OVERVOLTAGE DUE TO SINGLE AND THREE-PHASE CONNECTED PV

Enock MULENGA
Luleå University of Technology-Sweden
enock.mulenga@ltu.se

Math H. J. BOLLEN
Luleå University of Technology-Sweden
math.bollen@ltu.se

Nicholas ETHERDEN
Vattenfall R & D-Sweden
nicholas.etherden@vattenfall.com

ABSTRACT
This paper presents the overvoltage caused by single and three-phase connected PV to a low-voltage distribution grid. Statistics are obtained based on source-impedance data for 40,000 customers. A stochastic approach is applied to a 28-customer low-voltage network and the probability of overvoltage is assessed. It is shown that the voltage rise due to single-phase connected PV is six times the rise for three-phase connected PV.

To mitigate the overvoltage, grid-reinforcement, reactive power compensation, curtailment and coordinated connection of PV can be used. It is shown that reactive compensation is not effective in LV grids due to high R/X ratio. Coordinated connection helps in reducing the overvoltages caused by single-phase PV.

Policy suggestions towards three-phase PV installations and coordinated single-phase PV connections are included in the paper.

INTRODUCTION

The most significant electrical obstacle to the connection of considerable amount of solar photovoltaics (PV) installations to low-voltage grids is the voltage rise due to the injected power [1-4]. Already a smaller quantity of PV can produce undesirable overvoltages at some locations [5].

In this paper, the impact of individual and multiple PV connections will be studied. The voltage rise caused by single-phase and three-phase connected PV in a distribution grid has been calculated for 40,000 low-voltage customers. A stochastic approach is introduced and used to determine the hosting capacity for single and three-phase connected PV as a function of the PV size. Policy suggestions and a discussion of some mitigation methods concludes the paper.

VOLTAGE RISE DUE TO INDIVIDUAL UNITS

The voltage rise at the point of common coupling (PCC) is different for single-phase and three-phase PV connection.

The voltage rise \( \Delta U \) caused by an injected current \( I \) with a power factor \( \cos \phi \) can be approximated by (1):

\[
\Delta U = R_{eq}I\cos \phi + X_{eq}I\sin \phi
\]  

Where \( R_{eq} + jX_{eq} \) is the source impedance at the PCC. For a solar PV installation injecting active power only, \( \cos \phi = 1 \).

Single-phase connected PV

If the voltage at the PCC is close to the nominal phase-to-neutral voltage, the per-unit voltage rise due to single-phase injected power \( P_{1-\varnothing} \) can be approximated using (2):

\[
\Delta U_{1-\varnothing} = \frac{\Delta U_{1-\varnothing}}{U_{n1-\varnothing}} \approx \frac{R_{ef} \cdot P_{1-\varnothing}}{U_{n1-\varnothing}^2}
\]

Where \( R_{ef} \) is the resistive part of the earth-fault impedance, and \( U_{n1-\varnothing} \) the nominal phase-to-neutral voltage.

Three-phase connected PV

For three-phase injected power \( P_{3-\varnothing} \), if the voltage is assumed to be close to its nominal value, the per-unit voltage rise can be approximated using (3):

\[
\Delta U_{3-\varnothing} = \frac{\Delta U_{3-\varnothing}}{U_{n3-\varnothing}} \approx \frac{R_{sc} \cdot P_{3-\varnothing}}{3 \cdot U_{n3-\varnothing}^2}
\]

Where \( R_{sc} \) is the resistive part of the short-circuit impedance.

The source impedance for 40,000 low-voltage customers in two rural and semi-urban networks in Sweden has been used together with (2) and (3) to compare the voltage rise for single-phase and three-phase connected PV with 6 kW production. The probability distribution functions of the obtained results is shown in Figure 1. For single-phase connection, the voltage rise will exceed 3% at about half of the locations and exceed 5% at some 25% of the locations. For three-phase connection, the voltage rise is below 2% at almost all locations.

![Figure 1: Single and three-phase probability distribution functions for the calculated voltage rise with each PV size of 6,000 W and up to 10 % permissible voltage rise.](image-url)

The resistive part of the earth-fault impedance is compared with that of the short-circuit impedance. The probability...
density plot of the ratio between the resistances is shown in Figure 2.

![Probability density of the ratio of the resistive part of earth-fault and short-circuit impedance](image)

Figure 2: Probability density of the ratio of the resistive part of earth-fault and short-circuit impedance.

The ratio has minimum, maximum and mean values of 0.81, 8.25 and 2.16. From (2) and (3), the relation between voltage rise for single-phase and three-phase connection of the same amount of injected power:

\[
\frac{\Delta U_{1-\phi}}{\Delta U_{3-\phi}} = 3 \frac{R_{ef}}{R_{sc}}
\]

(4)

The ratio between the source resistances in the right-hand side of (4) is, for the majority of locations, between 1.5 and 3, see Figure 2. The voltage rise for a single-phase connection is, according to (4), between 4.5 and 9 times as much as for a three-phase connection, with an average of about 6.5.

**LV DISTRIBUTION STUDY GRID**

A 28-customer suburban low-voltage distribution grid in Northern Sweden is used to assess the impact of single-phase and three-phase connected PV on overvoltages. As is common in Scandinavia, this is a three-phase network all the way to the customers. Figure 3 shows the network structure and customers.

The distribution grid model built for Figure 3 is simple, linear and comprising node-impedance matrix. The node-impedance is obtained with calculations involving positive and zero-sequence series impedance of branches.

![28-customer distribution grid showing the feeder cables with lengths, transformer and cable cabinets (B2-B18). The colours of the individual houses are randomly chosen.](image)

Figure 3: 28-customer distribution grid showing the feeder cables with lengths, transformer and cable cabinets (B2-B18). The colours of the individual houses are randomly chosen.

The shunt impedance (capacitance) for the cables is not considered in this model. The model is built in Matlab environment and stochastic approach used to determine the overvoltage.

**STOCHASTIC HOSTING CAPACITY**

The overvoltage due to single-phase and three-phase connected PV for the distribution grid model was studied using the stochastic approach described below. For calculation of the voltage rise, the transfer impedance matrix and the associated superposition principle are used, as shown in (5) below. The assumption behind this calculation method is that the system is linear. The injected current is calculated for the given injected power assuming the nominal voltage. The reduction of injected current, for constant injected power, with increased terminal voltage is not considered in the model. This will somewhat underestimate the hosting capacity, but the error not be dominating, considering the various other uncertainties.

**Stochastic approach**

Stochastic approaches to the hosting capacity have been used by a number of authors [6-8]. The method used in this paper has been proposed in [10] and applied first to voltage rise in [6]. The method comprises of the following steps:

1. The hours of the year in which the production from solar PV is high are used to obtain the probability distribution function of the pre-installation no-load voltage in the grid. These voltages arise from the medium-voltage side of the grid.
2. A probability distribution function of the range of lowest consumption during the highest solar PV production hours of the year.
3. A probability distribution function of the 10-minute period solar PV production per installation that has highest effect when considered as a unit. This could be called the “after diversity maximum production” to be used next to the “after diversity maximum consumption”
4. Addition of solar PV power at random customers and in random phases. This is followed by calculation of the worst-case voltage distribution with increasing amount of solar PV.
5. Defining the performance index or indices for the distribution grid, selection of a suitable limit, and determining the hosting capacity. As performance index was used the 90th percentile of the voltage for each of the customers; 110% of the nominal voltage was used as a limit. The hosting capacity is the highest amount of PV for which the performance indices do not exceed their limits.

**Determination of overvoltage**

The transfer impedance matrix (together with the superposition principle) estimates the overvoltage by determining the influence of connected PV at one bus in the grid to another bus. Equation 5) shows the expression used to determine the voltage \(U_f\) at location \(f\) due to the influence of PV at a location \(g\)
\[ U_f = U_0 + \sum_{i=1}^{N} Z_f g \times (I_{SPVn} - I_{constn}) \] (5)

In (5), \( U_0 \) is the pre-installation voltage at the location during the periods with highest expected solar-power production. This voltage is the 10-minute average around noon during the summer period and the values should preferably be obtained from measurements. In this study, the values used is between 238 and 242 V.

The current \( I_{constn} \) is the 10-minute consumption per customer per phase during the sunny hours of the year. In this study, the consumption is assumed to be uniformly distributed between 0 and 250 W. The impedance \( Z_f g \) is the phase-to-neutral transfer impedance.

In determination of overvoltage, random and stochastically independent variables in the distribution grid model are used. The solar PV installations are distributed in a random way over the customers and phases in the model.

The forthcoming sections discuss voltage rise due to random connection of single-phase units and compare the results with coordinated phase allocation and three-phase units.

**SINGLE-PHASE CONNECTED PV**

Monte-Carlo simulations with 10,000 samples were used to obtain customers and phases with PV combinations for the network. This was performed by adding typical residential PV systems of 6 kW to 5, 9, 14, 19, 23 and 28 customers. The results for the probability distribution functions are shown in Figure 4.

Figure 5 shows the 90th percentile for each of the 28 customers compared with the overvoltage limit. The result shows that only three customers can be equipped with PV before the 110 % limit is exceeded.

The plots in Figure 4 shows how the customers’ overvoltage shift to higher values as the number of customers with single-phase PV increases. Already for five customers with PV, there is a non-zero probability that a customer surpasses the overvoltage limit of 110 %. The increase in the number of customers with PV up to 28 increases this probability. From the probability distribution plot in Figure 4 and considering the 90th percentile with a 110 % overvoltage limit, Figure 5 is obtained.

![Figure 4: Probability distribution for the highest worst-case voltage for increasing amount of single-phase PV](image)

![Figure 5: 90th percentile of the worst-case overvoltage as a function of the number of customers for 6 kW single-phase connected PV](image)

The hosting capacity is defined, from Figure 5, as the highest number of customers with PV for which none of the 90th percentile values exceeds 110% of the nominal voltage. The hosting capacity, for injected power from 1 kW to 7 kW, is shown in Figure 6. In reality, the injected power per installation will be less than the inverter size but for practical purposes, the two are considered equal.

![Figure 6: Hosting capacity for single-phase-connected PV as a function of injected power per installation](image)

For inverter size of 1 kW and 2 kW, all customers can install solar PV without a high probability of exceeding the 110 % limit, as shown in Figure 6. For inverter sizes 3 kW and above the number of customers that can connect (the hosting capacity) drops down to only one customer for increasing inverter size. When high penetration of PV is expected, un-coordinated single-phase connections above 3 kW are not recommended. Two possible mitigations methods, resulting in a higher hosting capacity, are discussed below.

**Coordinated single-phase connection**

The results obtained show that single-phase connected PV cause unacceptable overvoltage already for a small number of customers with PV.
A solution that can improve the overvoltage is by applying coordinated connection of PV inverters. With this solution, each inverter is connected to the phase with the lowest voltage before connection. The coordinated connection result is a natural kind of spread of the inverters over all the phases. The results for coordinated connection of single-phase PV are shown in Figure 7. The hosting capacity is increased significantly. If we neglect the single customer with 90th percentile just above 110%, the hosting capacity increases from 3 to 22 customers.

![Figure 7: 90th percentile of the worst-case overvoltage as a function of the number of customers for coordinated connection of single-phase PV.](image)

The results in Figure 7 shows that the outcome of coordinated connection is customers’ having lower values of overvoltages than that of random connections shown in Figure 5. Challenges remain with coordinated connection, the main challenge being to find out what is the phase with the lowest pre-connection voltage. The increasing presence of smart meters being able to measure much more than just energy consumption could be a useful asset here.

**REACTIVE-POWER MITIGATION**

The low-voltage grid is mostly cable dominated and highly resistive. The reactive compensation is therefore not as effective for voltage control as in medium-voltage or transmission networks. Especially for customers in remote areas, the source impedance is mainly resistive with high R/X ratio. The voltage rise with the customer point of connection can still be mitigated in theory using reactive power compensation. The reactive power needed to achieve this can be estimated using (4).

\[ Q_{ext} = -P_{PV} \frac{R_{eq}}{X_{eq}} \]  

(4)

For a 10 mm² (EKKJ/FFKJ) four-core cable, the R/X ratio is 21. Taking a single-phase installed PV size of 6 kW, the required reactive power compensation is 126 kVAR. The required inverter size would be approximately 126 kVA at a power factor of 0.048. Reactive power compensation is not very effective and results in large compensation units or inverter size as the installed PV size increases.

Even with a very large source of reactive power for each PV inverter, the issue cannot be easily solved. For most low-voltage connections, the voltage rise due to the injected power will be mainly over the cable and impact only local customers; the voltage drop by reactive power compensation will be mainly over the distribution transformer and affect all customers connected to that transformer. When a significant voltage rise has to be compensated, this could easily result in undervoltage for customers without PV.

**THREE-PHASE CONNECTED PV**

The probability distribution for the highest voltage magnitudes for 5, 9, 14, 19, 23 and 28 customers with three-phase connected PV is shown in Figure 8. For three-phase connected PV none of the 28 customers exceeds the 110% overvoltage limit, even when all of them are equipped with 6 kW PV.

By changing from single-phase to three-phase connected PV, the problem of overvoltages and exceeding the 110% limit is eliminated for the same PV inverter size.

![Figure 8: probability distribution for the highest worst-case voltage for increasing amount of three-phase PV.](image)

Considering the 90th percentile of the worst-case overvoltage in Figure 8, Figure 9 is obtained.

![Figure 9: 90th percentile of the worst-case overvoltage as the function of the number of customers for 6 kW three-phase connected PV](image)

Figure 9 shows even when all customers are equipped with PV, the 90th percentiles do not exceed 108%. The 28-customer network can accommodate far more PV with three-phase than with single-phase connection, for the same size. Comparing with Figure 7, also shows that the voltage rise due to three-phase connected units is still
significantly less than the rise due single-units even with coordinated connection.

The hosting capacity for three-phase connected PV is shown in Figure 10 as a function of the inverter size.

![Figure 10. Hosting capacity for three-phase-connected PV as a function of the inverter size. Note the difference in horizontal scale compared with Figure 6.](image)

The results in Figure 10 shows that for up to 10 kW PV size all the 28-customers can be equipped with PV, as long as long as PV is three-phase connected. Above 10 kW size, the number of customers that can be connected (the hosting capacity) reduces to 2 customers at 30 kW and only 1 customer at 60 kW.

**POLICY SUGGESTIONS**

According to [9], the number of solar PV installations in the Vattenfall grid for the first half of 2018 was around 3000 units. All of these units were three-phase connected with an average size of approximately 17 kW, with a typical size for residential installation of 6-8 kW.

The results obtained in this paper lead to a suggestion on policies with solar PV connections. The recommendation is to encourage installations of three-phase solar PV as opposed to single-phase installations. The voltage rise for three-phase connections is on average only 15% of the rise for single-phase connections. This mean that many times more PV can be accommodated in a grid if the units are three-phase connected. The widely used recommendation in Sweden is to use always three-phase above 3 kW PV. Units of size 3 kW and less still may be single-phase. Coordinated connection is recommended to help lower the likelihood of voltages exceeding the limit in the distribution grids. This study confirms that, when possible, PV units above 3 kW should be restricted to three-phase.

**CONCLUSIONS**

A stochastic approach has been used to determine the overvoltage caused by single-phase and three-phase connected PV to distribution grids in Northern Sweden. The connection of single-phase and three-phase connected PV installations in low-voltage grids result in a voltage rise. The rise is much higher for single-phase than for three-phase connected PV. To reduce the probability of unacceptable overvoltage the recommendation is that new installations are three-phase. When possible, upgrading of existing single-phase connected units to larger three-phase connected installations may be an efficient strategy to accommodate more PV in a network.

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**REFERENCES**


