Positive Effect of PV’s Constant Leading Power-Factor Operation in Power System

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Abstract – Overvoltage problem due to highly penetrated photovoltaic power generation (PV) has been regarded as the foremost concern in distribution network. To find an economical solution for the problem, the authors focus in the inherent ability of present distribution network and PV, and examine whether PV’s “Constant Leading Power-Factor Operation” can mitigate the overvoltage problem enough or not. Simulation based on accurate distribution system model, which is aggregated from many loads/PV using “Y-connection” aggregation method, has revealed that combination of PV’s “Constant Leading Power-Factor Operation” and distribution transformer’s “Line voltage Drop Compensator (LDC)” has important positive effects for solving the problem. Distribution system voltage is kept within the statutory voltage. Frequency of PV output restriction due to overvoltage is reduced. Frequency of tap change on on-Load Tap Changer (LTC) and Step Voltage Regulator (SVR) is also reduced. In addition, no negative effects are recognized in trunk power system.

Keywords: Photovoltaic, Constant leading power-factor operation, Overvoltage problem, Aggregated mode

1. Introduction

In Japan, PV is expected to penetrate up to 53GW by 2030 for reducing CO2 emission. However, highly penetrated PV cause some impacts on power system. In distribution system, overvoltage due to PV is the most serious problem. Many measures are already proposed to solve this problem. Static Var Compensator (SVC), Loop Controller [1], and the other additional voltage regulation equipment on distribution system are the typical. Decentralized autonomous or centralized control of PV’s reactive power [2], [3] has been focused on recently. However in spite of a large investment in those measures, voltage regulation ability of existing distribution system is not examined enough. LTC of distribution transformer, which is one of the most effective voltage controllers, is neglected in most studies. Adequately and strictly aggregated model of existing distribution system that insures reliability of simulation is not used in most studies. To consider the two neglected important factors above, the authors assess whether distribution system voltage (at the secondary terminal of pole transformer) can be kept within the statutory voltage of 101±6V by decentralized autonomous control using only inherent abilities of distribution system and PV.

The most important and effective decentralized autonomous control is the PV’s “Constant Leading Power-Factor Operation”. “Constant (Lagging) Power-Factor Operation” has been commonly used in local hydro power station for a long time, and has sufficient reliability. The second most important and effective decentralized autonomous control is LTC with LDC on distribution transformer. The authors examine these two decentralized autonomous controls by a voltage simulation program (CRIEPI’s V-method). An existing distribution system including distribution transformer with LTC that may be operated due to PV’s reactive power control is introduced as an example. The example having many lighting loads and highly penetrated PV is adequately and strictly aggregated.

2. Strictly Aggregated Model of Existing Distribution Network

It is essential to aggregate existing distribution network strictly to obtain reliable simulation results. The existing distribution network in this paper has a few thousands of loads. In addition, a few thousands of PV will be connected to the network. Therefore, it is impractical to analyze the
network in detail, and some aggregation methods are needed for practical analysis.

However, inadequate aggregation methods may bring quite different results from analysis on detailed network model if the analysis is possible. Therefore, the authors employ "Y-connection" aggregation method, which can approximately and practically maintain active/reactive power loss and voltage drop/rise of network through aggregation. Concept of the aggregation is shown in Fig. 1.

3. Effects of PV’S “Constant Leading Power-Factor Operation” in Distribution Network

3.1 He studied model of distribution network

Structure of the studied distribution network is shown in Fig. 2. Five distribution lines are fed by a distribution transformer with LTC. The network is aggregated into 56 nodes. Each node has series feeding impedance, an aggregated load, and an aggregated PV like the node #509 illustrated in the figure.

3.2 Simulation conditions

- Simulation program: CRIEPI’s V-method
- Voltage on primary side (66kV side) of distribution transformer: constant 1 [p.u.]
- PV are distributed uniformly in proportion to lighting load in each node.
- All PV generate power with the curve shown in Fig. 3.
- Function of PV’s output restriction is not used.
- The substation sending power (P_Ln, Q_Ln) is set to the measured values (shown in Fig. 4) of the model system.
- The substation sending power is distributed to each nodes proportionally to contract capacity of the node’s customers.
3.3 Simulation results

PV’s “Constant Leading Power-Factor Operation” is most effective in suppressing voltage rise in the feeder 4 that has many lighting loads at its ending part.

At first, tap operation of LTC and SVRs are locked. Total PV’s active power (P) in the model is maintained in 7MW, which is expected to penetrate into the model when 53GW capacity of PV penetrate in Japan at 2030 and the PV’s capacity in the feeder 4 is equal to 43% of the maximum capacity of the feeder 4 (5MW). PV’s reactive power output (Q) is set proportional to active power output (P) from Q=0 to Q=-0.4P. Voltage of nodes in feeder 4 is calculated as Fig. 5. Where, P and Q mean sum of PV’s active and reactive power respectively. As PV’s leading reactive power increases, voltage rise is mitigated in feeder 4. In the case of Q=-0.3P, the voltage becomes approximately equal to that before PV’s penetrate.

Fig. 5. Voltage of node points in feeder 4 at 12h.

Fig. 6. Voltage and Tap position of SVR3.

Next, tap operation of LTC and SVRs are used. As a base case, time sequential voltage in P=7MW and Q=0 without LDC on LTC and SVRs is shown in Fig. 6(a).

The voltage fluctuates largely due to PV, and PV’s fast output fluctuation and operation delay of SVR cause temporary overvoltage. As to the LDC case, time sequential voltage at P=7MW and Q=0 with LDC on LTC and SVR3 is shown in Fig. 6(b). The temporary overvoltage still remains. As to the Leading & LDC case, time sequential voltage at P=7MW and Q=-0.2P with LDC on LTC and SVR3 is shown in Fig. 6(c). The temporary overvoltage perishes. Tap position of SVR 3 in the case is shown in Fig. 6(d). PV’s “Leading Power-Factor Operation” can reduce tap change frequency.

Fig. 7. Frequency of over voltage.

To reveal the relation between overvoltage and tap change, the number of occurrences in overvoltage at all
nodes and the number of tap change on LTC and SVR 3 are counted up as affected by PV’s leading power-factor strength. The results are shown in Fig. 7 and Fig. 8(a), (b).

The number of overvoltage occurrence from Q=-0.1P to Q=-0.4P is smaller than at Q=0. However, the number of overvoltage occurrence from Q=-0.5P to Q=-0.6P is larger than at Q=0 in some load patterns. The number of Tap change in LTC from Q=0 to Q=-0.4P is almost constant.

![Graph showing frequency of LTC Tap change](image)

![Graph showing frequency of SVR3 Tap change](image)

**Fig. 8.** Frequency of LTC and SVR3 Tap change.

The number of Tap change in SVR3 becomes smallest from Q=−0.2P to Q=−0.3P. Effect of leading power-factor from Q=0 to Q=−0.1P is recognized as insufficient. Stronger leading power factor as Q=−0.4P to Q=−0.6P brings a negative effect that low voltage due to leading power factor causes unnecessary tap change (up) in SVR3. Combination of PV’s “Leading Power-Factor Operation” in Q=−0.2P to Q=−0.3P and LDC reduces the number of overvoltage occurrence, which means PV’s output restriction.

### 4. Effects of PV’S “Constant Leading Power-Factor Operation” in Trunk Power Systems

Impact of synchronized output change of highly penetrated PV on trunk power system is assessed in this chapter. As a very severe case, all PV in Hokuriku region are supposed to change their output synchronously within only 10 minutes.

### 4.1 Model of the trunk power system

Structure of the model is shown in Fig. 9. The system, which connects to outer system by only one tie-line, has 2 generators and 1 load. PV is connected to the load. Branches 10 to 50 represent trunk power system (154kV or higher voltage), branches 60 to 90 represent secondary system (66 or 77kV). In the figure, 1.5GW PV’s output and 5GW load correspond to penetrated PV’s capacity and peak load in 2030.

![Diagram of trunk power system](image)

**Fig. 9.** Model of trunk power system.

### 4.2 Simulation conditions

- Simulation program: CRIEPI’s V-method
- Power of 0.5GW constantly flows out toward the outer system through Branch＜10＞, and load is 5GW.
- Trunk power system has a group of reactors (ShR, capacity: 30MVA) that is switched-on/off to maintain reactive power that flows through Branch＜10＞ at the reference value. (Dead band: 2%)
- The system has a group of capacitors (SC, capacity: 30MVA) that is switched-on/off to maintain primary reactive power of primary transformer (Branch-50) in 154/66(77) kV class at the reference value. (Dead band: 2%)
- Each voltage on the secondary side of primary transformer and distribution transformer (Branch-90) is controlled by LTC. (Nominal voltage: 1 [p.u.], Dead band: 2%)
- Unit tap notch of primary and distribution transformer is 0.012 and 0.013[p.u.].
- Output of generator G1 is controlled for frequency regulation and load following. Output of generator G2 is kept constant.
- Reactive power of generator G1 is kept constant.
- Terminal voltage of generator G2 is kept constant.
After 10 minutes since the simulation starts, PV’s output increases from 0.2GW to 1.5GW in 10 minutes.

Reactive power of PV is set from Q=0 to Q=-0.6P by a step of 0.1P.

4.3 Simulation results

A) Active power by generator and active power loss

Active and reactive power loss ($P_{LOSS(n-m)}, Q_{LOSS(n-m)}$) from Branch-$<n>$ to Branch-$<m>$ is calculated as follows:

\[
P_{LOSS(n-m)} = \sum_{k=n}^{m} \left( \frac{P_k^2 + Q_k^2}{V_k^2} \right) \text{[MW]} \quad (1)
\]

\[
Q_{LOSS(n-m)} = \sum_{k=n}^{m} \left( \frac{P_k^2 + Q_k^2}{V_k^2} \right) X_k \text{[MVar]} \quad (2)
\]

Where $k$ is number of Branch (10, 20, ..., 100), $n,m$ is start node number and end node number of the Branch, $P_k$ is active power of Branch-$<k>$ at receiving end [MW], $Q_k$ is reactive power of Branch-$<k>$ at receiving end [MVar], $R_k$ is resistance of Branch-$<k>$ [Ω], $X_k$ is reactance of Branch-$<k>$ [Ω], $V_k$ is voltage of Branch-$<k>$ at receiving end [kV].

Active power loss ($P_{LOSS(10-100)}$ from Q=0 to Q=-0.6P) in the model system are shown in Fig. 10. $P_{LOSS(10-100)}$ decreases due to variation of power flow from generator to load. Since $R_k$ is very small, the difference in $P_{LOSS(10-100)}$ before and after PV’s output change (0.12 to 0.14GW) is very small compared to the PV’s output change (1.3GW). Therefore, operating PV’s active power from Q=0 to Q=-0.6P, the difference in $P_{LOSS(10-100)}$ is also very small. “Constant Leading Power-Factor Operation” can’t make a great impact for $P_{LOSS(10-100)}$.

B) Reactive power by generator and reactive power loss

Since reactive power through Branch-50 is kept within ±0.02GVar due to SC switched-on/off as described in the simulation conditions, we present both $Q_{LOSS(10-40)}$ and $Q_{LOSS(50-100)}$ respectively when PV operates at Q=0 to Q=-0.6P. The results are shown in Fig. 11. $Q_{LOSS(10-40)}$ and $Q_{LOSS(50-100)}$ decreases due to decrease of power flow from generator to load. Since $X_k$ is not small, the difference in $Q_{LOSS(10-40)}$ and $Q_{LOSS(50-100)}$ through PV’s output change is very large. However, difference of reactive power loss (0.01, 0.05GVar) by PV’s reactive power operation (Q=0 to Q=-0.6P) is very small. “Constant Leading Power-Factor Operation” can’t make a great impact for $Q_{LOSS(10-100)}$.

To maintain adequate voltage in trunk power system, surplus/shortage of reactive power must be balanced by ShR and SC in next section.

C) Reactors

Fig. 12. Reactive power loss and Capacity of ShR (Q=-0.3P). $Q_{LOSS(4)}$, $Q_{LOSS(10-40)}$, and Reactors (Q =-0.3P) in model system are shown in Fig. 12. $Q_{LOSS(10-40)}$ decreases with
increasing PV’s output due to decrease of power flow from generator to load. As the result, reactive power balance is maintained by switching-on Reactors, which is the nearly equal to the decreased QLOSS(10-40). Amount of switching-on Reactors is hardly affected by PV’s reactive power operation from Q=0 to Q=-0.6P. “Constant Leading Power-Factor Operation” can’t make a great impact on Reactors operation.

**D) Capacitors**

![Image](QLOSS.png)

QLOSS(k) from Branch-50 to Branch-100 are shown in Fig. 13(a). Reactive power of Capacitors, G2, PV and their sum \( \Sigma Q(SC+G2+PV) \) are shown in Fig. 13(b). Similarly to before section, QLOSS(50-100) decreases with increasing PV’s output. On the contrary, reactive power balance is maintained by switching-off of Capacitors. \( \Sigma Q(SC+G2+PV) \) is nearly equal to the decreased QLOSS(50-100). Capacity of operating Capacitors by PV’s reactive power operation (Q=0 to Q=−0.6P) is shown in Fig. 13(c). When PV’s leading power-factor operation is strengthened from Q=0 to Q=−0.4P, amount of switching-off Capacitors decreases in inversely proportion to strength of PV’s leading power-factor operation. As operating PV’s reactive power is strengthened from Q=−0.5P to Q=−0.6P, reactive power balance is maintained by switching-on Capacitors. Thus, “Constant Leading Power-Factor Operation” provides optimal effect for Capacitors operation compared to Q=0.

**E) The tap variations of primary and distribution transformer**

![Image](TapVariations.png)

The tap variations of primary and distribution transformer are shown in Fig. 14. Primary voltage of primary transformer rise because QLOSS(40) decreases with increasing PV’s output. As a result, the tap position of primary transformer shifts down. When PV’s leading power-factor operation is strengthen from Q=0 to Q=−0.4P, primary voltage of distribution transformer rises because QLOSS(60) and QLOSS(80) decreases with increasing PV’s output. But the tap position of distribution transformer don’t shifts down caused by shift down of primary transformer tap on ahead. When PV’s leading power-factor operation is strengthen from Q=−0.5P to Q=−0.6P, the tap position shifts up because secondary voltage of distribution transformer falls below the lower limit of the dead band by tap shift down of primary transformer. Thus the simulation results suggest that “Constant Leading Power-Factor
Operation” at Q=0~0.4P can’t make a great impact for the tap change of primary and distribution transformer.

F) Effects of PV’s “Constant Leading Power-Factor Operation” in Trunk Power System

As demonstrated above by PV’s “Constant Leading Power-Factor Operation”, switching frequency of ShR and LTC on connection primary transformer never increases in trunk power system (154kV or higher), that of SC slightly decreases at secondary system bus (66 to 77kV), and that of LTC on distribution transformer never increases from Q=0 to Q=-0.4P. Since reactance is quite larger than resistance in trunk power system, PV’s output fluctuation occur a large change in reactive power loss, and as the result, burden of reactive power regulation equipments quite increases. PV’s “Constant Leading Power-Factor Operation” that absorbs reactive power with increasing PV’s output will mitigate the burden.

5. Conclusions

As a typical high PV penetration case, a distribution network fed by a distribution transformer with LTC and LDC is studied. PV penetrates uniformly into lighting loads. Simulation results suggest that PV’s “Constant Leading Power-Factor Operation” brings following positive effects in voltage and reactive power regulation.

1) Combination of the proposed PV’s reactive power operation and LDC on distribution transformer successfully reduces the number of occurrences in overvoltage due to PV’s output.

2) Combination of the proposed PV’s reactive power operation from Q=-0.2P to Q=-0.3P and LDC on distribution transformer reduces the tap change on distribution transformers and SVR. Frequency of PV’s output restriction is also reduced.

3) Compared to conventional Q=0 operation, the proposed PV’s reactive power operation from Q=-0.1P to Q=-0.4P does not give negative impact on trunk power system.

These positive effects demonstrated above are seen from utility’s point of view. From customer’s point of view, it is a disadvantage that the proposed PV’s reactive power operation at Q=-0.2P increases PV’s current by 2% above than Q=0 operation. In addition, Q=0 operation is the better for mitigating active power loss in network. However PV voltage at its high power output will be higher than 102%, and Q=-0.2P operation hardly bring PV’s inverter overcurrent and PV’s output restriction. Therefore, the authors conclude that PV’s “Constant Leading Power-Factor Operation” at Q=-0.2P is favorable.

References