VOLTAGE CONTROL OF ACTIVE DISTRIBUTION NETWORKS BY MEANS OF DISPERSED GENERATION

Alejandro MARANO
University of Seville – Spain
alejandromm@us.es

José M. MAZA ORTEGA
University of Seville
jmmaza@us.es

José L. MARTÍNEZ RAMOS
University of Seville
camel@us.es

David TREBOLLE
Unión Fenosa Distribución – Spain
dtrebolle@gasnatural.com

ABSTRACT

The aim of this paper is to analyze how the dispersed generators can be used to effectively control the voltage of the distribution network. The technical and economical viability of this proposal can be assessed throughout a systematic analysis of how the voltage of the point of common coupling (PCC) increases as a function of the injected active power, and the required reactive power needed to maintain the voltage of the PCC to a given value.

INTRODUCTION

The electrical distribution business is currently facing a critical situation due to a combination of factors: continuous load growth, social and environmental objections to building new electrical infrastructures, economic difficulties for utilities to invest in new network assets under uncertain regulatory contexts, and higher power quality standards demanded by industrial, commercial and even domestic customers [1].

This scenario is further complicated by traditional distribution networks being steadily transformed into the so-called intelligent or smart grids, characterized among other things by the massive presence of distributed generation (DG). In fact, this is already a reality in several countries, even before the networks become smart, owing mainly to the attractive economic bonus applied to renewable energy sources such as photovoltaic, biomass or wind energy.

When operation issues are analyzed, distribution networks with high DG penetration may face a number of well-known problems: voltage regulation, reversing power flows, reduction of power quality (mainly harmonics and power fluctuations leading to flicker phenomena) and malfunction of protective devices. However, it should not be obviated the number of benefits that the distributed resources could represent to the utility in case of adequate operation, especially taken into account that most distributed generators introduced in the last years rely on power electronic devices. These devices allow a very flexible operation regarding the active and reactive power control [2, 3].

The aim of this paper is to analyze how these generators can be used to effectively control the voltage of the distributed network. Note that the active power injected by distributed generators has to be always maintained to the maximum available primary power as far as the objective of the DG owners is to maximize their profit. Hence, reactive power injections are the unique way in which DG units can be used to control the voltage.

The technical and economical viability of this proposal can be assessed throughout a systematic analysis covering the following topics:

- Reactive power capability of DG units. This issue depends on each particular energy conversion technology, i.e. asynchronous generator, double fed induction machine, synchronous generator, voltage source converter, etc. In turn, the use of each of these technologies depends on the primary source of energy. All these technologies with the exception of the asynchronous generator may regulate the reactive power to some extent depending on its rating.
- Influence of the point of common coupling (PCC). The sensibility of the PCC voltage with respect to the reactive power injection depends on the R/X ratio of the network which is a function of its rated voltage. Moreover, the power factor of the DG injected power is another parameter to be taken into account.
- Regulatory issues regarding the economical bonus applied to those DG units providing this voltage control ancillary service. As a matter of fact the Spanish regulation regarding renewable energy generation and cogeneration, the so-called *special regime*, moves forward changing the connection requirements for DG units. The Royal Decree 2819/1998 [4] established the need for adjusting the power factor as much as possible to the unity. Taken this requirement into account it is not possible to control the PCC voltage so that DG units are considered in a similar way that standard loads. To overcome this problem the Royal Decree 661/2007 [5] approves an economical bonus for those DG units able to regulate the power factor within a specific range depending on the hour of the day. However, it is important to note that the regulation of the power factor is not equivalent to the regulation of the PCC voltage. As a result of this regulatory change, sudden voltage fluctuations had appeared in networks with high DG penetration during the transition from inductive to capacitive references of power factor. Therefore, regulation has been changed again and the Royal Decree [6] imposes a power factor close to the unit, but

maintaining the economical bonus related to reactive power.

This paper is focused on the influence of the PCC on the voltage control problem. Two analyses have been performed regarding this topic. On the one hand, it has been analyzed how the PCC voltage increases as a function of the injected active power. On the other hand, the required reactive power needed to maintain the PCC voltage to a given value has been studied. Finally, this analysis has been applied to characteristic case studies involving different voltage levels in order to quantify the reactive power requirements of the PCC voltage control.

ANALYSIS OF THE PCC VOLTAGE VARIATIONS

Figure 1 shows the network equivalent as seen from the PCC. The DG unit injects both active and reactive powers into the distribution network represented by a voltage source and the Thevenin impedance.

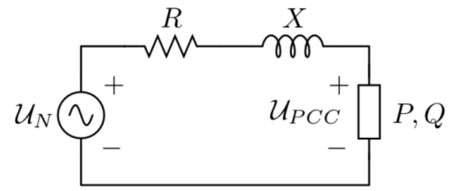

Figure 1 Network equivalent as seen from the PCC.

The equations that relate the active and reactive powers injected to the system, expressed in per unit (pu) with respect to the static power transfer capacity of the line, are the following:

$$P - kQ = -V \sin \delta$$

$$Q + kP = V^2 - V \cos \delta$$

where k is the R/X ratio of the line, δ is the angle difference between the network and the PCC voltages and V is the ratio between the amplitudes of the PCC and the network voltages.

The relationship between the PCC voltage and the active and reactive powers injected is obtained by eliminating the angle difference from the former equations:

$$V = 0.5 + Q - kP \pm \sqrt{0.25 + Q - kP - (P - kQ)^2}.$$

Low values of the R/X ratio are characteristic of high voltage systems (> 66 kV), and its value is increasing as the voltage level decreases, being close to one for low voltage lines.

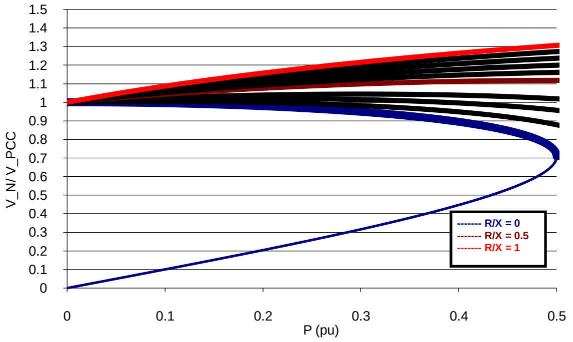

Figure 2 PV curves for different R/X ratios.

Figure 2 shows the influence of the R/X ratio on the PCC voltage when there is an injection of active power with unity power factor. It can be noticed that when the line resistance, R, is neglected, the more injected active power the higher voltage drop. This is the typical case of very high voltage lines (220 kV, 400 kV). On the contrary, when the resistance and reactance of the line have similar magnitudes, the PCC voltage tends to increase with the active power injection. Obviously, the problem of PCC overvoltages becomes even more serious if reactive power is also injected.

The influence of a reactive power injection is outlined in Figure 3 for a system with an R/X ratio of 0.5. In this case, a reactive power consumption is needed to keep the voltage close to 1 p.u. even for low values of active power injection.

Normally, DGs work injecting the active power with unity power factor or at a variable power factor ranging from 0.95 lagging and leading depending on the network conditions and regulatory issues. Figures 4 and 5 show that for MV and LV lines (R/X = 0.5 and 1) this fixed power factor should be not enough for regulating the PCC voltage to normal values, being the voltage variations very pronounced for low voltage lines even with reactive power consumption.

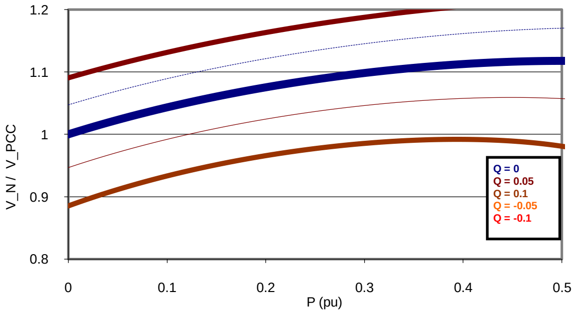

Figure 3 PV curves for different reactive power injection and R/X=0.5.

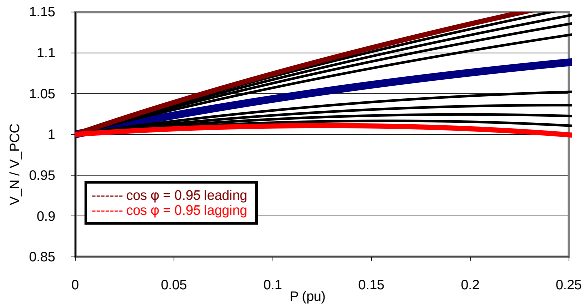

Figure 4 PV curves for different power factors in a system with R/X=0.5.

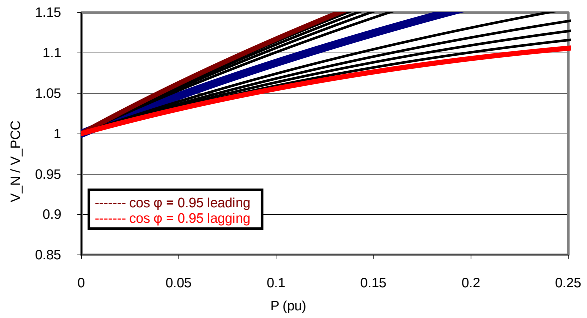

Figure 5 PV curves for different power factors in a system with R/X=1.

ANALYSIS OF THE REACTIVE POWER REQUIREMENTS

Figure 6 depicts the need of reactive power to keep the PCC voltage at its nominal value for different R/X ratios, ranging from almost 0 (400 kV line) to 1 (400 V line). From these data it can be understood the intense need of reactive power to maintain the voltages inside the interval of feasible operational values in MV and LV lines. On the contrary, in high voltage lines (> 132 kV), were the R/X ratio approaches to 0, the effect of injecting active power causes a voltage drop in the lines, being now useful a reactive power injection to keep the voltage close to its nominal value.

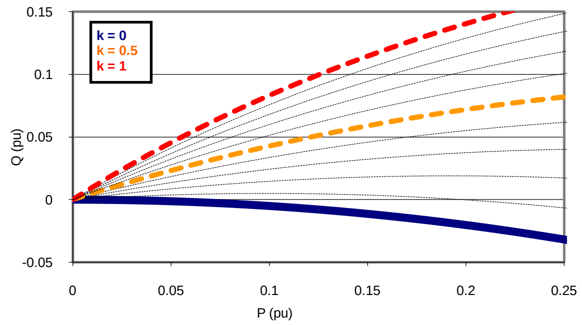

Figure 6 Reactive power needed to maintain the PCC voltage at its nominal value for different values of *k*.

CASE STUDIES

Table 1 shows typical values of line resistance, reactance and shunt capacitance of the most characteristic Spanish voltage levels. With these data, and taking into account the results of the previous section, a study was performed to investigate the additional reactive power needed to control the PCC voltage as a function of the voltage level.

Table 1 Typical R, X and B values for lines of different voltages levels.

Voltage	R (Ω/Km)	X (Ω/Km)	B (Ω^{-1}/Km)
400 V	0.4	0.09	-
20 kV (underground)	0.27	0.118	-
20 kV	0.4261	0.4000	-
66 kV	0.1194	0.3856	$3.386 \cdot 10^{-6}$
132 kV	0.0718	0.4100	$2.710 \cdot 10^{-7}$
220 kV	0.0463	0.3155	$3.676 \cdot 10^{-6}$
400 kV	0.0268	0.2766	$4.159 \cdot 10^{-6}$

For voltages upper than 66 kV the exact model of the line, where the shunt capacitance of the line is involved, was used for this study. The error committed deprecating the shunt capacitance for lower voltage levels is negligible, so a simplified model of those lines was employed.

Note that an increase of the DG unit rated power, i.e. the synchronous generator or the voltage source converter, is required in case of considering that the DG unit has to provide the reactive power for controlling the PCC voltage. In this way, Table 2 summarizes the rated power needed to maintain the PCC voltage at 1 p.u. The obtained quantity is compared to the value needed to maintain a power factor bigger that 0.95 as required by [5].

It can be noticed that keeping the PCC voltage at its rated value represents an important increase in the rated power of the DG units in low voltage levels. This is especially true in the case of LV lines and MV underground lines where R/X ratios are close to 1.

It is also relevant that for voltage levels bigger than 66 kV trying to keep the power factor in the range of 0.95 lagging to leading demands more power than maintaining the voltage at 1 p.u.

Finally, Figure 7 represents the ratio of the apparent power with respect to the active power in case of controlling the PCC voltage to 1 p.u. Note that if the DG unit injects only active power (unity power factor) its rated apparent power equals 1 p.u. The red line represents the same ratio when the objective is to operate at a power factor above 0.95. The apparent power increases due to the reactive power injection needed for controlling the PCC to 1 p.u. This increase is huge in case of LV and underground MV but fair in the other analyzed cases. Therefore, from a technical point of view it is not recommended to perform the voltage control through DG reactive power injections.

Table 2 Apparent power needed (MVA) to keep the PCC voltage close to 1 p.u. or the power factor bigger than 0.95.

Voltage (length, active power injection)	**Cos φ = 0.95 to 1**	**V = 1**
400 V (500 m, 100 kW)	0.105	0.263
20 kV underground (10 Km, 2 MW)	2.1	4.8
20 kV aerial (10 Km, 2 MW)	2.1	2.9
66 kV (25 Km, 30 MW)	31.6	31.1
132 kV (50 Km, 50 MW)	52.6	50.5
220 kV (100 Km, 250 MW)	263.2	251.2

CONCLUSIONS

This work has performed a simple analysis on the voltage control problem of distribution networks in presence of distributed generators (DGs). The traditional operational scheme based on unity power factor injection should be reconsidered as the number of DGs is constantly increasing. As a matter of fact, the voltage regulation approach in MV and LV distribution networks could be not enough in case of high DG penetration levels.

As DSOs are so-called ‘natural monopolies’, all their actions depend on regulatory rules and incentives. In addition to that, at present day regulatory framework defines distribution companies as distribution network operators (DNOs) which are in charge of managing the network without any control over the distributed energy resources spread along the network. The new active network management role will allow DNOs to become distribution system operators (DSOs). This new role will require new agreements between DSOs and DGs and will enable DSOs to demand ancillary services from DGs.

Considering this point of view, this work has analyzed the reactive power injections needed to establish some kind of voltage control service by means of DG units. This paper reveals two major conclusions. In one hand, the set point voltage control requires important additional reactive power absorption in case of MV and LV levels. In the other hand, new regulatory framework is needed to allow DSOs the integration of DGs in terms of quality of service and security of supply contribution.

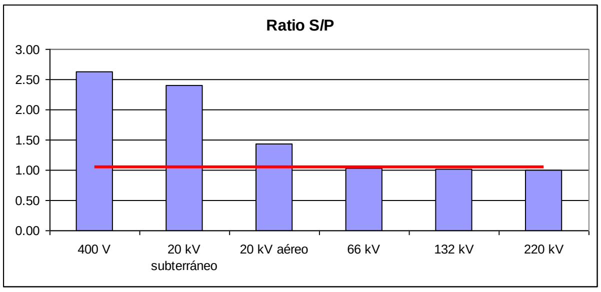

Figure 7 Ratio between the apparent power needed to maintain the voltage at its nominal value and the active power injection for different voltage levels.

ACKNOWLEDGEMENT

This work has been supported under projects EN2011-24137, REDES2025 (PSE-120000-2009-5) and PRICE (IPT-2011-1501-920000) financed by the Spanish Ministry of Economy and Competitiveness.

REFERENCES

[1] Jiyuan Fan and Stuart Borlase, “The Evolution of Distribution To Meet New Challenges, Smart Grids Need Advanced Distribution Management Systems”, *IEEE Power and Energy Magazine*, Vol.7 No.2, March/April 2009.

[2] R. Simanjorang, Y. Miura and T. Ise, “Controlling Voltage Profile in Loop Distribution System with Distributed Generation Using Series Type BTB Converter”, *7th International Conference on Power Electronics*, pp. 1167-1172, Daegu (Korea), 22-26 October 2007.

[3] R.A.A. de Graaff, J.M.A. Myrzik, W.L. Kling and J.H.R. Enslin, “Series Controllers in Distribution Systems- Facilitating Increased Loading and Higher DG penetration”, *IEEE Power Systems Conference and Exposition*, pp. 1926-1930, USA, 2006.

[4] Royal Decree 2819/1998 which regulates the electricity transmission and distribution activities.

[5] Royal Decree 661/2007 which regulates the production of electricity under the *special regime.*

[6] Royal Decree 1565/2010 which establishes and modifies certain aspects of the electricity generation under the special regime.