VOLTAGE UNBALANCE DUE TO SINGLE-PHASE PHOTOVOLTAIC INVERTERS

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ABSTRACT

In this paper, the negative-sequence voltage unbalance is calculated for increasing numbers of single-phase photovoltaic inverters (PVIs) connected to low-voltage distribution networks. The transfer impedance matrix is used to calculate the negative-sequence voltage for each of the possible locations in the networks and a stochastic method is applied to estimate the voltage unbalance. The method has been applied to a 6 and 28-customer network for the connection of 6-kW single-phase PVIs. Furthermore, the hosting capacity for each network has also been estimated. From the results, it was observed that it is likely that the contribution from single-phase photovoltaic inverters to the voltage unbalance exceeds 1%, but unlikely that it will reach 2%.

INTRODUCTION

With the increasing amount of distributed power generation connected to the grid, especially for low voltage, it is important to estimate the impact of such generation on the system. The connection of single-phase generators can increase the voltage unbalance and in other ways deteriorate the voltage quality and the reliability [1, 2]. In most European countries the voltage unbalance limit is between 1 and 2%.

Several studies have been performed related to hosting capacity and negative sequence voltage unbalance (VU), see [3] for an overview.

Uncertainty is an important aspect to be considered with renewable power generation. The time-varying and unpredictable nature of the production are rather well known and often referred to as “intermittence” or “stochastic intermittence”. It is very difficult to predict the actual production from wind or solar power more than a few days ahead of time. This is a serious concern for transmission-system operation. For distribution-system planning this is less of a concern as it are the extreme values of voltage, current, unbalance, etc. that should be considered during planning.

There is however another type of uncertainty and that concerns the location and properties of future installations. This is especially a concern for small installations like single-phase connected solar power, the subject of this paper, where the amount of pre-notice on new installations for the network operator is small or even non-existing. In this paper, three specific uncertainties will be addressed: the number of customers with PV; the location of those customers; and the phase to which the PVI is connected. More details of the study and the study results are presented in [4].

This paper will first present the calculation method used, including the way in which the transfer impedance matrix has been calculated. Next some of the results are presented, starting with the probability distribution functions for a fixed number of PVIs, followed by a stochastic indicator as a function of the number of PVIs. The paper closes with a brief discussion of additional uncertainties that would need to be considered for a more accurate estimation of the hosting capacity.

CALCULATION METHOD

Transfer impedance matrix

The voltage unbalance is calculated using the transfer impedance method, where the voltage unbalance at any location is obtained as the complex sum of the contributions from all individual installations. The transfer impedance links the voltage at a certain location (r) with the current injected at another location (s). The elements of the matrix are obtained using (1).

$$\underline{Z}_{sr}=\frac{\underline{U}_{sr}}{\underline{I}_{s}} \tag{1}$$

From this, the negative-sequence voltage for busbar r due to a single-phase inverter connected at busbar s, is obtained by (2).

$$\underline{U}_{r}=\underline{Z}_{sr}\cdot\underline{I}_{s} \tag{2}$$

With multiple (N) inverters, the negative-sequence voltage at location r is obtained from the superposition of the contributions from the individual units and the background negative-sequence voltage $U_{background}$

$$\underline{U}_{r}=\underline{U}_{background}+\sum_{s=1}^{N}\underline{Z}_{sr}\cdot\underline{I}_{s} \tag{3}$$

The voltage unbalance (VU) is then obtained using (4).

$$VUN_r[\%]=\frac{U_r}{0.4}\cdot 100\% \tag{4}$$

Obtaining the probability distribution

To calculate all the possible cases (busbars and phases), a Monte-Carlo method has been used. A fixed number of customers with single-phase connected PV (all injecting 6-kW of power) are randomly selected from all the customers connected to the low-voltage network under study. For each of the customers with PV, the inverter is connected to a randomly-selected phase. For this given configuration the voltage unbalance is calculated for each of the customers. This is repeated many times (10 000 times for most of the results shown in this paper) resulting in many random values for the voltage unbalance. From these values the (cumulative) probability distribution function is obtained; which in practice accounts to sorting the values.

Obtaining the transfer impedance matrix

There are different ways of obtaining the elements of the transfer impedance matrix. In this study, these elements were obtained using DigSilent PowerFactory 15.2, by connecting individual PVIs with each of the customer busses. The following procedure has been applied for this:

1) Connect PVI at busbar s
2) Calculate the negative-sequence current (amplitude and phase angle) at busbar s
3) Calculate the negative-sequence voltage (amplitude and phase angle) at busbar r
4) The ratio between the voltage at busbar r and the current at busbar s gives the transfer impedance, which is element rs of the transfer impedance matrix.
5) Repeat step 3 and 4 for all busses
6) Repeat step 1 through 5 for all busses

Next it was assumed that the elements of the transfer impedance matrix were not impacted by the presence of additional PVIs or by any other parameters. It was also assumed that the injected negative-sequence current was independent of the terminal voltage. In short, it was assumed that the transfer impedance matrix is constant and that the system is linear. This assumption allowed us to calculate the unbalance for many different cases in a short time.

STUDIED NETWORKS

In this work, two networks were considered: one with 6 customers and another with 28 customers. In the 6-customer network a rural grid in the Northern part of Sweden, a few houses are spread over a few hundred meters and are connected to a 100 kVA transformer. In the 28-customer network, considered as a suburban grid, the customers are supplied from a 500 kVA transformer. Details of the network are given in Appendix A.

FIXED NUMBER OF INVERTERS

For the networks, the random connection of a given number of inverters at different locations and phases has been studied. The probability distribution function of the unbalance due to PV was obtained by means of a Monte-Carlo simulation generating random locations and phases for the PVIs, as explained before. Using the transfer impedance matrix, all possible combinations of inverters at the different busbars and in different phases were considered, with the same total number of PVIs. The results are presented in Fig. 1 through Fig. 6.

Rural (6-customer) network

For the 6-customer network, Fig. 1 shows the probability distribution function for the case of one PVI connected in random phase and customer. Fig. 2 and Fig. 3 present a comparison for the lowest and highest VU for the case of three and six PVIs connected.

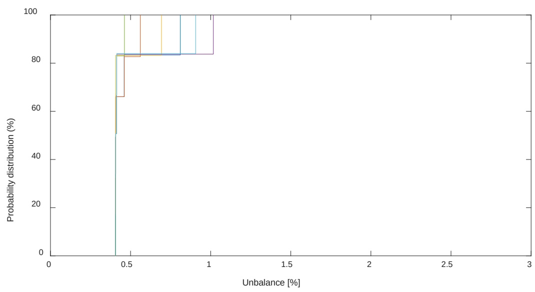

Fig. 1 Probability distribution function of the VU for one PVI at random busbars and phases in a 6-customer network; the different colors refer to different customers

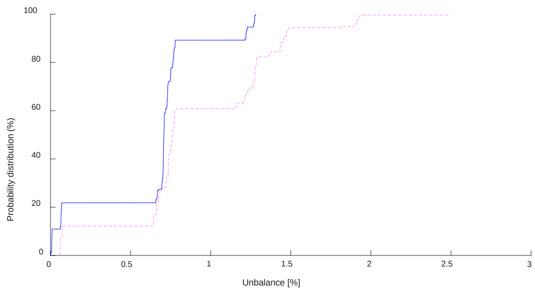

Fig. 2 Probability distribution function of the lowest unbalance for three (dotted line) and six (dashed line) 6-kW inverters at random busses and phases for a 6-customer network

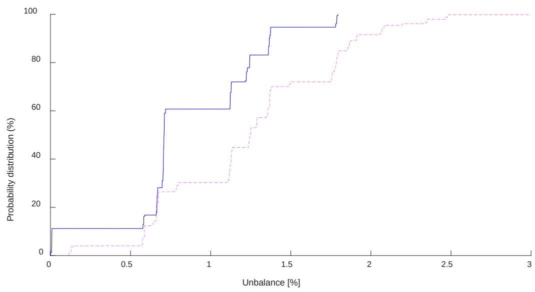

Fig. 3 Probability distribution function of the highest unbalance for three (dotted line) and six (dashed line) 6-kW inverters at random busses and phases for a 6-customer network

Fig. 1 shows that the probability of reaching the limit of 1% for all cases is low and the limit of 2% will never be reached. Fig. 1 shows the results for each of the six customers. For each of the combinations of locations and phases generated at random, the unbalance was calculated for these six customers. Next to that also the highest and lowest unbalance over the six customers was calculated for each of the combinations. Also for these highest and lowest values a probability distribution function can be obtained. The results of this are shown in Fig. 2 and Fig. 3. Fig. 2 presents the results for the lowest VU simulated, in which the probability distribution is the lowest when compared to the other customers. The results for the highest VU simulated are presented in Fig. 3. For the connection of three PVIs, in the two cases, the probability of reaching 1% of VU is high, but the probability to reach 2% is low. When connecting six PVIs, there is a big probability that the VU will exceed the 2% limit, for both cases.

Suburban (28-customer) network

For the case of 28-customer network, Fig. 4 shows the probability distribution with four PVIs connected in random phase and customer. Fig. 5 and Fig. 6 present a comparison for the lowest and highest VU for the case of 14 and 28 PVIs connected.

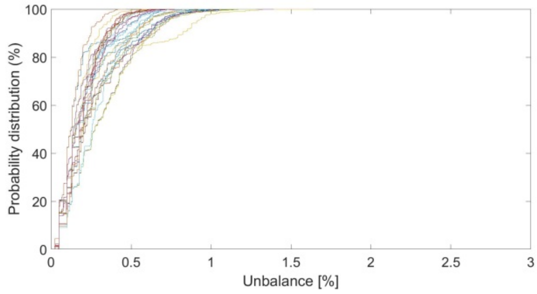

Fig. 4 Probability distribution function of the VU with four PVIs connected to random busbars and phases in the 28-customer network; the different colors refer to different customers

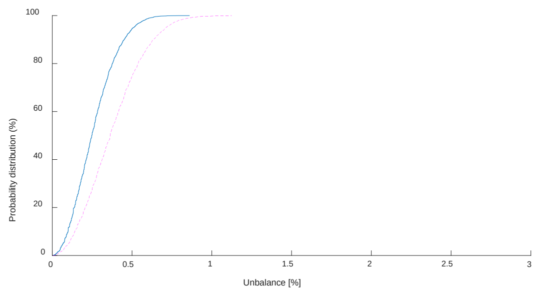

Fig. 5 Probability distribution function of the lowest unbalance for 14 (dotted line) and 28 (dashed line) 6-kW inverters at random busses and phases for a 28-customer network

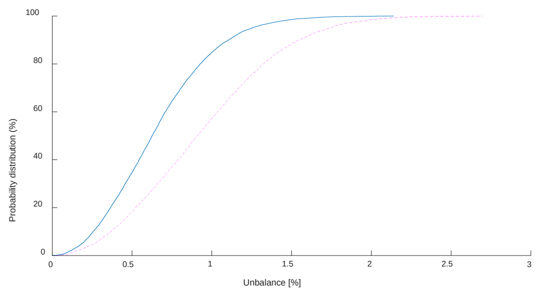

Fig. 6 Probability distribution function of highest unbalance for 14 (dotted line) and 28 (dashed line) 6-kW inverters at random busses and phases for a 28-customer network

Fig. 4 shows that there is a high probability that the VU will be less than 1% and that the limit of 2% will never be exceeded. Fig. 5 shows the results for the lowest VU cases with the connection of 14 and 28 PVIs, and Fig. 8 for the highest VU. For the best cases (lowest unbalance), the probability of exceeding 1% VU is zero when 14 PVIs are connected. However, when connecting 28, the probability of exceeding 1% is high, but low for the limit of 2%. In Fig. 6, for the case of connecting 14 PVIs, the probability of the VU reaching 2% is high and for the case of 28 PVIs connected the probability of exceeding the limit is very high.

HOSTING CAPACITY

The hosting capacity is defined as the maximum amount of distributed energy source penetration in the power system that ensures a reliable system operation and keeps the power quality indicators in limits [1]. For this study, the hosting capacity is the maximum number of PVIs that can be connected in a specific network that, with a high probability, will not exceed 2% VU. For this, simulations were performed using the 6 and 28-customer networks and the obtained results are presented in Fig. 7 and Fig. 8 using the 95% values for the negative-sequence voltage unbalance versus the number of PVIs.

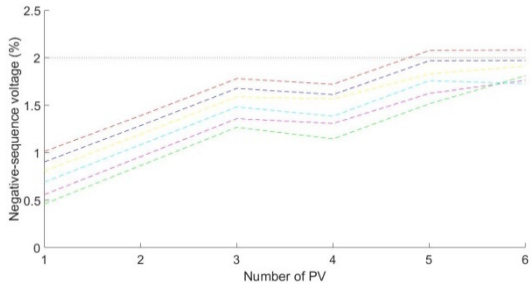

Fig. 7 95% values for the expected unbalance when connecting on to six 6-kW inverters at random busses and phases

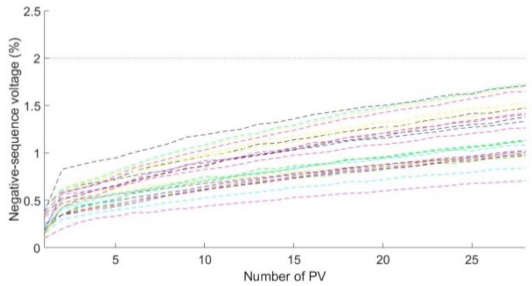

Fig. 8 95% values for the expected unbalance when connecting on to 28 6-kW inverters at random busses and phases

For the 6-customer network, it can be observed, in Fig. 7, that the 95% value is above the 2% limit for one of the busses when five or six inverters are connected. From this, it is possible to observe that the hosting capacity for this network is 4 PVIs, as defined here. For the case of 28-customer network, Fig. 8, the hosting capacity for this case is 28 PVIs; Even with this amount connected the VU does not reach the limit of 2%. With these results it is possible to estimate the most suitable hosting capacity, depending on what is aimed.

DISCUSSION : MORE UNCERTAINTIES

In this paper it has been assumed that all customers with PV inject 6 kW in one phase at the same time. The location of the customers with PV and the phase in which this power is injected are treated as random variables. There are additional uncertainties that need to be considered for a more accurate estimation of the hosting capacity. Some of these additional uncertainties are:

- Not all panels will have a maximum injected power of 6 kW; in fact 6 kW is a rather big installation for domestic customers.
- Not all panels will produce their maximum amount of power at the same time, e.g. because of different tilt angle and different tilt direction.
- The presence of three-phase load will reduce the value of the transfer impedances. In [4], it was shown, for the 6-customer network, that the elements of the negative-sequence transfer impedance matrix were reduced by 15 to 29% (diagonal) and by 30 to 34% (off-diagonal). Due to this, there was a reduction of unbalance in a range of 15 to 34%, depending on the busses.
- The unbalance as calculated in this paper will add (as complex numbers) to the background voltage unbalance (the unbalance without PV).

The first two uncertainties can be treated in the same way as the location and phase in this paper. The treatment of the latter two is more complicated. Both the transfer impedance and the background unbalance will show a time-varying character in a similar way as the solar power production (but with smaller deviations from the average value). Next to that the stochastic properties of these variations will be uncertain as, for example, the future amount of single phase and three-phase loads will be unknown.

The first three uncertainties above will make that the unbalance as calculated here is an overestimation; the fourth uncertainty makes that it is an underestimation. Much more detailed studies are needed to know how much of an underestimation or overestimation it is. However, the somewhat simplified approach presented here does still give an indication of the number of single-phase PVIs can be allowed before the voltage unbalance reaches unacceptable levels.

CONCLUSIONS

In this paper, a stochastic method has been presented to estimate the contribution of single-phase photovoltaic inverters (PVIs) to VU in a 6 and 28-customer network networks. The uncertainty in location and phase is included in a number of stochastic indicators.

For the two networks studied, the introduction of 6 kW PVIs will likely give a contribution from the inverters exceeding 1% when they are connected randomly; exceeding 2% is shown to be unlikely but not impossible. With these results the hosting capacity has been obtained for each of the cases. From this, it was observed that it is likely that with the connection of PVIs the VU will reach 1% when they are connected randomly, but the probability of exceeding the limit of 2% is low. It is also shown that the simplified approach used here, calculating the transfer impedance matrix using a commercial power-system analysis package, can provide useful information for making investment decisions by network operators.

ACKNOWLEDGEMENTS

This work was financially supported by the VindForsk program (Energiforsk and Swedish Energy Agency) and by the Risk Analysis program (Energiforsk)

REFERENCES

[1] M. Bollen F. Hassan, 2006, *Integration of distributed generation in the power system*, Wiley.

[2] J. Smith, M. Rylander, L. Rogers, R. Dugan, 2015, It’s all in the plans – Maximizing the benefits and minimizing the impacts of DERs in an integrated grid, *IEEE Power & Energy Magazine*, March/April, pp. 20-29.

[3] D. Schwanz, F. Moller, S.K. Ronnberg, J. Meyer and M.H.J. Bollen, 2016, “Stochastic Assessment of Voltage Unbalance due to Single-Phase-Connected Solar Power”. *IEEE Trans on Power Delivery*, in print.

[4] D. Schwanz, M. Bollen, S. Ronnberg 2015. ”Obalans fran enfasanslutna solpaneler,” (in Swedish and English), Stockholm: Energiforsk. Report 2015:130.

APPENDIX A. NETWORK DATA

6-customer Network

The single-line diagram for this network is presented in Fig. A1. Detailed data is given in Table A1 through A3, where CB stands for “customer bus”.

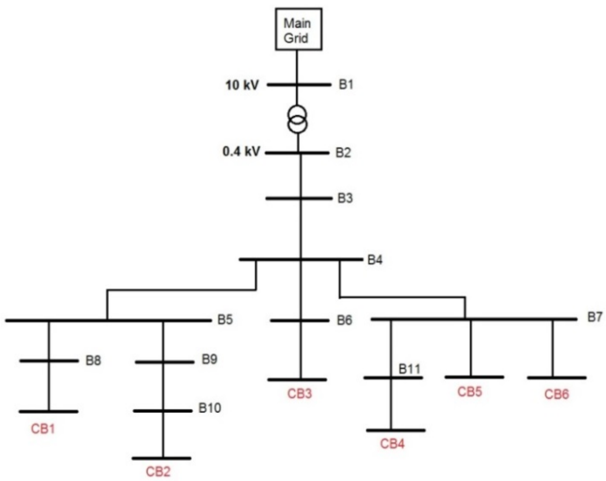

Fig. A1. Single-line diagram: 6-customer network

TABLE A1 - TRANSFORMER DATA – 6-CUSTOMER NETWORK

Power	100 kVA
Voltage	10/0.4 kV
Connection	Dyn11
Positive sequence impedance	4%
Frequency	50 Hz

TABLE A2 - CABLE AND LINE IMPEDANCES

Type	Code	R (Ω/km)	X (Ω/km)	B (μS/km)
1	EKKJ-10	1.83	0.091	100.53
2	N1XE-10	1.83	0.0817	--
3	ALUS-25	1.2	0.0785	1288.04
4	ALUS-50	0.641	0.0754	157.8
5	N1XV-50	0.641	0.0754	157.8
6	N1XE-150	0.206	0.0723	40.8395
7	AKKJ-150	0.206	0.0628	--------
8	AKKJ-240	0.125	0.0565	--------
9	FKKJ-35	0.524	0.0723	--------
10	N1XV-10	1.83	0.0817	25.132

TABLE A3 - CABLE AND LINE DATA - 6 CUSTOMER NETWORK

Line	Length (m)	Type	Line	Length (m)	Type
B2-B3	14	5	B4-B6	46	4
B3-B4	108	4	B6-CB3	31	1
B4-B5	26.9	4	B4-B7	1.9	3
B5-B8	41.2	4	B7-B11	54.4	2
B8-CB1	41.5	1	B11-CB4	41.3	1
B5-B9	0.1	4	B7-CB5	8.9	1
B9-B10	0.1	3	B7-CB6	79.5	2
B10-CB2	17	1			

28-customer Network

For this network, the data is presented in Table A4 and A5; the single-line diagram is shown in Fig. A2.

TABLE A4 - TRANSFORMER DATA - 28 CUSTOMER NETWORK

Power	500 kVA
Voltage	10/0.4 kV
Connection	Dyn11
Positive sequence impedance	4.9%
Frequency	50 Hz

TABLE A5 - CABLE AND LINE DATA – 28-CUSTOMER NETWORK

Line	Length (m)	Type	Line	Length (m)	Type
B1-B2	15	6	B1-B12	196.9	7
B2-B3	77.9	7	B12-CB21	33.8	1
B3-CB1	68.7	1	B12-CB22	65.7	1
B3-CB2	24.9	1	B12-CB23	17	1
B4-CB3	22.4	1	B12-B13	89.5	9
B3-CB4	48.9	1	B13-CB15	42.7	1
B4-B5	64.1	7	B13-CB16	27.7	1
B5-CB5	28.2	1	B12-B15	71	9
B5-B6	67.4	7	B15-CB20	21.2	1
B6-CB6	23-1	1	B15-B14	58.6	9
B8-CB7	34.2	6	B14-CB17	28.9	10
B1-B9	270.1	8	B14-CB18	21.7	10
B9-CB12	29.8	1	B14-CB19	33	10
B9-CB13	46.1	1	B1-B16	157	7
B9-CB14	23.4	1	B16-B17	50.6	7
B9-B10	86	7	B17-CB28	22.9	1
B10-CB10	47.2	1	B17-CB27	41.8	1
B10-CB11	27.7	1	B17-B18	93.4	9
B10-B11	96.1	9	B18-CB24	76.2	1
B11-CB8	29.9	1	B18-CB25	37.4	1
B11-CB9	37.8	1	B18-CB26	28.5	1

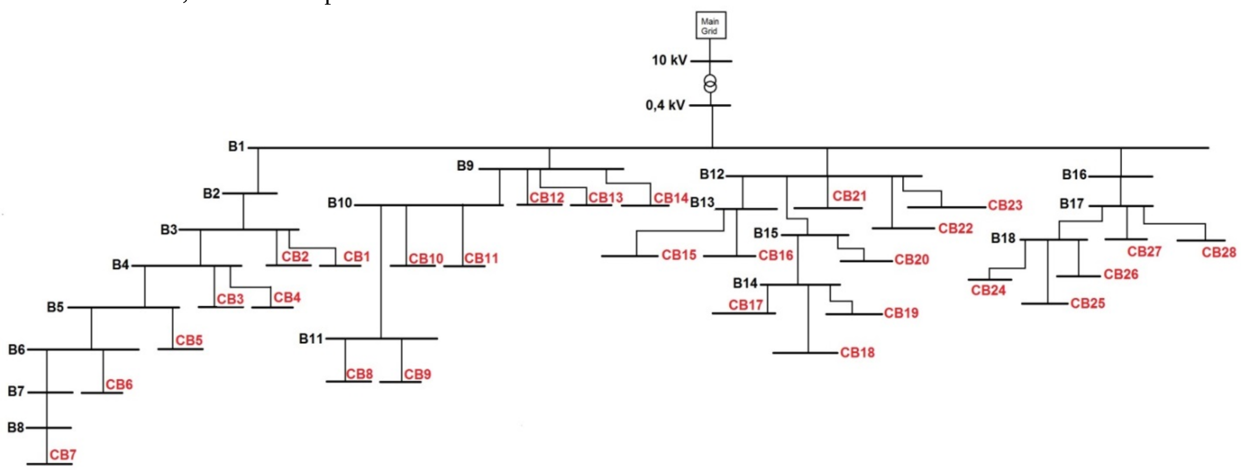

Fig. A2. Single-line diagram – 28-Customer network