ON THE EFFECTIVENESS OF VOLTAGE CONTROL WITH PV INVERTERS IN UNBALANCED LOW VOLTAGE NETWORKS

Benoît BLETTERIE
AIT – Austria
benoit.bletterie@ait.ac.at

Serdar KADAM
AIT – Austria
serdar.kadam@ait.ac.at

Antony ZEGERS
AIT – Austria
antony.zegers@ait.ac.at

Zoran MILETIC
AIT – Austria
zoran.miletic@ait.ac.at

ABSTRACT

Unsymmetrical loads and PV infeed limits the hosting capacity of LV feeders due to a faster exceeding of the over-voltage limit. While current connection rules require from inverters to control the voltage, they do not address at all the behaviour of three-phase inverters under unbalanced conditions. This paper investigates the impact of different control options on the network performance (voltage levels, voltage unbalance, neutral conductor loading and losses).

INTRODUCTION

Solar power is widely acknowledged as one of the most promising resources to meet sustainability targets. The integration of photovoltaic (PV) generation into distribution networks faces some limitations due to the network constraints. The hosting capacity of low voltage (LV) networks is for some rural and sub-urban feeders exhausted. One of the main limitation is the voltage rise caused by the power infeed which must stay below a certain threshold [1][2] to ensure that the distribution system operator is able to meet the normative requirements ([3]).
Unbalanced PV infeed resulting from e.g. small single-phase generators worsens the problem. Indeed, besides the voltage unbalance itself caused by the unsymmetrical infeed, the voltage rise caused by an unsymmetrical PV infeed is significantly higher (up to 6 times greater [4]) than for a symmetrical infeed. In order to limit the impact of unsymmetrical PV infeed on the network, the maximal power of single-phase generators (or the maximal power imbalance between phases) is usually limited to about 5 kVA (4.6 kVA in Germany and Austria, 5 kVA in Belgium, 6 kVA in France and Italy) to limit voltage unbalance.
Against this background, some requirements appeared in most the grid codes, connection guidelines or national standards of most European countries to allow generators to control the voltage (through reactive power) and partly compensate the voltage rise caused by the PV infeed and therefore enhance the hosting capacity as investigated in several research and demonstration projects [5][6][7].
These requirements usually consist of a reactive power capability (P-Q operation diagram) and several voltage control scheme (e.g. Q(U), cosφ(P), P(U)).

However, under unbalanced conditions (caused by unsymmetrical loads or PV generation), the behaviour of three-phase generators is specified in none of the existing regulation and has been poorly investigated. [8] reported for example two different implementations of a Q(U) control (using as the average or the maximum of the three phases controller input).
This paper tries to answer the question of how existing voltage control concepts behave under unbalanced conditions from the network point of view (implications on inverter designs are briefly mentioned but not in the focus of the paper).

I. VOLTAGE UNBALANCE IN LV NETWORKS

Several definitions of voltage unbalanced can be used depending on the effects considered.
[3] defines voltage unbalance as the condition in a polyphase system in which the r.m.s. (root mean square) values of the line-to-line voltages (fundamental component), or the phase angles between consecutive line voltages, are not all equal. It is quantified by the voltage unbalance factor – VUF defined as the ratio between the negative and the positive sequence and specifies that it should lie below 2 % for 95 % of the time (in specific cases up to 3 % according to [3]).
The IEEE defines the phase voltage unbalance rate (PVUR) as the maximal voltage deviation from the average phase voltage divided by the average phase voltage.
In addition to these definitions, the phase spreading which is computed as the difference between the highest and the lowest voltage among the three phases in p.u. has been proposed in [9].

Voltage unbalance: general causes and consequences

As previously stated, voltage unbalance in normal operation is mainly caused by unsymmetrical loads (e.g. single-phase loads) in LV networks. With the deployment of small single-phase PV generators, PV generation turned to be an additional potential source of voltage unbalance.

The main consequences of voltage unbalance are:

- earlier exceeding of the upper-voltage limit [3][10][11]
- additional losses in the neutral conductor of cables and in transformers [12]
- loss of performance, over-heating of induction motors [13]
- addition uncharacteristic harmonics, unsymmetrical currents flow in the three phases which can even lead to over-heating or even over-load tripping for frequency converters [14]

II. VOLTAGE CONTROL OF SINGLE-PHASE GENERATORS

In [5], the effectiveness of reactive power-based voltage control has been investigated with a three-phase four-wire network model for single-phase generators. For the three cases considered (three PV generators evenly connected to the three phases, two generators connected to two of the three phases and a single PV generators), the effectiveness of a Q(U) control has been investigated. The voltage rise caused by a single-phase infeed can be compensated to an even greater extent than in the three-phase balanced case. This has also been confirmed by field tests in e.g. [5]. However, a side-effect is mentioned in [5]: the voltage in the phase with the PV infeed is decreased but at the same time the voltage decreases in one of the other two phases due to the star point displacement [15]. This might lead to an under-voltage situation in case of additional unfavourable load imbalance.
The rest of the paper considers three-phase inverters and their behaviour under unbalanced conditions.

III. MITIGATION OF VOLTAGE UNBALANCE

As mentioned in the introduction, unsymmetrical PV infeed strongly limits the hosting capacity due to the voltage rise. For this reason, several authors have proposed different concepts to limit the PV generation imbalance at its source. [16] proposed to use smart meters to identify situations requiring a reduction of unbalance and to use monte-carlo simulations to determine a sorted set of switching combinations allowing to reduce the infeed imbalance according to the pareto principle.
A similar approach has been proposed in [17] with however a different purpose, namely to reduce network losses caused by the large neutral currents under heavily unbalanced conditions.
Besides these concepts trying to improve the PV infeed distribution over the three phases, other authors investigated the possibility to actively mitigate voltage unbalance by three-phase PV inverters.
[18] tries for example to reduce the voltage unbalance by injecting imbalanced currents into the network on the basis of a comparison between the phase voltages and the positive sequence component. The authors report about a reduction of the voltage unbalance, a decrease of the neutral current and the line losses.
[19] considered the use of a storage system to try to inject or consume a symmetrical current. The benefits on terms of voltage profiles, star point displacement and neutral current.
[20] proposes the use of a DSTATCOM to control the phase voltages individually with a droop factor. This paper proposed to place the DSTATCOM at 2/3 of the feeder length to reach an optimal reduction of the voltage unbalance factor.
[21] proposes the control of reactive power only (reactive power management method) to reduce voltage unbalance with plug-in hybrid electric vehicle chargers. As in [19], the controller tries to symmetrise the line currents, which leads as a side effect to a reduction of the voltage unbalance.
Using PV inverters to actively compensate the voltage unbalance has some implications in terms of inverter design. Some considerations are given in the conclusions.

IV. VOLTAGE CONTROL OF THREE-PHASE GENERATORS UNDER UNBALANCED CONDITIONS

In this section, the behaviour of current control schemes under unbalanced conditions is analysed through extensive simulations.

Considered controls

In this paper, the considered voltage control schemes have been limited to the most investigated schemes which are currently mentioned in some connection guidelines [2][22], namely cosφ(P) and Q(U). The following implementations have been considered (some of them being reported in [8]):

- symmetrical cosφ(P)
- Q(U)
  - unsymmetrical Q-control (“Q(U_{ind})”) (Q_i=(U_{LiN}), i=1..3)
  - symmetrical Q-control:
    - based on the maximal voltage (“Q(U_{max})”): ($Q_1=Q_2=Q_3=Q(\max\{U_{LiN}, i=1..3\})$)
    - based on the average voltage (“Q(U_{mean})”) ($Q_1=Q_2=Q_3=Q(\mathrm{mean}\{U_{LiN}, i=1..3\})$)
    - based on the pos. seq. (“Q(U_+)”) ($Q_1=Q_2=Q_3=Q(U_+)$)

In addition, a P(U) control as proposed in [23] has also been considered in some scenarios.

Models, assumptions

For the investigations, a simple network consisting of a standard 400 kVA distribution transformer and a single overhead feeder (600 m – 4x70 Al) modelled as three-phase four-wire systems has been used. A long overhead line has been used to ensure a high impact of the reactive power control.

At the end of the feeder, a three-phase PV inverter rated 5 kWp per phase is connected and different voltage unbalance situations are created by an imbalanced load/generator object. The three-phase generator causes at the end of this long feeder a voltage rise of about 2.3 %.

For the imbalanced and uncontrolled load/generator object, an active power flow between -5 kW and +5 kW (with steps of 1 kW) per phase is used. The corresponding single-phase power infeed of 5 kW causes a voltage rise of about 4.5 %. With this model, the behaviour of the three-phase inverter under all the possible unbalance conditions can be investigated (more than 3.000 cases for 19 different control schemes).

The inverter has been modelled as a controlled power source for which the reactive power can be adjusted to follow each of the control options previously mentioned. The inverters are considered to be oversized in order to be able to operate at power factor 0.9 (Q_{max}=0.44) at full power and to not exhibit any minimal power factor.

The controller settings used in this study are shown in Figure 1 for the Q(U) (and P(U)) control. For the cosφ(P) control, the standard settings from [2] have been used.

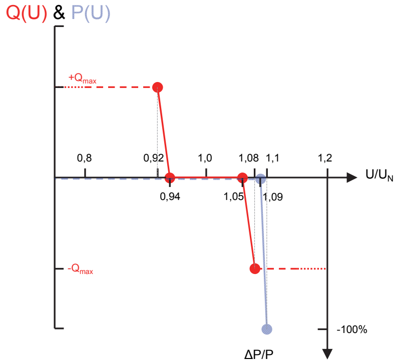

Figure 1 – Considered settings for the Q(U) and optional P(U) controls. Qmax=0.44 p.u.

Results

The results of the simulations have been processed automatically and a distribution function has been derived for all the relevant magnitudes (voltages, VUF, PVUR, voltage spreading, neutral current, losses, …).

These distribution functions show for which percentage of the possible combinations a magnitude would exceed a threshold (without considering the real distribution of input parameters (solar irradiance and load)).

Figure 2 shows the cumulated distribution function of the maximal voltage (over the three phases) for the five considered control schemes, the most relevant part being of course on the upper right part of the curve corresponding to large voltage rise values (due to a high generation/load imbalance). It shows that the most effective control is the (unsymmetrical) individual control ($Q(U_{ind})$). Considering the 99 % most unfavourable combination, the maximal voltage rise can be reduced by about 12 % with the $Q(U_{max})$ control and 19 % with the $Q(U_{ind})$ control representing about 1.3 % of the nominal voltage. These values might appear to be small, but it corresponds to more than half of the voltage rise caused by the three-phase generator.

From all the symmetrical controls $Q(U_{mean})$ and $Q(U_{+})$ are as expected the least effective controls.

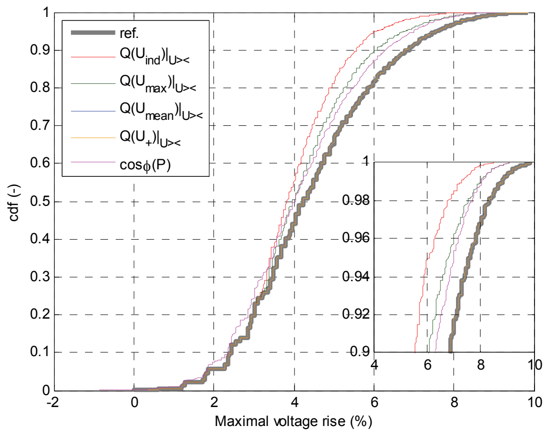

Figure 2 – Maximal voltage rise for all load/generation combinations

Figure 3 shows the cumulated distribution function for the voltage unbalance factor, clearly showing that the better effectiveness of the $Q(U_{ind})$ control is reached at the cost of a higher negative sequence component. For the worst unbalance combination, the normative value of 2 % [3] is even slightly exceeded.

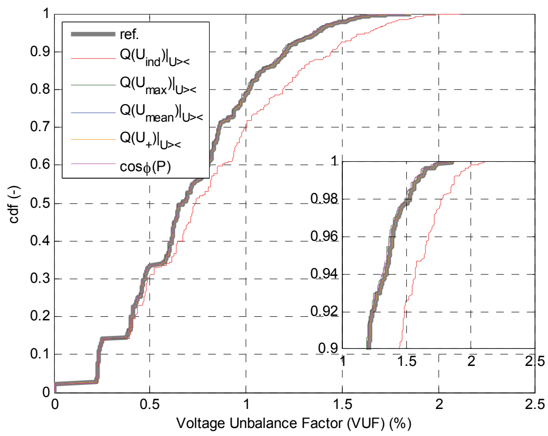

Figure 3 – Maximal VUF for all load/generation combinations

Figure 4 shows the vector diagram for three different control schemes (without control, with $Q(U_{ind})$ and with $Q(U_{max})$) and for the unbalance combination leading to the highest voltage unbalance factor (i.e. negative sequence component). The operation point for the $Q(U_{ind})$ control is shown in Figure 5.

The origin of the diagrams represents the earth potential and the star point displacement is shown with the purple arrow (Earth-Neutral voltage, multiplied with a factor 100 compared to the phase voltages to allow a proper visualisation). To allow a proper visualisation, the three phase-neutral L_X-N phasors are shown with an offset in magnitude. Although this transformation is not fully correct (phase to phase voltages cannot be constructed), it allows visualising the magnitude and angle of each phase.

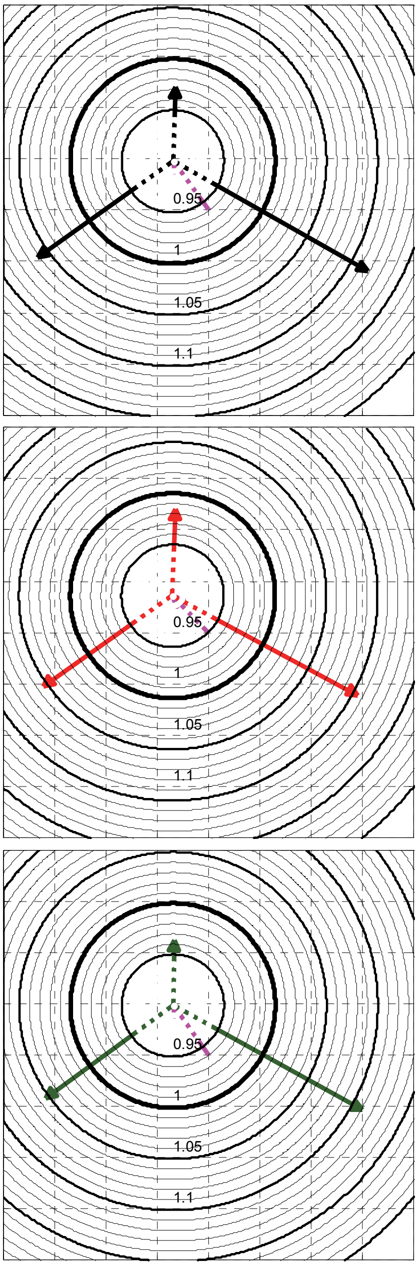

Figure 4 – Phasor diagram. Top: without control / Middle: with $Q(U_{ind})$ / Bottom: with $Q(U_{max})$

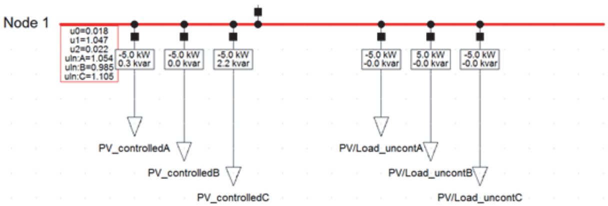

Figure 5 – Operation point for the considered combination leading to the highest VUF (for $Q(U_{ind})$)

This diagram confirms that the $Q(U_{ind})$ control allows a larger decrease of the highest voltage while at the same time increasing of the lowest voltage. The $Q(U_{max})$ control leads to a smaller decrease of the highest voltage and at the same time a further decrease of the lowest voltage. The angle between the two phases with the highest voltage deviates more from 120° for the $Q(U_{ind})$ control than for the $Q(U_{max})$ control: 116.2 instead of 117.5° compared to 117.3° without control. This leads to an increase of the negative sequence component which directly impacts the voltage unbalance factor VUF as already shown in Figure 3.
For highly unbalanced situations (99 % percentile), the $Q(U_{ind})$ control leads to approximately 6 % less losses than the reference case (without control) while the $Q(U_{max})$ and cosφ(P) lead to approximately 7 % more losses (relative increase / decrease).

V. CONCLUSION

The investigations shown in this paper demonstrate that under unbalanced conditions, the maximal voltage can be reduced to a greater extent with the unsymmetrical control using the individual phase voltages than with the symmetrical controls. In addition, the phase spreading and the phase voltage unbalance factor can also be more reduced with this control. However, this control intends to control the phasor magnitude without controlling the angle between phasors which results in a higher voltage unbalance factor (negative sequence) under heavily unbalanced conditions. In some cases, the normative 2 %-limit can even be exceeded.
From the network point of view, the unsymmetrical control using the individual phase voltages provides the highest benefits except for the negative sequence component. In theory, the control could evaluate the negative sequence component and limit the reactive power control to avoid exceeding the limit.
The inverter design point of view has been left out of this paper but designing and operating a three-phase inverter under unbalanced voltage conditions and injecting unbalanced currents has many implications, mostly in terms of:

- higher rating needed to exploit most of the benefits
- need to oversize the DC-link in order to mitigate voltage and current ripple caused by instantaneous active power oscillation
- limited MPPT-window and reduced MPP tracking efficiency due to the voltage ripple on the DC-link
- impact on harmonic distortion of phase currents which can lead to additional magnetics core losses.

This paper only considers the unbalanced operation of three-phase inverters operated with existing control schemes ("passive compensation" of voltage unbalance). Other concepts for actively compensating the voltage unbalance within the inverter capabilities are feasible and a cost/benefit analysis should be conducted accordingly.

REFERENCES

[1] E-CONTROL, “Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen. Teil D: Besondere technische Regeln. Hauptabschnitt2: Richtlinie zur Beurteilung von Netzrückwirkungen.” Sep-2006.

[2] VDE-FNN, “VDE-AR-N 4105:2011-08 Power generation systems connected to the low-voltage distribution network.” Aug-2011.

[3] CENELEC, “Voltage characteristics of electricity supplied by public electricity networks.” 01-Mar-2011.

[4] B. Bletterie, A. Gorsek, A. Abart, and M. Heidl, “Understanding the effects of unsymmetrical infeed on the voltage rise for the design of suitable voltage control algorithms with PV inverters,” in *Proc. 26th European Photovoltaic Solar Energy Conference and Exhibition*, Hamburg, 2011, pp. 4469 – 4478.

[5] B. Bletterie, A. Stojanovic, S. Kadam, G. Lauss, M. Heidl, C. Winter, D. Hanek, A. Pamer, and A. Abart, “Local voltage control by PV inverters first operating experience from simulation, laboratory tests and field tests,” in *Proc. 27th European Photovoltaic Solar Energy Conference and Exhibition*, Frankfurt, 2012, pp. 4574–4581.

[6] E. Demirok, P. C. González, K. H. B. Frederiksen, D. Sera, P. Rodriguez, and R. Teodorescu, “Local Reactive Power Control Methods for Overvoltage Prevention of Distributed Solar Inverters in Low-Voltage Grids,” *IEEE J. Photovolt.*, vol. 1, no. 2, pp. 174–182, Oct. 2011.

[7] T. Stetz, M. Kraiczy, M. Braun, and S. Schmidt, “Technical and economical assessment of voltage control strategies in distribution grids,” *Prog. Photovolt. Res. Appl.*, vol. 21, no. 6, pp. 1292–1307, Sep. 2013.

[8] P. Esslinger, “Studie Q(U),” Munich, Aug. 2012.

[9] B. Bletterie, A. Abart, S. Kadam, D. Burnier, M. Stifter, and H. Brunner, “Characterising LV networks on the basis of smart meter data and accurate network models,” in *Proc. Integration of Renewables into the Distribution Grid, CIRED 2012 Workshop*, 2012, pp. 1–4.

[10] D. Habijan, M. Cavlović, and D. Jaksić, “The issue of asymmetry in low voltage network with distributed generation,” in *Proc. 22nd International Conference on Electricity Distribution CIRED*, Stockholm, 2013.

[11] E. De Jaeger, A. DU BOIS, and B. Martin, “Hosting capacity of LV distribution grids for small distributed generation units, referring to voltage level and unbalance,” in *Proc. Electricity Distribution (CIRED 2013), 22nd International Conference and Exhibition on*, 2013, pp. 1–4.

[12] R. Salustiano, E. Neto, and M. Martinez, “The unbalanced load cost on transformer losses at a distribution system,” in *Electricity Distribution (CIRED 2013), 22nd International Conference and Exhibition on*, 2013, pp. 1–3.

[13] A. Siddique, G. S. Yadava, and B. Singh, “Effects of voltage unbalance on induction motors,” in *Proc. Electrical Insulation, 2004. Conference Record of the 2004 IEEE International Symposium on*, 2004, pp. 26–29.

[14] A. Von Jouanne and B. Banerjee, “Assessment of voltage unbalance,” *Power Deliv. IEEE Trans. On*, vol. 16, no. 4, pp. 782–790, 2001.

[15] L. Degroote, B. Renders, B. Meersman, and L. Vandevelde, “Neutral-point shifting and voltage unbalance due to single-phase DG units in low voltage distribution networks,” in *Proc. PowerTech, 2009 IEEE Bucharest*, 2009, pp. 1–8.

[16] B. Bletterie, S. Kadam, R. Pitz, and A. Abart, “Optimisation of LV networks with high photovoltaic penetration—Balancing the grid with smart meters,” in *Proc. PowerTech 2013 IEEE Grenoble*, 2013, pp. 1–6.

[17] G. Roupioz, X. Robe, and F. Gorgette, “First use of smart grid data in distribution network planning,” in *Electricity Distribution (CIRED 2013), 22nd International Conference and Exhibition on*, 2013, pp. 1–4.

[18] R. D. Lazar and A. Constantin, “Voltage balancing in LV residential networks by means of three phase PV inverters,” in *Proc. 27th European Photovoltaic Solar Energy Conference and Exhibition*, Frankfurt, 2012, pp. 4068 – 4071.

[19] M. J. E. Alam, K. M. Muttaqi, and D. Sutanto, “Effectiveness of traditional mitigation strategies for neutral current and voltage problems under high penetration of rooftop PV,” in *Power and Energy Society General Meeting (PES), 2013 IEEE*, 2013, pp. 1–5.

[20] F. Shahnia, A. Ghosh, G. Ledwich, and F. Zare, “Voltage Unbalance reduction in low voltage distribution networks with rooftop PVs,” in *Proc. 20th Australasian Universities Power Engineering Conference (AUPEC)*, Christchurch, 2010.

[21] J. Fernandez, S. Bacha, D. Riu, H. Turker, and M. Paupert, “Current unbalance reduction in three-phase systems using single phase PHEV chargers,” in *Industrial Technology (ICIT), 2013 IEEE International Conference on*, 2013, pp. 1940–1945.

[22] E-CONTROL, “Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen. Teil D: Besondere technische Regeln. Hauptabschnitt D4: Parallelbetrieb von Erzeugungsanlagen mit Verteilernetzen.” 2013.

[23] S. Kadam, B. Bletterie, G. Lauss, M. Heidl, C. Winter, D. Hanek, and A. Abart, “Evaluation of voltage control algorithms in smart grids: results of the project: morePV2grid,” in *Proc. 29th European Photovoltaic Solar Energy Conference and Exhibition*, Amsterdam, 2014.