9th International Conference. Electrical Power Quality and Utilisation. Barcelona, 9-11 October 2007

Impact of embedded generation on the voltage quality of distribution networks

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***Abstract*— The increasing concerns related to the global warming process determined the shifting towards the use of distributed generation (DG) designed to meet the environmental restrictions. The increasing penetration rate for the DG in the energy systems is raising technical and non technical problems that must be quickly solved in order to deeply exploit the opportunities and benefits offered by the DG technologies. In this paper, the analysis of the impact of distributed generation units on the voltage quality in a 6 kV medium voltage network is conducted. The distributed generation units may require an inverter before their interconnection to the mains. Thus, these converters can produce harmonics that propagate in the distribution network. The case studies are conducted using the software package ATP-EMTP on an existing 6 kV network.**

Keywords-distributed generation, power quality, harmonics

I. INTRODUCTION

The electricity market deregulation and the advanced developments in energy generation and distribution are leading to continuous growth of embedded or distributed generation (DG) units interconnected with the distribution network. The reasons of the increased widespread are: i) the benefits that DG offers to the customers and to the utility, ii) governmental public policies and regulations, and iii) the economic opportunities [1].

However, the increasing penetration rate of DG in the power systems is raising technical problems, as voltage regulation, network protection coordination, loss of mains detection, and DGs operation following disturbances on the distribution network [2]. These problems must be quickly solved in order to deeply exploit the opportunities and benefits offered by the DG technologies. As the DGs are interconnected to the existing distribution system, the utility network is required to make use of DGs maintaining and improving the supply continuity and power quality delivered to the customers [3].

The harmonic currents generated by the grid-side converters used by some DGs (fuel cells, photovoltaics, wind turbine, microturbine) can affect the power quality in the distribution network. The harmonic perturbations are bounded by standardized limits for ensuring good power quality delivered to the load customers [4].

The paper deals with the impact of the DGs operation on the distribution networks. The attention is focused on the harmonics generated by the power electronics equipped DG. The most frequently used commutation techniques of the DG interface converter are implemented. In this paper, a case study referred to a 6 kV radial distribution, implemented in the ATP-EMTP environment, is analyzed.

II. THE DG INTERFACE CONVERTER

The use of an inverter in order to connect the DG systems with the grid is leading to harmonic distortion and general requirements can be found in standards, especially those for the interconnection of distributed generation systems to the grid [5].

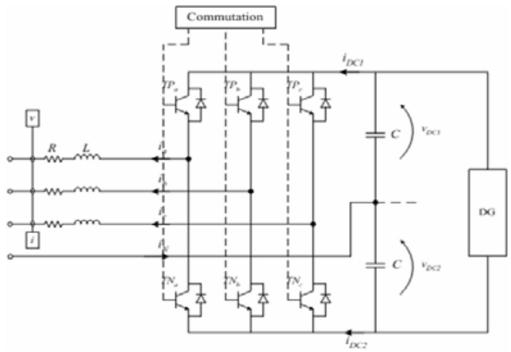

Figure 1. Layout of the DG interface converter

The commonly inverter used for this application are self-commutated ones. The layout of the DG interface converter is illustrated in Fig. 1. The switching elements used are ideal IGBTs, with anti-parallel diodes considered ideal [6]. The IGBTs are named TP_a, TN_a, TP_b, TN_b, TP_c, TN_c. In Fig. 1 are shown the internal resistances R of the converter inductors L, the three legs of the IGBT voltage source converter, and the dc link smoothing capacitors C with middle point grounded. As illustrated in Fig. 1, the measured quantities are v_{DC1}, v_{DC2}, and v_{abc}, i_{abc}.

III. Current Modulation

The reference current template is obtained by multiplying the ac line voltage with a suitable equivalent conductance, in accordance with

$$\bar{i}(t) = G \cdot \overline{v_1}(t) \quad (1)$$

where $\bar{i}$ is the vector of the ac phase current, G is the output of a proportional-integral controller, and $\overline{v_1}$ is the fundamental component of the ac contact line voltage.

The ac grid voltage it can be written as

$$\bar{v}(t) = \overline{v_1}(t) + \overline{v''}(t) \quad (2)$$

where v'' is corresponding to the perturbations present in the ac grid.

The instantaneous real power of the three phase system is given by

$$p(t) = \mathrm{Re}\left(\bar{v} \cdot \underline{i}\right) = G \cdot \mathrm{Re}\left(\bar{v} \cdot \underline{v_1}\right) = G \cdot v_1^2 + G \cdot \mathrm{Re}\left(\overline{v''} \cdot \underline{v_1}\right) \quad (3)$$

where $\underline{v_1}$ is the complex conjugated value of $\overline{v_1}$.

From the real power balance between the ac main supply and the dc side expressed as

$$p(t) = \mathrm{Re}\left(\bar{v} \cdot \underline{v_1}\right) = v_{DC} \cdot i_{DC} \quad (4)$$

it can be obtained, neglecting the ripple, the dc current

$$i_{DC} = G \cdot \frac{\mathrm{Re}\left(\bar{v} \cdot \underline{v_1}\right)}{v_{DC}} \quad (5)$$

Considering the currents flowing through the dc bus, a linear relation between the dc voltage V_{DC} and the control variable G can be written

$$\frac{C}{2} \cdot \frac{d\Delta v_{DC}}{dt} = -\frac{V_1^2}{V_{DC}} \cdot \Delta G + G \cdot \frac{V_1^2}{V_{DC}^2} \cdot \Delta v_{DC} + d \quad (6)$$

where d represents a perturbation.

For the dc voltage control, a proportional–integral controller that guarantees null steady state error has been chosen. Its transfer function is

$$\Delta G = \left(k_P + \frac{k_I}{s}\right) \cdot F(s) \cdot \Delta v_{DC} \quad (7)$$

where F(s) is the transfer function of the low pass filter required for reducing the dc bus ripple.

The equations (6) and (7) constitute the closed loop of the dc voltage control that allows to compute the values of the PI parameters. In a first approximation it can be neglected the transfer function F(s) and is obtained

$$\Delta v_{DC}(s) = \frac{s}{s^2 \cdot \frac{C}{2} + s \cdot \left(k_P - \frac{G}{V_{DC}}\right) \cdot \frac{V_1^2}{V_{DC}} + k_I \cdot \frac{V_1^2}{V_{DC}}} \cdot d \quad (8)$$

The denominator, considering a damping ratio of 0.707, constrains the PI controller parameters to respect

$$k_P > \frac{G}{V_{DC}} \quad \text{and} \quad k_I = \left(k_P - \frac{G}{V_{DC}}\right) \cdot \frac{V_1^2}{V_{DC}} \cdot \frac{1}{C} \quad (9)$$

For the IGBT commutation, three pulse width modulation (PWM) switching strategies are considered: hysteresis band technique, the sinusoidal pulse width modulation, and the square wave operation.

A. *Hysteresis band technique*

The hysteresis band modulation technique is easy to implement and offers high precision for the ac current to follow the reference pattern [6]. The control strategy illustrated in Fig. 2 shows the hysteresis current controller for phase *a*, forcing the phase currents to follow the reference template. Identical controllers are used in phase *b* and *c*. The Fryze control strategy imposes the template of the reference current i_{ref1} that is obtained multiplying the ac voltages v_a for a gain G. The method switches the transistors when the error

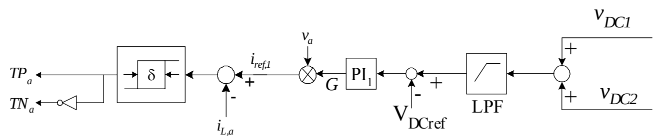

Figure 2. Fryze control strategy of the converter using hysteresis band technique.

between reference value $i_{ref,1}$ and the measured current $i_{L,a}$ exceeds a fixed magnitude.

The high frequency ripple band is constant, while the commutation frequency is variable reaching the maximum value in correspondence of the zero crossings of the ac phase voltages. The main drawback of the hysteresis band modulation is the variable switching frequency of the IGBTs. This can determine the stress of the valves and a difficult filtering process of the high frequency ripple.

The maximum value of the switching frequency can be evaluated through the following equation

$$f_s \cdot \Delta I_{L,a} = \frac{\left(\frac{V_{DC}}{2}\right)^2 - v_a^2}{L \cdot V_{DC}} \tag{10}$$

where f_s is the switching frequency [Hz], $\Delta I_{L,a}$ is the amplitude of the current ripple [A], V_{DC} is the dc voltage [V], v_a is the phase voltage [V] and L is the converter reactor inductance [H].

B. *Sinusoidal pulse width modulation*

The control is achieved by creating a sinusoidal voltage template $V_{control}$, which is modified in amplitude and angle to interact with the mains voltage V. The template $V_{control}$ is generated using the differential equation that governs the rectifier. The sinusoidal pulse width modulation (SPWM) uses the comparison between the control voltage template and the triangular carrier to generate the PWM, as shown in Fig. 3.

There are two important parameters to define: the modulation index m_a and the frequency modulation ratio m_f, given by

$$m_a = \frac{\hat{V}_{control}}{\hat{V}_{tri}}; \quad m_f = \frac{f_{TRI}}{f_s} \tag{11}$$

where $\hat{V}_{control}$ and $\hat{V}_{tri}$ are the peak amplitudes of the control signal $V_{control}$, respectively the triangular signal V_{tri} The frequency f_{tri} corresponds to the triangular carrier waveform, while f_s is the frequency of the mains. This modulation method has a harmonic content that changes with m_f and m_a. If m_f is chosen to be odd multiple of 3, the PWM modulation of the three phases will be identical and even harmonics will be eliminated. When m_a increases, the amplitude of the fundamental voltage increases proportionally, but some harmonics decrease.

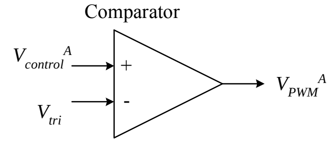

Figure 3. Sinusoidal modulation method based on triangular carrier

C. *Square wave operation*

The square wave commutation is obtained from the sinusoidal PWM by operating the VSC in the overmodulation region, i.e. with a modulation index m_a>>1 [6]. In this case the control voltage waveform intersects with the triangular waveform only at the zero-crossings of $v_{control}$. As the inverter itself can not control the magnitude of the output ac voltage, the dc input voltage must be controlled in order to control the output in magnitude. With respect to the sinusoidal pulse width modulation, in the overmodulation region more sideband harmonics appear centered around the frequencies of harmonics m_f and its multiples. However, the dominant harmonics may not have as large amplitude as for the case with $m_a \leq 1$.

IV. Harmonics Limits

Harmonic analysis, when are present multiple DG sources, is done with laborious programs, difficulties appearing in determination of the harmonic impedances of the sources [7], [8]. Table I presents the limits in percent for the individual harmonics and for total current distortion that must be respected in an electrical network with DG sources, in conformity with IEEE 1457 [5]. The standards IEC 61000-3-6 [9] and EN50160 [10] stipulate the acceptable voltage planning levels for the low voltage and medium voltage networks connected installations. The planning levels for the MV network, function of the harmonic order, are given in Table II [9].

V. Case Studies

For analyzing the harmonic impact of the various DG converter commutation techniques, the electrical network shown in Fig. 4 is considered. The electric utility supply is provided at a 110kV busbar with a fault level of 4000MVA. The 650 kW DG unit supplies, through a 10km feeder, the busbar B. A 6kV/20kV transformer connects the DG system with the mains. The 10km feeder has a resistance r=0.26Ω/km, a reactance x_L=0.4 Ω/km and a shunt capacitance C=5nF/km. The numerical simulations are carried out using the ATP/EMTP software package [11].

In order to evaluate the propagation of the harmonics generated by the DG interface converter, Fourier analyses were carried out for each switching commutation technique.

TABLE I. Maximum Harmonic Current Distortion Data In Percent Of The Fundamental Current

Individual harmonic order	**h<11**	**11≤h<17**	**17≤h<23**	**23≤h<35**	**35≤h**	**TDD**
Percent (%)	4	2	1.5	0.6	0.3	5

TABLE II. PLANNING LEVELS FOR MV NETWORKS

Odd harmonics ≠ 3k		**Odd harmonics = 3k**		**Even harmonics**	
Order k	***Harmonic voltage [%]***	***Order k***	***Harmonic voltage [%]***	***Order k***	***Harmonic voltage [%]***
5	5	3	4	2	1.6
7	4	9	1.2	4	1
11	3	15	0.3	6	0.5
13	2.5	21	0.2	8	0.4
17	1.6	> 21	0.2	10	0.4
19	1.2		4	12	0.4
23	1.2		1.2	> 12	0.2
25	1.2				0.2
> 25	0.2+0.5·(25/k)				
THD: 6.5 % at MV					

A. *Hysteresis commutation*

In the first case the DG interface converter is commutated using the hysteresis band technique. The switching frequency varies along the current waveform. The maximum switching frequency is established at 5kHz. The harmonic spectrum of the output voltage of the DG interface converter and the IEC planning levels are shown in Fig. 5. For comparison purposes, in Fig. 5 are reported the planning levels imposed by IEC 61000-3-6. As it can be seen high voltage distortion appears at the DG output between 1 and 2kHz. As shown in Fig. 5, excursions of the IEC planning levels occur for the high order voltage harmonics for even order, in the range 1–2 kHz.

A reason for concern appears when the harmonics propagation along the feeder, until the IEC limits are respected, is investigated. In Fig. 6 the harmonic spectrum of the voltage at a distance of 3.8 km from the DG is illustrated.

As shown, the voltage harmonics are under the IEC planning levels.

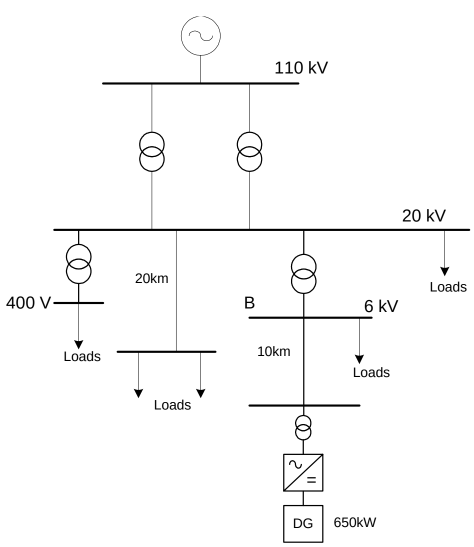

Figure 4. Layout of the system used for test

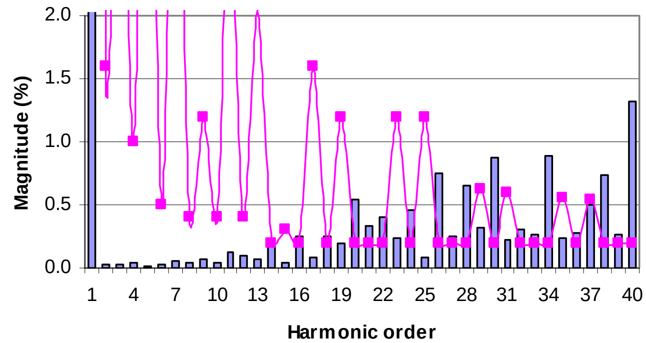

Figure 5. Harmonic spectrum of output voltage of the DG interface converter, using the hysteresis band commutation

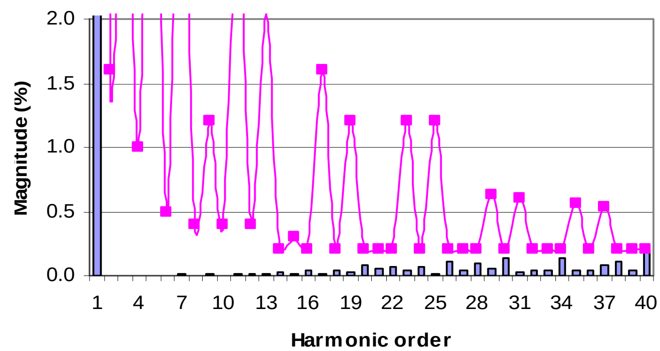

Figure 6. Harmonic spectrum of the voltage at 3.8km from the DG, using the hysteresis band commutation

B. *Sinusoidal pulse width modulation*

In the second case, the DG interface converter is commutated using the sinusoidal pulse width modulation technique. For this case study, a frequency modulation ration m_f is set to 15 and the amplitude-modulation ratio m_a is set to 0.8. The harmonics in the DG output voltage waveform will appear as sidebands, centered around the switching frequency and its multiples. The harmonic spectrum of the output voltage of the DG interface converter is shown in Fig. 7. For comparison reasons, the IEC planning levels are also illustrated.

The voltage harmonics propagation along the 10km feeder is illustrated in Fig. 8. In this case, the voltage harmonics at a

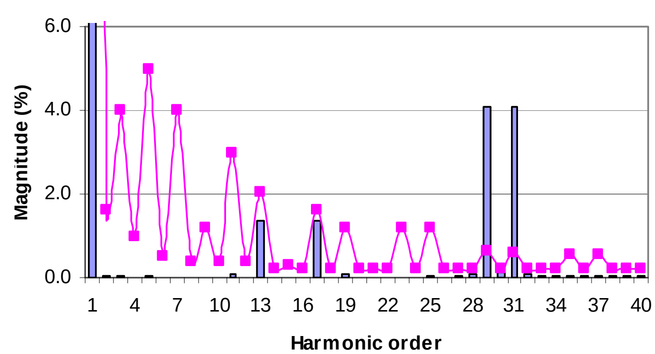

Figure 7. Harmonic spectrum of output voltage of the DG interface converter, using sinusoidal pulse width modulation

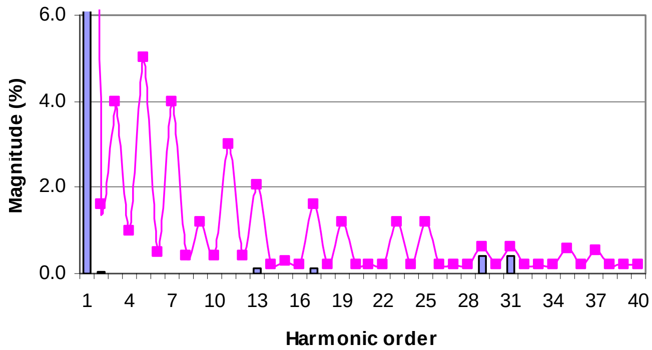

Figure 8. Harmonic spectrum of the voltage at 4.3km from the DG, using sinusoidal pulse width modulation

distance of 4.3km from the DG are under the IEC planning levels.

As it can be seen, the propagation area of the voltage harmonics when the DG interface converter is commutated using the sinusoidal pulse width modulation is wider than in case A.

C. Square wave operation

The DG interface converter is commutated using the square wave operation. This case is obtained from case B imposing a large value for the amplitude-modulation ratio m_a.

The output voltage waveform contains harmonics whose amplitude decrease inversely proportional to their harmonic order. The harmonic spectrum of the output voltage of the DG interface converter and the IEC planning levels are illustrated in Fig. 9.

The voltage harmonics propagation along the 10km feeder is illustrated in Fig. 10. In this case, the voltage harmonics at a distance of 3km from the DG are under the IEC planning levels.

Even if in this case the voltage harmonics have a shorter propagation length, the voltage total harmonic distortion THD at the point of common coupling of the DG can exceed the admissible IEC limit.

In fact, the output voltage THD is 7.6%, being higher than the limit 6.5% set for the medium voltage networks.

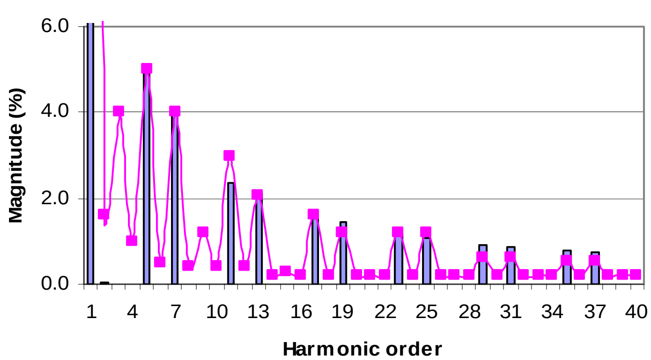

Figure 9. Harmonic spectrum of output voltage of the DG interface converter, using square wave operation

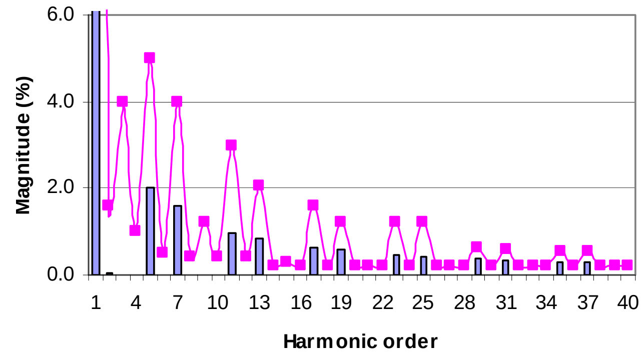

Figure 10. Harmonic spectrum of the voltage at 3km from the DG, using square wave operation

VI. Conclusions

The presence of electronic devices in the components of the DG systems determines the increase of the voltage perturbations like harmonics injected in the power system that must not exceed the standardized limits. Distorted voltage and current waveforms deteriorate the quality of the electrical energy delivered to the customers, the good operation of their equipments being jeopardized.

In this paper the study of the harmonics propagation, for various commutation techniques of the DG interface converter, in the medium voltage network, is performed. The harmonic propagation study is conducted on a 6kV network where a 650kW DG unit is scheduled to be connected.

The application results of the most frequently techniques for the commutation of the DG interface converters are given. For comparison purposes, the generated voltage harmonics are reported to the standardized limits. The hysteresis commutation gives rise to high order voltage harmonics, in the range 1-2kHz, that propagate along the network for a distance of 3.8km. The sinusoidal pulse width modulation technique determines a small number of harmonics of higher amplitudes that propagate for a distance of 4.3km. Even if the square wave operation of the converter generates voltage harmonics that have a smaller propagation length, attention must be given to the harmonic distortion index at the point of common coupling.

Acknowledgment

The research presented in this paper has been carried out in collaboration with LEAP, a laboratory funded by Fondazione di Piacenza e Vigevano and Regione Emilia Romagna.

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