VOLTAGE CONTROL ISSUES IN LOW VOLTAGE NETWORKS WITH MICROGENERATION

Rui Castro, M. E. Almeida, Célia Jesus, Pedro M. S. Carvalho and Luís A. M. Ferreira
Centre for Innovation in Electrical and Energy Engineering (Cie^3), IST – Technical University of Lisbon, Lisbon, Portugal

Keywords: Voltage Control, Microgeneration, Transformer Tap Changer, Unbalanced Load Flow.

Abstract: In the framework of the so-called microgeneration, small photovoltaic units are being installed in the roofs of the buildings and connected to the low-voltage distribution networks. This is posing some new challenges to the distribution network operators. On one hand, the off-service regulation of the transformer taps must comply with a hard twofold objective: to mitigate the undervoltages during peak load periods and to mitigate voltage rise during peak generation periods. On the other hand, the voltage profile is almost insensitive to microgeneration injected reactive power, which forces control to actuate on active power with the consequent impact on energy produced and also on network security. These two aspects of the problem are addressed in this paper with help from an illustrative test network, on which several case-studies have been built to highlight the main voltage control problems and to test different strategies to overcome such problems.

1 INTRODUCTION

Recently, governments are encouraging the installation of small Photovoltaic (PV) units (usually in the roofs of the buildings), typically sized in the range of some kW and connected to the Low Voltage (LV) distribution network, in the framework of the so-called microgeneration (µG). This is a way of indirectly reduce the net load as seen from the electrical system, because these generation units can produce locally part of the energy consumed by the system.

µG consists of a combination of generation sources, usually renewable, that interface with the LV distribution network through fast acting power electronics. LV networks have been originally designed to feed loads, so the introduction of generation sources is a quite innovative aspect that can significantly impact the flow of power and voltage conditions.

PVs will produce electrical energy during daylight, a period in which the load as seen from the distribution transformer is expected to be quite low in domestic areas. As a consequence, the power that flows to the loads will be reduced or even be reversed, which may cause the bus voltages to rise. This will require some countermeasures to be undertaken. Traditionally, this issue is dealt with by an appropriate reactive power control. This can be locally performed by the inverters of the PV, which hold power factor regulation capabilities. However, reactive power control is very ineffective in LV networks due to the low inductive component of the LV lines/cables. Therefore, the alternative is to reduce the active power injected by the PVs into the network. To cope with this purpose, the PVs must be able to receive commands specifying the maximum power generation level, when the voltage is out of its range. The control of µG induced overvoltages is to be dealt with in the scope of this paper.

Another issue related to the penetration of µG in the LV networks concerns the tap setpoint of the MV/LV transformer. Usually, MV/LV transformers do not have automatic on-load tap-changing capabilities. Instead, a fixed tap is selected with the transformer off service. Until now, this tap has been chosen so that the voltage along the entire feeder is above the lower limit at peak-load hours (off-peak generation hours). However, with embedded µG, the chosen tap must also guarantee that the voltage along the feeder is under the upper limit at off-peak load hours (peak generation hours). This twofold objective can be hard to achieve. Furthermore, it is expected that the transformer tap changes impact differently on voltage profile depending on the

Castro R., Almeida M., Jesus C., M. S. Carvalho P. and A. M. Ferreira L..
VOLTAGE CONTROL ISSUES IN LOW VOLTAGE NETWORKS WITH MICROGENERATION.
DOI: 10.5220/0003952700790084
In *Proceedings of the 1st International Conference on Smart Grids and Green IT Systems* (SMARTGREENS-2012), pages 79-84
ISBN: 978-989-8565-09-9

elasticity of the loads and on the existence of connected µG. The topic related to the impact of MV/LV transformer tap changes is also addressed in the paper.

The paper has been organized in case studies based on the same test network. Case-studies have been built with the aim of illustrating voltage control problems in LV networks with µG and the effectiveness of the proposed solutions to those problems.

2 NETWORK MODEL

As LV networks are close to end-consumers, load unbalance can be significant. Most small consumers are single-phase consumers and therefore return neutral currents can be high.

Sometimes neutral currents are even higher than phase currents (Chen, 2001). Neutral currents depend on the neutral earthling system in use, which changes from utility to utility and from country to country (Meliopoulos, 1998).

Several neutral earthling options are available. These are usually designated by TN, TT and IT earthing systems. The TN basic system is commonly used in Europe and is characterized by the transformers' neutral being earthed and the electrical load frames being connected to the neutral.

Usually, for TN earthing systems, the earthing impedance of the load frames grounding is high enough to consider that all neutral current flows back to the transformer, i.e., that the current through the load earthing impedances is negligible during normal operation. In such case, the system can be well represented by a four-wire circuit (3-phases and neutral) instead of a five-wire one (Chen, 2001); (Ciric, 2003).

There is a scarce knowledge of the behaviour of the LV distribution network in presence of concurrent unbalanced generation and loads (Chindriş, 2007); (Carvalho, 2008); (Thomson, 2007). The multidimensional stochastic dependence structure of the joint behaviour of the generation and load can be very complex to model. In this paper, we assess the behaviour of unbalanced LV networks for fixed load/generation profiles and variable load-to-voltage elasticity with the so called three-phase, four-wire, unbalanced power flow (Monfared, 2006); Ciric, 2003); (Teng, 2002).

3 MITIGATION OF INDUCED OVERVOLTAGES WITH POWER CONTROL

A small test network is used to get insight into the voltage control problems caused by the injection of µG into the radial LV networks. The test network is a 5 bus network as depicted in Figure 1.

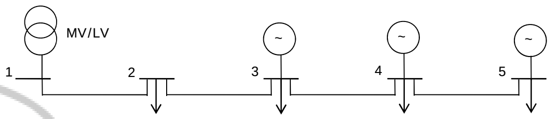

Figure 1: One-line diagram of the test network.

An unbalanced load flow study is carried out in the following conditions: (*i*) the four cables are equal with R/X = 10; (*ii*) the voltage in bus 1 is considered constant and equal to 1.05 pu; (*iii*) the loads were modelled as "constant current" (elasticity equal to 1); (*iv*) the operating point is unbalanced, the load complex power being presented in Table 1 (active power negative values correspond to µG).

Table 1: Unbalanced load profile, $\mathbf{S}_{RST}$, for the 5 bus test network.

Bus	2	3	4	5
$\mathbf{S}_{R}$ (pu)	0.10+j0.05	0.10+j0.05	0.20+j0.15	-0.25+j0.05
$\mathbf{S}_{S}$ (pu)	0.10+j0.05	0.00+j0.15	-0.20+j0.05	0.05+j0.00
$\mathbf{S}_{T}$ (pu)	0.05+j0.05	-0.20+j0.05	0.05+j0.01	0.10+j0.05

3.1 Base-case

The base-case load-flow results are presented in Figure 2.

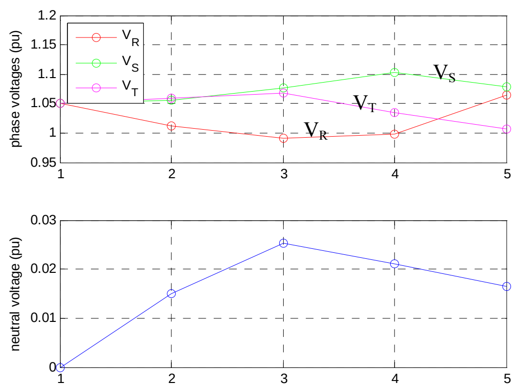

Figure 2: Voltage at the three phases (R, S, T) and at the neutral for the base case.

From Figure 2 one can observe that the voltage profile is high, namely in the phases and busbars where the µG is connected (V_{3T}, V_{4S}, V_{5R}). For instance, in busbar 4, phase S, the voltage is higher than 1.1 pu. The unbalance is noticeable as the neutral voltage magnitude is significant.

In order to improve the voltage profile, the control system features of the µGs may be used, namely its capability to regulate reactive power.

3.2 Case 1: Reactive Power Control

This case-study concerns the effects of controlling µG#4 (connected in phase S) in order that it absorbs reactive power with tg(ϕ)=0.4. Figure 3 shows the unbalanced load flow results for case-study 1.

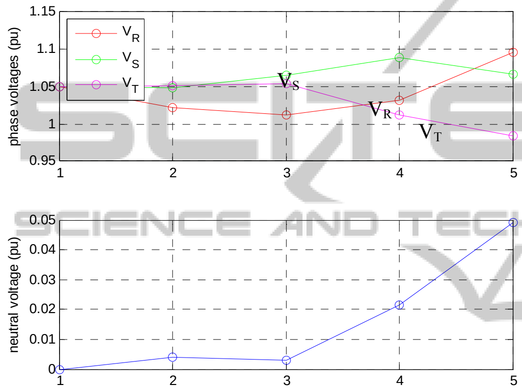

Figure 3: Voltage at the three phases (R, S, T) and at the neutral for case-study 1.

We can see that the improvement is marginal: the voltage V_{4S} is now about 1.09 pu, against 1.1 pu before this control action was undertaken. However, voltage V_{5R}, which was 1.08 pu, is now close to 1.1 pu. The increase in the unbalance of the grid is evidenced by the neutral voltage.

As this control action has shown to be not effective, an alternative is to disconnect the µG. This is to be dealt with in the next section.

3.3 Case 2: On/Off Control

Case-study 2 is related to the disconnection of µG#4. The obtained results are shown in Figure 4.

As far as busbar 4 is concerned, the consequence is now much more effective: voltage V_{4S} has dropped to 0.96 pu. Nonetheless, other issues emerged: voltages V_{3T} and V_{5R} have risen to 1.1 pu and 1.09 pu, respectively. Globally, the network is more unbalanced, as shown by the neutral voltage.

The next step is to disconnect the µG# 3, which will be performed in case-study 3.

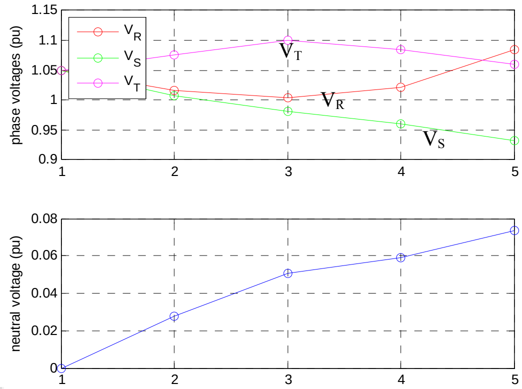

Figure 4: Voltage at the three phases (R, S, T) and at the neutral for case-study 2.

3.4 Case 3: On/Off Cascade

For case-study 3 (disconnection of µG#3), the obtained results are shown in Figure 5.

As would be expected, the problem associated with busbar 3 was fixed, but the issue now is related to busbar 5, whose voltage has increased to 1.13 pu. It should be pointed out that the unbalance of the network is even larger than before. In order to obtain an acceptable voltage profile, µG#5 ought to be disconnected. Under these conditions, it could be shown that all busbar voltages would stay below 1.05 pu.

It has been illustrated that by disconnecting a single µG a cascade may occur. Furthermore, it has been shown that µG induced overvoltages are to be mitigated by limiting the active power they can inject in the grid, the reactive power control option being much ineffective.

It would be desirable taking less extreme measures to control voltage. A way of doing so is to shed µG injection in steps instead.

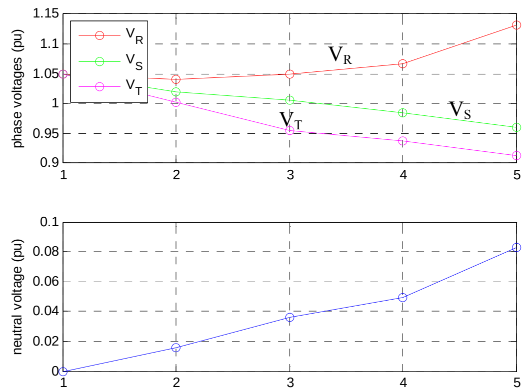

Figure 5: Voltage at the three phases (R, S, T) and at the neutral for case-study 3.

3.5 Case 4: Active Power Control

In this case-study, the control system will issue an order of cutting off half of the active power injected in busbar 4, phase S. The unbalanced load flow results for this situation may be analysed in Figure 6.

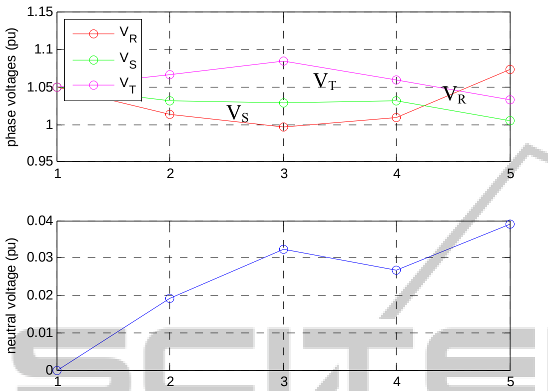

Figure 6: Voltage at the three phases (R, S, T) and at the neutral for case-study 4.

From Figure 6, one can conclude that this more moderated action is enough to obtain an acceptable voltage profile at the distribution network. The voltage V_{4S} is equal to 1.03 pu and both the voltages V_{3T} and V_{5R} are below 1.1 pu. Under these circumstances, no further corrective action is required.

4 VOLTAGE CONTROL USING MV/LV TRANSFORMERS TAP CHANGING

To illustrate the problems of voltage control using MV/LV transformer tap changers, a similar approach based on case-studies will be followed.

4.1 Case 1: The Effect of Elasticity

This case-study addresses a peak load situation with unbalanced load and no injection by the µG. The test network is represented in Figure 7, in which $\mathbf{S_i}$ = 0.525+j0.1715 pu for i=2, 3, 4 and 5.

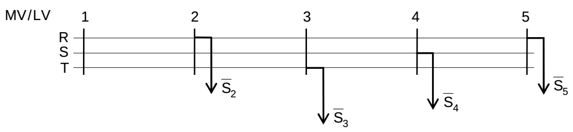

Figure 7: Test network for case-study A; load peak situation.

Power flow results are synthetized in Figure 8 for the phase voltage changed induced by increasing the voltage set-point of the transformer. This Figure shows the maximum (ΔV_{max}) and minimum (ΔV_{min}) bus voltage variation when the tap of the MV/LV transformer changes from 1.05 pu to 1.075 pu. This study was carried out for two types of load elasticity: 2 (constant impedance) and 0 (constant power).

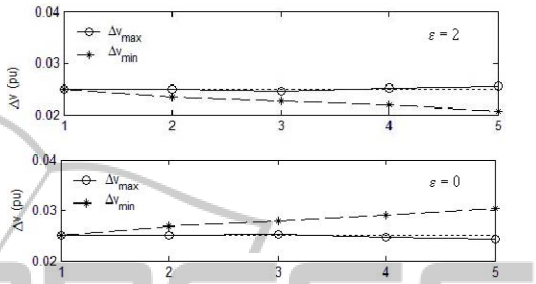

Figure 8: Maximum and minimum bus voltage variation, when the tap of the transformer changes from 1.05 pu to 1.075 pu; load elasticity: 2 (top) and 0 (bottom); case-study 1.

The figure shows that the maximum bus voltage variation follows closely the variation in the transformer tap changer (ΔV_{ref}=0.025 pu). However, the minimum bus voltage variation does not. If the load elasticity is 2, the minimum bus voltage variation is smaller than the variation in the transformer reference voltage; if the load elasticity is 0, the opposite behaviour is observed.

4.2 Case 2: Elasticity Opposite Effect

This case-study addresses an off-peak load situation with both unbalanced load and µG. The test network is represented in Figure 9, in which the load was reduced to half the previous value and µG injected power was set equal to two thirds of the previous load. It should be remarked that the generators are absorbing reactive power.

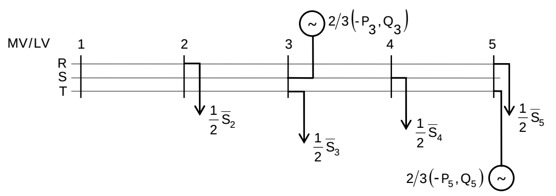

Figure 9: Test network for case-study 2; off-peak load situation with microgeneration.

A summary of the power flow results is depicted in Figure 10 for this case. This Figure shows the maximum (ΔV_{max}) and minimum (ΔV_{min}) bus voltage variation, when the tap of the transformer changes from 1.05 pu to 1.025 pu. The reduction in the reference voltage set-point (ΔV_{ref}=–0.025 pu) is necessary because overvoltages are expected to occur in this situation. As before, two elasticities were considered.

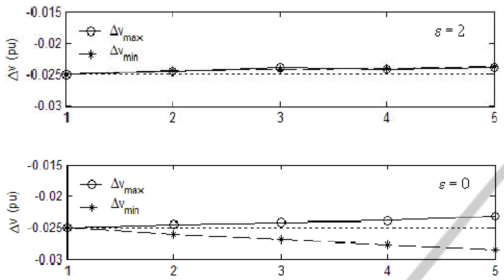

Figure 10: Maximum and minimum bus voltage variation, when the tap of the transformer changes from 1.05 pu to 1.025 pu; load elasticity: 2 (top) and 0 (bottom); case-study 2.

From Figure 10, the following conclusions can be undertaken:

- Regardless of the load type, the maximum bus voltage reduction is always smaller than the transformer reference voltage variation.
- For loads with elasticity of 2, the minimum bus voltage variation follows closely the maximum bus voltage variation.
- For loads with zero elasticity, the minimum bus voltage variation is higher than the transformer voltage variation.

The results of cases 1 and 2 allow the conclusion that, in LV networks, changes in the transformer tap may impact the feeder voltages in a way that is hard to predict. The impact in minimum voltages can be either amplified or reduced significantly depending on the elasticity being small or large. This, together with the need to regulate for both high voltages in off-peak periods and low voltage in peak periods, makes tap changing voltage regulation a difficult approach to voltage control in LV networks.

5 CONCLUSIONS

Up to now, it is common knowledge that voltage decreases along the feeders in LV networks, due to the effect of the loads. However, this might not be the case nowadays, with the increasing penetration of small PV generators directly connected to the LV grids. It is expected that the voltage rises in the daylight, when the load is low and the generation is high. The traditional voltage control method trough proper management of reactive power flow is ineffective, due to the high resistive characteristics of the LV cables/lines. Therefore, active power control is required and the disconnection of PV microgeneration is the straightforward solution. This paper tries to demonstrate that this drastic measure may be avoided, if the PVs are able to receive commands specifying the maximum power generation level, when the voltage is out of its acceptable operation range. In most cases, partial generation shedding may prove effective to control the voltage.

The issue of proper regulation of the taps of the MV/LV transformer is also an important one. This is hard to achieve because it must comply with a twofold conflicting objective: on one hand, it must mitigate the undervoltages during peak load periods and, on the other hand, to control the overvoltages during off-peak load periods. Furthermore, it has been shown in the paper that transformer tap changes effects are difficult to predict because they depend on the load elasticity. This makes tap changing voltage regulation a difficult approach to voltage control in LV networks.

ACKNOWLEDGEMENTS

This work was partially supported by EDP Distribuição via the InovGrid project.

REFERENCES

Monfared, M., Daryani, A. M., Abedi, A. M., 2006. Three Phase Asymmetrical Load Flow for Four-Wire Distribution Networks, *2006 IEEE PES Power Systems Conference and Exposition, (PSCE'06)*, Atlanta.

Ciric, M., Feltrin, A., Ochoa, L., 2003. Power Flow in Four Wire Distribution Networks – General Approach, *IEEE Transactions on Power Systems*, Vol.16, No.4.

Teng, J.H., Chang, C.Y., 2002. A Novel and Fast Three-Phase Load Flow for Unbalanced Radial Distribution Systems, *IEEE Transactions on Power Systems*, Vol.17, No.4.

Chindriş, M., Anderu, A. S., Bud, C., Tomoiaga, B., 2007. The Load Flow Calculation in Unbalanced Radial Electric Networks with Distributed Generation, *9th International Conference on Electrical Power Quality and Utilization, (EPQU'2007),* Barcelona.

Carvalho, P. M. S., Correia, P. F., Ferreira, L. A. M., 2008. Distributed Reactive Power Generation Control for Voltage Rise Mitigation in Distribution Networks, *IEEE Transactions on Power Systems*, Vol.28, No.2.

Thomson, M., Infield, D. G., 2007. Impact of Widespread Photovoltaics Generation on Distribution Systems, *IET Renewables Power Generation*, Vol.1, Iss.1.

Thomson, M., Infield, D. G., 2007. Network Power-Flow Analysis for a High Penetration of Distributed Generation, *IEEE Transactions on Power Systems*, Vol.22, No.3.

Chen, T., Yang, W., 2001. Analysis of multi-grounded four-wire distribution systems considering the neutral grounding, *IEEE Transactions on Power Delivery*, Vol.16, No.4.

Meliopoulos, A., Kennedy, J., Nucci, C., Borghetti, A., Contaxis, G., 1998. Power distribution practices in USA and Europe: Impact on power quality, *8th IEEE International Conference on Harmonics and Quality of Power*, Vol.1.