IMPROVING POWER QUALITY USING VSC-BASED DISTRIBUTED GENERATION UNITS

Jose M. MAZA-ORTEGA, University of Sevilla–Spain, jmmaza@us.es
Manuel NIEVES-PORTANA, University of Sevilla–Spain, manuelnieves@us.es
Juan M. MAURICIO, University of Sevilla–Spain, jmmauricio@us.es
Jesús M. MARTIN-GIRALDO, Unión Fenosa Distribución, jmmartin@gasnatural.com

ABSTRACT

This paper analyzes how the distributed generators based on voltage source converter (VSC) technology can be used to improve power quality by reducing unbalance and harmonic distortion. Voltage or current compensation strategies are proposed depending on the utility expectations. For this purpose the classical control algorithm of the DG unit has been modified in order to inject an additional compensating current. The oversizing of the DG unit due to this additional current is analyzed as a function of representative power quality indices.

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. 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) [1]. 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 [2]. In spite of this, it cannot be forgotten that this number of distributed resources along the distribution networks can report a number of benefits to the utility in case of adequate operation.

The aim of this paper is to analyze the technical feasibility of using DG units based on voltage source converters-VSC (mainly photovoltaic, microcogeneration, variable speed wind power technologies) to improve the power quality of distribution networks by reducing the harmonic distortion and unbalance. The paper is organized as follows. First, the proposed compensation strategies are presented. Second, the modification of the conventional control algorithms to achieve the proposed objectives is detailed. Then, simulation results are provided in a case study involving a low voltage distribution network. Finally, the main conclusions of this work are summarized.

COMPENSATING STRATEGIES

This work proposes to use VSC-based DG units to compensate harmonic distortion and unbalance as explained in Fig. 1.

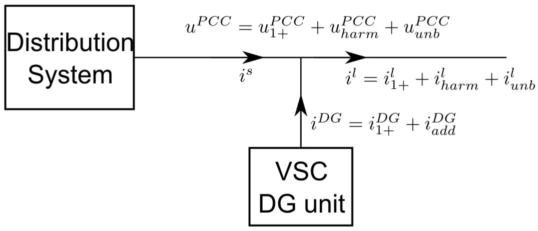

Figure 1. One-line diagram of the VSC-based DG unit connected to the distribution network.

Nowadays, the DG units mainly inject active power or, at most, a current with a power factor previoulsy defined by the current regulation. In this way, the DG units contribute indirectly to control the voltages in the distribution network obtaining an additional income for this ancilliary service. In any case, the current injections are always of fundamental frequency and positive sequence, $i^{DG}{}_{1+}$. In order to reduce the harmonics and unbalance a compensation current, $i^{DG}{}_{add}$, in addition to the fundamental current has to be injected. Two compensation criteria have been considered according to the possible expectations of a utility:

- Current compensation. The DG unit mitigates the harmonics or unbalance of the current drawn by a disturbing facility connected downstream of the point of common coupling (PCC) turning the upstream current, i^s, balanced and distorted-free. For this purpose, and according to Fig. 1, the additional current injected by the VSC-based DG unit must be the unbalance and harmonic components of the dowstream current, $i^l{}_{unb}$ and $i^l{}_{harm}$ respectively.
- Voltage compensation. The DG unit reduces the unbalanced and distortion of the PCC trying to turn the node voltage sinusoidal. This should be interesting in case of a facility demanding high power quality requirements in the PCC. The additional current injection for this case must produce a voltage drop in the upstream line impedance that mitigates the unbalance and harmonic components of the PCC voltage, $u^{PCC}{}_{unb}$ and $u^{PCC}{}_{harm}$.

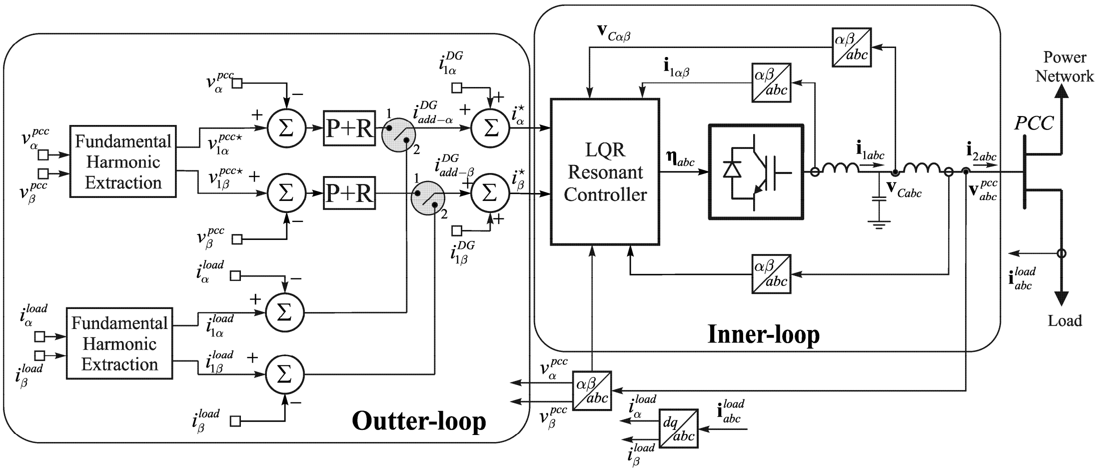

Figure 2. Block diagram of the proposed control algorithm.

CONTROL ALGORITHM

The aim of the VSC-based DG unit is to inject a power at the fundamental frequency and mitigate harmonics using a PWM technique. Hence, high frequency harmonics due to the switching exist being necessary to use grid-side filters for mitigation purposes. LCL filters are suitable for these applications because they are more cost-effective compared to simple L filters because smaller inductors can be used to achieve the same mitigation effect. However, one important drawback of the LCL filters is the introduction of a resonance in the system, being neccesary to perform either passive [3] or active [4]-[7] damping. The latter method is preferred becuase no additional losses are introduced. Hence, this paper proposes an active damping method using the complete state information as proposed in [8].

The block diagram of the proposed control system is shown in Fig. 2. This control algorithm, formulated in the stationary reference frame $\alpha\beta$, could be divided in an outter-slow and an inner-fast loops.

The outter control loop generates the reference current which must follow the VSC. This reference current is composed by the fundamental term plus the additional components needed to perform either the voltage (switch in possition 1) or current (switch in possition 2) compensation as explained in the previous section. In both cases the harmonic or unbalance detection is done by applying a DFT-based algorithm [9]. Note that in case of voltage compensation a resonant integrator (P+R) has been used to transform the voltage error into a reference current, because no estimation of the line impedance has been considered.

The inner loop is designed to track the previously computed reference current $i^*_{2\alpha\beta}$ and to achieve the adequate damping of the LCL filter resonance. A controller based on state feedback with a number of generalizaed integrators included in an extended dynamic is considered. The LQR technique has been used to compute the gains in order to assure the stability of the closed-loop operation [10].

CASE STUDY

The objective of this section is to provide the following results of the current and voltage compensating strategies:

- Required rated power of the VSC. The injection of the additional current for mitigating the unbalance or the harmonic components leads to an oversizing of the VSC. A possible measure of this fact is to refer the apparent power for the unbalance and harmonic compensation schemes with respect to the rated apparent power in the base case, where no compensation is performed. Assuming that the voltage at the PCC is almost the same in both cases, the apparent power ratio is equal to the ratio of the RMS phase currents before, I_{abc}, and after compensation, I_{abco}. However, note that for unbalance compensation the currents injected by the VSC are different in each phase. Hence three indices are proposed to take into account this issue:
  - Ratio of geometrical average of phase currents:
  $$OR_1 = \frac{\sqrt{I_a^2 + I_b^2 + I_c^2}}{\sqrt{I_{ao}^2 + I_{bo}^2 + I_{co}^2}}$$
  - Ratio of arithmetical average of phase currents:
  $$OR_2 = \frac{I_a + I_b + I_c}{I_{ao} + I_{bo} + I_{co}}$$
  - Ratio of maximum phase currents:
  $$OR_3 = \frac{\max(I_a, I_b, I_c)}{\max(I_{ao}, I_{bo}, I_{co})}$$

  Note that for the harmonic compensation strategy these ratios are identical because the magnitudes are completely balanced.
- Effectiveness of the compensating strategy. In real situations the harmonic or unbalance compensation is not completely perfect, in spite of the control algorithm applied. As a consequence, a residual of distortion or unbalance in the compensated magnitude always exists. In order to assess the effectiveness of the compensation the following ratios are defined:

$$ER_{harm} = \frac{THD}{THD_o} \qquad ER_{unb} = \frac{X_2}{X_{2o}}$$

where THD is the total harmonic distortion and X_2 is the negative sequence of the either the source current or the PCC voltage.

A low voltage distribution system, shown in Fig. 3, has been considered to analyze the proposed strategies. The distribution system has been represented by a voltage source and a line impedance with representative length and section for this voltage level. The VSC-based DG unit, connected through a LCL arrangement and the load are connected to the PCC. The source voltage and the load current may present unbalance or harmonic distortion depending on the analyzed compensating strategy. The following subsections details the simulation conditions and the main results for each compensating strategy.

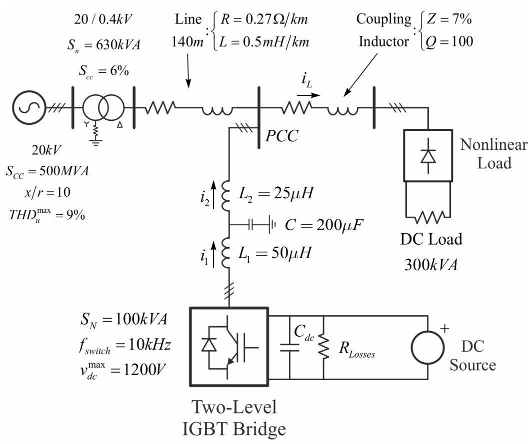

Figure 3. One-line diagram of the low voltage network.

Current compensation

As far as the harmonic current compensation is concern, the voltage source is considered sinusoidal. The load is composed by a balanced linear part demanding a sinusoidal current and a non-controlled rectifier with a resistor and capacitor in the DC side representing an AC drive. This load scheme provides the classical harmonic pattern $6k\pm1$. Varying the proportion between the linear and non-linear load components is possible to modify the THD of the load current maintaining its RMS value. Fig. 4 shows how the oversizing and effectiveness ratios vary as a function of the load current distortion. On the one hand, the oversizing ratio increases with the THD of the load current because additional harmonic currents have to be injected by the DG unit. On the other hand, the effectiveness of the compensating strategy is almost constant and independent of the load current distortion.

When unbalance compensation is analyzed, the source voltage is also considered sinusoidal. The load is assumed without distortion but with a variable unbalance degree. Fig. 5 shows the oversizing and effectiveness ratios for this case. It is important to note that the ratio OR_3, which relates the maximum value of the phase currents, should be taken into account for VSC rating purposes. As expected, and in a similar way than in the previous case, a growth in the negative sequence of the load current leads to an increase of the oversizing ratio.

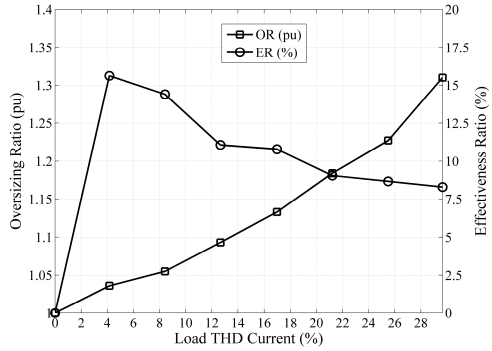

Figure 4. Compensation of harmonic current. Oversizing and effectiveness ratios vs. THD of the load current.

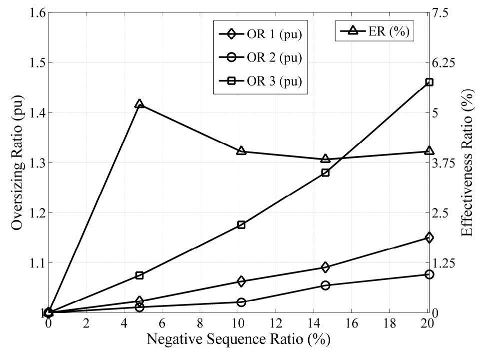

Figure 5. Compensation of unbalance current. Oversizing and effectiveness ratios vs. negative sequence of the load current.

Voltage compensation

This analysis assumes that the load is linear demanding a sinusoidal current and the source voltage is unbalance or distorted. The maximum unbalance and harmonic distortion levels have been selected according to [11]. Fig. 6 illustrates the compensation of harmonic voltages being the PCC voltage almost sinusoidal in spite of the voltage source distortion.

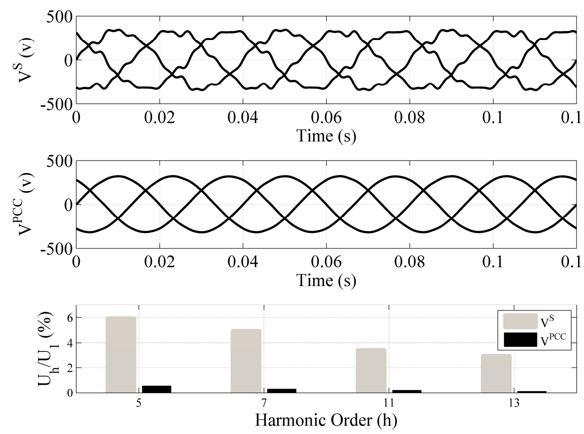

Figure 6. Compensation of voltage harmonics. Waveforms of the source and PCC voltages and their corresponding harmonics.

The behaviour of the oversizing and effectiveness ratios follow a similar trend that in the current compensation case as shown in figures 7 and 8. However, it is important to point out that the oversizing ratios for the harmonic distortion compensation are lower than the unbalance compensation ones. Note that the PCC voltage turns sinusoidal because the additional current injections of the VSC-based DG unit lead to a voltage drop in the line impedance. For the harmonic compensation case, the current injections are lower as the line impedances increase with the frequency.

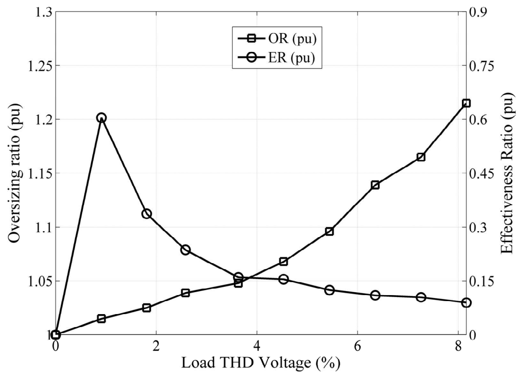

Figure 7. Compensation of harmonic voltage. Oversizing and effectiveness ratios vs. THD of the PCC voltage.

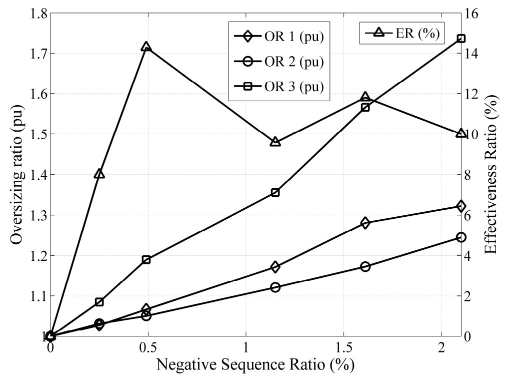

Figure 8. Compensation of unbalance voltage. Oversizing and effectiveness ratios vs. negative sequence of the PCC voltage.

CONCLUSIONS

This paper has presented two compensation strategies that can be implemented by VSC-based DG units to improve the power quality of a distribution network. These strategies have been based on the injection of additional harmonic and unbalance currents for mitigating either the PCC voltage or the load current. The results have shown the effectiveness of the proposed control algorithm due to the achieved mitigation irrespective of the harmonic distortion or unbalance of the compensated magnitudes. However, the injection of additional current terms to provide this new ancillary service has led to an increase of the rated power of the VSC units. The results have shown than VSC oversizing may be high especially when the harmonic distortion or unbalance of the compensated magnitude is high.

Acknowledgments

This work was supported by the Spanish Ministry of Science and Innovation under the projects ENE2007-68032-C04-04 and PSE-120000-2009-5 (REDES2025).

REFERENCES

[1] E.M. Lightner, S.E. Widergreen, 2010, “An orderly transition to a transformed electricity system”, *IEEE Trans. on Smart Grid*, vol. 1, no. 1, pp. 3-10.

[2] T. Ackermann, V. Knyazkin, 2002, “Interaction of distributed generation and the distribution network: Operation aspects”, *Proceedings PES T&D Asia Pacific Conference*, vol. 2, 1357–1362.

[3] M. Liserre, F. Blaabjerg, S. Hansen, 2005 , “Design and control of an LCL-filter-based three-phase active rectifier”, *IEEE Trans. on Industry Applications*, vol. 41, no. 5, pp. 1281- 1291.

[4] C. Wessels, J. Dannehl, F.W. Fuchs, 2008, “Active damping of LCL-filter resonance based on virtual resistor for PWM rectifiers - stability analysis with different filter parameters”, *IEEE Power Electronics Specialists Conference*, pp.3532-3538.

[5] P.A. Dahono, 2002, “A control method to damp oscillation in the input LC filter”, *IEEE Power Electronics Specialists Conference*, pp. 1630- 1635.

[6] E. Twining, D.G. Holmes, 2002 ,”Grid current regulation of a three-phase voltage source inverter with an LCL input filter”, *IEEE Power Electronics Specialists Conference*, vol.3, pp. 1189-1194.

[7] J. Dannehl, F.W. Fuchs, S. Hansen, 2007, “PWM rectifier with LCL-filter using different current control structures”, *European Conference on Power Electronics and Applications*, pp.1-10.

[8] E. Wu, P.W. Lehn, 2006 , “Digital Current Control of a Voltage Source Converter With Active Damping of LCL Resonance”, *IEEE Trans. on Power Electronics*, vol.21, no.5, pp.1364-1373.

[9] J.M. Maza, J.A. Rosendo, A. Gómez, S. Ceballos, M. Barrágan, 2010, “Reference Current Computation for Active Power Filters by Running DFT Techniques”, *IEEE Trans. on Power Delivery*, vol. 25, no.3, pp. 1986-1995.

[10] B. Kedjar, K. Al-Haddad, 2007, “LQR with Integral Action to Enhance Dynamic Performance of Three-Phase Three-Wire Shunt Active Filter”, *IEEE Power Electronics Specialists Conference*, pp.1138-1144.

[11] EN 50160, Voltage characteristics of electricity supplied by public distribution systems, 1999.