller in the case of constant power characteristic. In order to verify the reason, the active power output, displacement angle, terminal voltage, and control signal of AVR of generator 3 in Case 2 (PV capacity is 30GW) are shown in Fig. 9 (a) and (b). Where, red and blue lines represent the constant power and current characteristic, respectively, and fault clearing time is 0.050[sec].

First, the fault occurs at 0.10[sec] and it causes the sudden decrease of active power output of the generator. In
the case of constant power characteristic, the apparent load becomes smaller because the PV output does not decrease by the voltage drop. Thus, the accelerating energy becomes larger in the case of constant power characteristic.

Additionally, from fault clearing time to around 1.0[sec], the terminal voltage is smaller than reference voltage as shown in Fig. 12, and vice versa. According to the logic described in section 2.2, which means that decelerating energy is smaller in the case of constant power characteristic before the operating point reaches the swing back point at around 1.0[sec]. Where, it should be noted the time when active power output and displacement angle become maximum values are not the same because the simulation results are based on multi-machine system model.

As above, it is expected that the power swing becomes larger in the case of constant power characteristic, and CCT becomes smaller in the case of constant power characteristic from a viewpoint of both the accelerating energy during the fault and the decelerating energy after the fault clearing time. Above discussion corresponds with simulation results shown in Fig. 8. It should be noted that it is important to study the relationship between the voltage characteristic of PV output and the synchronous stability considering the control effect of excitation controller.

4. Conclusion

In this paper, the synchronous stability with a large amount of PVs is evaluated based on CCT. Supposing that the voltage characteristic of PV output is constant power or constant current, the following results are given by the analysis of the relationship between CCT and PV capacity.

- CCT increases significantly as PV capacity becomes larger in the case that the demand and supply balance is adjusted without using unit commitment.
- CCT becomes almost the same value in the case that the demand and supply balance is adjusted with the stop of generators.
- CCT becomes smaller in the case of the constant power characteristic. Especially in the case that some generators are stopped, it is possible that CCT decreases slightly compared with the case without PV introduction.

The relationship between voltage characteristic of PV output and synchronous stability depends on the effect of excitation control. Hence, the CCT change considering excitation control should be analyzed theoretically and the change of stability margin should be shown clearly in the future work.

References


Mitsutaka Yoshida was born on September 9, 1986. He is currently a student of Graduate School of Engineering, Yokohama National University in Japan. His research interest is mainly on transient stability analysis of power systems.

Takao Tsuji was born in Japan on November 22, 1977. He received his Dr Eng. degree from Yokohama National University in 2006. In April of the same year, he was appointed as research associate in the Graduate
School of Information Science and Electrical Engineering of Kyushu University. Since April of 2007, he is with Yokohama National University, and his current position is associate professor. His research interests include the planning, operation and control of electric power systems. He is a member of IEEJ and IEEE.

Tsutomu Oyama is a professor at Yokohama National University, Yokohama, Japan. He received his B.S., M.S., and Dr.Eng. Degrees in electrical engineering from the University of Tokyo, Tokyo, Japan, in 1978, 1980, and 1983, respectively. Since 1983, he is with Yokohama National University. His research interests include analysis, operation, and planning of power systems. He is a member of CIGRE, IEEE, Japan Society of Energy and Resources, and IEE of Japan.

Takuhei Hashiguchi received the D.E. degree in Electrical and Electronic Engineering from Osaka University, Osaka, Japan, in 2005. Currently, he is assistant professor at Graduate School of Information Science and Electrical Engineering in Kyushu University, Fukuoka, Japan. His research interests are in the areas of analysis and control of power systems.

Tadahiro Goda was born in Osaka, Japan, in 1949. He received B.E. degree, M.E. degree, and D.E. degree in 1971, 1973, and 1995 respectively from Osaka University. He joined Mitsubishi Electric Corp. in 1973, and engaged in research and development on power system operation and control. He received paper award from IEE of Japan in 1975 and 1991. He has been a professor at Department of Electrical and Electronic Engineering Kyushu University since 2006. His field of interests includes power system dynamic stability of large-scaled power systems, integration of dispersed energy systems, and deregulation of electric power industry.

Hidemi Kihara was born on September 11, 1963. He received his M. Eng. degree in Department of Electrical Engineering, Graduate School from Kumamoto University in 1988. He joined Kyushu Electric Power Company, in April of the same year. In March of 1996, he received Dr. Eng. degree. Since July in 2010, he is with Power System Engineering Group of Research Institute, Engineering Division. His research interests include operation, control, and analysis of power systems.

Fumitoshi Nomiyama was born on May 18, 1969. He received his M. Eng. degree in Department of Electrical Engineering, Graduate School of Engineering from Doshisha University in 1994. He joined Kyushu Electric Power Company in April of the same year. Since July in 2008, he is deputy senior research engineer of Power System Engineering Group of Research Institute, Engineering Division. His research interests include operation, control, and analysis of power systems.

Naoto Suzuki was born on October 4, 1974. He received his Dr. Eng. degree in Graduate School of Science and Technology from Kumamoto University in 2002. He joined Kyushu Electric Power Company, in April of the same year. Since August in 2004, he is with Power System Engineering Group of Research Institute, Engineering Division. His research interests include operation, control, and analysis of power systems.