Design of Capacitor Bank in Parallel to Photovoltaic Power Plant

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Abstract: The purpose of the paper is to develop a solution for application of PV (photovoltaic) generators in MV (medium voltage) distribution system without unacceptable voltage changes due to drops of PV power output. The proposed solution includes operation of PV with predetermined leading power factor and addition of a capacitor bank in parallel to PV plant in order to compensate the reactive power absorbed by the PV inverters. The analytical expression of required power factor angle is derived. Adding a capacitor bank in parallel to PV power plant may pose a problem because of space limitations. The dimensions and cost of small MV capacitor banks depend significantly on the capacitor bank protection against internal faults. Application of the developed negative-sequence current difference method for the unbalance protection of the capacitor banks enables to achieve a compact and cost-reduced design of the banks connected in parallel to PV power plants. A real-world example of operation of the PV plant in parallel to the capacitor bank with the novel protection scheme is described.

Key words: Photovoltaic power plant, power quality, capacitor bank, unbalance protection.

1. Introduction

Nowadays, the traditional, conventional power system is facing the problems of gradual depletion of fossil fuel resources, poor energy efficiency and environmental pollution. These problems have led to DG (distributed generation)—a new trend of generating power locally at distribution voltage level by using renewable energy sources like wind power and solar photovoltaic cells [1-4].

DG is now being promoted worldwide as a means of solving a number of technical, environmental, political and social problems [2, 3]:

- cut down greenhouse gas emissions;
- decrease dependence on fossil fuel resources;
- create high-technology jobs;
- rely on market forces and consumer choice;
- reduce transmission and distribution losses.

In order to encourage application of the renewable energy sources more than 50 countries all over the world have introduced a feed-in-tariff [4].

On December 28, 2009, the Israeli Public Utility Authority approved a feed-in tariff for PV (photovoltaic) power plants. Up till now the IECo (Israel Electric Corporation) has received 330 proposals for connection of private PV to the company MV (medium voltage) distribution system. The total power of the future PV plants is 1,580 MW.

According to the Israeli government goal, about 10% of the total kWh production in Israel will be generated by renewable energy power plants in 2020.

In compliance with the system study performed in IECo, the installed power of a distributed generator connected to the company distribution system at the voltage levels of 22 kV and 33 kV should lie in the range of 1-11 MW.

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According to the analysis performed in Ref. [5] PV integration in distribution systems is twofold. On the one hand, PV systems, when properly sized and placed, can reduce feeder losses, improve feeder voltage profile, and diminish lifetime operation and maintenance costs of transformer load tap changers. One the other hand, randomness in the output power of PV systems due to irregular solar radiation is considered to be one of the main drawbacks of the large-scale application of PV in distribution networks. Moving clouds can produce fast irradiance fluctuations, which can cause rapid voltage changes at the PCC (point of common coupling) of the PV plant and the distribution system. This effect is the most important in weak distribution systems with high series resistance.

The above rapid voltage changes at the point of PV plant connection may have adverse effects on the nearby customers. The inability to maintain power quality at PCC may impose limitations on power capacity of PV plants.

The work objective is to develop a simple, low-cost solution for large scale application of PV plants in real-world distribution system that enables to limit voltage changes due to sudden reduction of power output of PV as well as to maintain the voltage and reactive power control in the system with DG. The proposed solution should be technically and economically feasible for private PV plants.

2. Solution Formulation

The voltage changes at the point of PV plant connection to a distribution system due to sudden drop of PV power output, when the PV operates with unity power factor, are usually analyzed in the circuit shown in Fig. 1 [5].

The voltage change can be analytically studied using the circuit shown in Fig. 2.

The voltage source $V_S$ is the voltage at the PCC, when PV plant is in no-load state. The resistance $R$ and reactance $X$ represent the short-circuit impedance of the distribution system at the PCC that includes the impedances of HV (high voltage) transmission system, the utility transformer and the feeder (Fig. 1).

The sudden drop of power output of PV plant $P$ results in voltage drop at the PCC from $V$ to $V_S$. The pu voltage drop $\Delta V$ is proportional to the product of the PV power output $P$ and the equivalent system resistance $R$:

$$\Delta V = \frac{V - V_S}{V} = \frac{PR}{V^2} \quad (1)$$

One can see that the voltage drop at PCC point of PV plant with high power capacity connected to a weak distribution system may exceed the permissible voltage change. The problem is illustrated using a real-world case of PV plant connection to IEC 33 kV distribution system (Fig. 1). The utility is represented by a 161/36 kV step-down transformer fed from an infinite HV busbar. The equivalent parameters of the transformer are: MVA rating 45 MVA; short-circuit impedance -18%; pu copper losses -0.00375. The system source strength at the MV utility busbars is 250 MVA.

The distance between the substation 33 kV busbars
and the PCC is 35 km. The PV is connected to a typical distribution feeder with specific impedance of 0.24 + 0.35j \Omega/km. According to IECo requirements, the maximum voltage change $\Delta V_{\max}$ due to sudden load change/disconnection of private power plant shall not exceed 2.5%.

Assume a fast irradiance decrease due to a moving cloud, resulting in power drop of the PV plant from its installed power capacity to zero. The voltage change at the PCC versus installed power of the PV plant is shown in Fig. 3.

The curve in Fig. 3 shows that if installed power of the PV plant exceeds 3.17 MW, the 100% power drop may lead to unacceptable voltage change at PCC.

In order to limit the voltage change due to PV power drop the PV power plant should work with leading power factor [5]. The reactive power $Q$ absorbed by the PV plant inverters can be presented as a product of power output $P$ and $\tan \varphi$ of PV plant (Fig. 4):

$$Q = P \tan \varphi$$  \hspace{1cm} (2)

Operation of PV with predetermined negative $\tan \varphi$ should reduce the voltage drop $\Delta V$ at the PCC in the case of sudden reduction of PV power output $P$ due to reactive power flow:

$$\Delta V = \frac{V - V_S}{V} = \frac{PR - QX}{V^2}$$  \hspace{1cm} (3)

The component of voltage drop caused by the reactive power flow $QX/V^2$ is in antiphase to the component caused by sudden reduction of active power $PR/V^2$. Absorption of the reactive power $Q$ proportional to the generated active power $P$ may reduce the voltage drop $\Delta V$ to zero. On the other hand, absorption of considerable amount of the reactive power may significantly increase kva rating of the PV plant inverters. It may be prudent to select the value of $\tan \varphi$ from the condition that the voltage drop $\Delta V$ does not exceed its permissible value $\Delta V_{\max}$:

$$\tan \varphi = \begin{cases} 0 & \text{if } \frac{PR}{V^2} \leq \frac{\Delta V_{\max}}{100} \\ \frac{V^2}{P \times 100} \times \frac{\Delta V_{\max} - R}{X} & \text{otherwise} \end{cases}$$  \hspace{1cm} (4)

The above expression enables to calculate the value of $\tan \varphi$ corresponding to the minimal amount of the absorbed reactive power $Q$ that is needed to produce power $P$ without unacceptable voltage changes due to 100% power drop.

The required leading power factor $pf$ and the absorbed reactive power $Q$ can be determined on the base of $\tan \varphi$. The power factor $pf$ and reactive power $Q$ versus active power $P$ for the considered case of a PV connection to the 33 kV distribution network are shown in Figs. 5 and 6.

One can see that if the installed power of PV plant exceeds 3.17 MW, it should operate with non-unity power factor. The $pf$ goes down with $P$ increase. It arrives at 0.944, if the installed power of PV plant reaches 11 MW.
In order to enable operation of PV power plants with leading power factor without increase of the reactive power flow in the distribution system it is proposed to connect a capacitor bank to PCC in parallel to PV plant (Fig. 7).

A capacitor bank is connected by an individual circuit breaker to PCC in parallel to the PV installation. Its reactive power $Q_C$ is selected to compensate the reactive power $Q$ absorbed by the PV inverters. As a result, the PV plant together with its capacitor bank is seen by the distribution system as a generator with controllable reactive power.

If the PV plant produces its rated active power $P$, the reactive power flow to the PCC is $Q_C - Q$, i.e., is close to zero. In the case of a sudden drop of the PV power output due to rapid irradiance change of the sun or because of some failure, the sudden power variation seen at the PCC is $P - jQ$.

If the PV plant operates with predetermined $\tan \varphi$ calculated in compliance with Eq. (4), 100% power drop of the PV will result in the permissible voltage change at the PCC.

3. Design of Capacitor Bank in Parallel to PV Power Plant

The capacitor banks with their circuit breakers will be supplied by private PV plants, operating with leading power factor in order to reduce the maximum voltage change to its permissible value. Switching of the banks will be performed by the power utility in order to perform voltage control at PCC. The rated power of the banks should be close to the maximum reactive power absorbed by the PV inverters under the following limitations [6]:

$$0.5 |P \tan \varphi| \leq Q_C \leq 0.02 S_{SC} \quad (5)$$

In Eq. (5) $P \times \tan \varphi$ is a maximum reactive power absorbed by PV inverters; $S_{SC}$ is a short-circuit power at PCC.

IECo distribution networks usually use low-impedance grounded neutral or resonant grounded
neutral. This is why capacitor units of the capacitor banks should be connected into ungrounded wye or ungrounded double-wye [7].

In order to minimize a number of restrikes during switching the capacitor banks on daily basis, the circuit breakers of capacitor banks should be selected in compliance to the definitions of class M2 of mechanical operation duty and class C2 of capacitive current switching operations [8, 9].

In densely populated countries the lion share of the area allocated for PV plant is used by PV arrays. Designers of PV plants make every effort to install the rest of electrical equipment, i.e., inverters, transformers, circuit breakers in a very limited space, for example, inside some substation building.

According to our experience, adding a capacitor bank in parallel to PV plant may pose a difficult problem because of very limited space available for its installation. In some cases the capacitor banks built in compliance with standard capacitor bank designs [6, 7] could not be installed because of the space limitations. This is why it is very important to develop a compact capacitor bank design for capacitor banks applied in parallel to PV power installations.

A footprint area required for a capacitor bank depends on number of capacitor units and type of protection against internal faults. According to Ref. [6], rated power of MV capacitor units varies from 50 kvar to 1,000 kvar. Thus, it is possible to design a capacitor bank with rated power up to three MVAr using 3 capacitor units only.

Using the neutral current for the unbalance detection requires connection of the capacitor units unto a double-wye with CT (current transformer) connected between the wye neutrals [7]. In this case the capacitor bank should include at least six capacitor units (Fig. 8). The increased number of capacitor units and the neutral CT enlarge the footprint area of the capacitor bank.

![Fig. 8 Traditional protection schemes of an ungrounded MV capacitor bank.](image)
Utilizing the neutral voltage for the unbalance protection allows connection of the capacitor units into a single-wye with a VT (voltage transformer) between the bank neutral and the ground. A separate surge arrester may also be necessary to protect the VT (Fig. 8). The VT and surge arrester increase the footprint area of the capacitor bank as well as its cost.

The typical protection of a capacitor bank connected to MV network through a separate circuit breaker also includes other functions such as an overcurrent protection, a protection against ground faults, overvoltage and undervoltage protection (Fig. 8) [7].

The above functions are based on measurement of the capacitor bank phase currents $I_a, I_b$ and $I_c$ as well as on measurement of phase to ground voltages $V_a, V_b$ and $V_c$.

The Israel Electric in cooperation with Cooper Power Systems has developed a patented, cost-reduced approach to detecting unbalances within ungrounded capacitor banks [10, 11]. The new technique is based on an algorithm that uses the NSCD (negative-sequence current difference) to provide unbalance detection without any voltage or current transducer in the bank neutral (Fig. 9).

The idea of the new protection algorithm is based on the fact that any failure of capacitor elements or capacitor units inside the capacitor bank results in appearance of the negative-sequence current, which magnitude is proportional to the asymmetry of the capacitor bank phase capacitances caused by the failure.

On the other hand, it is necessary to distinguish between the negative-sequence current caused by internal failures inside the capacitor bank and between the negative-sequence current that may appear due to other reasons. The negative-sequence current of the capacitor banks may be caused by the system voltage unbalance at the capacitor bank terminals $V_1$ and $V_2$, as well as by the inherent phase unbalance due to manufacturing tolerance (i.e., not all phases of the bank have identical capacitance).

The predetermined negative-sequence current $I_{2un}$ is calculated on the basis of positive-sequence and negative-sequence voltages at the capacitor bank terminals $V_1$ and $V_2$, as well as on the basis of positive-sequence capacitor bank current $I_1$:

$$I_{2un} = ((Y_{21C})V_1 + (Y_{11C})V_2)\times\frac{I_1}{V_1Y_{11C}}$$

(6)

In Eq. (6) $Y_{11C} = G_{11C} + jB_{11C}$ and $Y_{21C} = G_{21C} + jB_{21C}$ are elements of the sequence admittance matrix of the shunt bank calculated when the bank was being commissioned. These values are kept in non-volatile memory of the protective device implementing the techniques.

The positive-sequence and negative-sequence currents $I_1$, $I_2$ and the positive-sequence and negative-sequence voltages $V_1, V_2$ are calculated on the basis of the measured capacitor bank phase currents $I_a$, $I_b$, $I_c$ and voltages $V_a$, $V_b$ and $V_c$ (Fig. 9).
The algorithm for calculation of the above matrix elements $Y_{11C}$ and $Y_{21C}$ is detailed in Ref. [11].

The predetermined negative-sequence current $I_{2un}$ takes into account the following factors (Eq. (6)):

- Negative-sequence current due to unbalance of the system voltages represented by the term $Y_{11C} \times V_2$;
- Negative-sequence current due to the inherent unbalance in the bank due to manufacturing tolerances represented by the term $Y_{21C} \times V_1$;
- Change of the capacitor bank capacitance with temperature variations represented by the ratio $I_1/V_1 \times Y_{11C}$.

The vector difference $I_{UN}$ between the phasors $I_2$ and $I_{2un}$ does not depend on the system voltage unbalance, the inherent unbalance of the capacitor bank or on changes of the bank capacitance with ambient temperature

$$I_{UN} = I_2 - I_{2un} \quad (7)$$

The NSCD (negative-sequence current difference) $I_{UN}$ is proportional to the internal asymmetry of a protected bank due to internal faults (capacitor elements failures requiring a protective response from the protection).

The protection detects an internal fault, when $I_{UN}$ exceeds a predetermined threshold.

The proposed NSCD method was implemented in iCP-630 Idea Relay developed by the Cooper Power Systems [12].

Application of the protection method for capacitor banks in parallel to PV plants enables to achieve a compact and cost-reduced design of the banks.

### 4. Application Example

An example of a capacitor bank design is shown in parallel to PV plant connected to a 33 kV distribution system (Fig. 1). The parameters of the 161/36 kV step-down transformer and the distribution feeder are given above. The installed power capacity of the PV plant is 5 MW. Operation of the PV with unity power factor may cause unacceptable voltage changes at the PCC due to 100% power drops (Fig. 3).

The minimum values of tan$\varphi$ of the PV plant and the reactive power $Q$ absorbed by the PV invertors calculated to limit the voltage change $\Delta V$ at the PCC to 2.5% (Eqs. (2) and (4)) as well as the selected values of tan$\varphi$ and $Q$ are given in Table 1.

To compensate the reactive power $Q$ absorbed by the PV invertors a capacitor bank with output of 1,000 kvar at 33 kV should be applied. Taking into account that the rated voltage of the capacitor bank must not be less than the maximum system voltage (36 kV) the capacitor bank of 36 kV, 1,200 kvar was selected [6].

A capacitor bank that was proposed for the PV power plant was based on standard capacitor bank design (Fig. 10).

<table>
<thead>
<tr>
<th>Minimum values</th>
<th>Selected values</th>
</tr>
</thead>
<tbody>
<tr>
<td>tan$\varphi$</td>
<td>-0.179</td>
</tr>
<tr>
<td>$Q$ (absorbed kvars)</td>
<td>896</td>
</tr>
<tr>
<td>$\Delta V$ (%)</td>
<td>2.5</td>
</tr>
</tbody>
</table>

### Fig. 10 Design of the capacitor bank using a traditional unbalance protection.
Table 2 Comparison of the footprints and the costs of 1,200 kvar, 36 kV capacitor bank.

<table>
<thead>
<tr>
<th>Protection Method</th>
<th>Width × Depth (mm)</th>
<th>Budget Price ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double-Y current unbalance</td>
<td>3,100 × 1,200</td>
<td>14,600</td>
</tr>
<tr>
<td>NSCD protection</td>
<td>1,100 × 350</td>
<td>6,700</td>
</tr>
</tbody>
</table>

Fig. 11 Design of the capacitor bank using NSCD protection.

The bank included 12 unfused capacitor units of 10.39 kV, 100 kvar connected into double-wye. Each phase in one wye was comprised of two double-bushing capacitors connected in series. The CT for unbalance protection was connected between the wye neutrals.

The dimensions of the proposed capacitor bank (Fig. 10) exceeded the space available for capacitor bank installation in the PV plant.

The alternative design proposed by IECO included the Cooper iCP-630 Idea Relay used as a relay for overall capacitor bank protection and a compact capacitor bank, composed of three capacitor units. The proposed capacitor bank design is shown in Fig. 11.

The capacitor bank includes three single-bushing 400 kvar, 20.78 kV capacitors connected into a single-wye with floating neutral. The dimensions and cost of the bank in comparison to the dimensions and cost of the bank using the traditional protection method are shown in Table 2.

The data in Table 2 illustrate that application of the NSCD protection method enables to reduce significantly the capacitor bank footprint as well as its cost.

The proposed compact capacitor bank was installed in the substation building of the PV plant. The capacitor bank with its circuit breaker and the protection relay using the NSCD technique were commissioned and put into operation together with the PV plant.

5. Conclusions

In order to reduce the rapid voltage changes at the terminals of PV plants a simple, low-cost solution is developed. The solution includes operation of PV with predetermined leading power factor and addition of a capacitor bank in parallel to PV plant in order to compensate the reactive power absorbed by the PV inverters.

A simple analytical expression for the required power factor angle of the PV generator is derived.

Adding a capacitor bank in parallel to PV power plant may pose a problem because of space limitations. The dimensions and cost of small MV capacitor banks depend significantly on the relay protection scheme against internal faults.

The Israel Electric in cooperation with Cooper Power Systems has developed a NSCD method for the unbalance protection of ungrounded capacitor banks. The new technique enables to detect internal faults without any voltage or current transducer in the bank neutral.

Application of the protection relay implementing NSCD method enables to achieve a compact and cost-reduced design of the banks connected in parallel to PV power plants.

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References


