Harmonic distortion analysis on the MV and LV distribution networks: problems, influencing factors and possible solutions

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Abstract.

Harmonic distortion problems are increasing on the MV and LV distribution networks, especially with the application of power factor correction capacitors that resulting resonances close to the 5^{th} harmonic. This paper describes two case studies of solving harmonic resonance problems on distribution networks. Procedures to prevent high voltage distortion are presented based on the identification of potential resonance conditions in most probable network configurations.

Key words

Harmonic distortion, power quality monitoring, resonance, HV/MV substation, MV/LV transformer and capacitor bank.

1. Introduction

All types of customers generate harmonics. Residential and commercial customers have more and more electronic load and industrial customers have a wide range of nonlinear loads that can be important. These can include ASD, dc drives, process rectifiers, induction furnaces, welders and arc furnaces. Harmonic limits for small loads (e.g. IEC 61000-3-2 [1]) and guidelines for harmonic injection from customer facilities (e.g. IEC 61000-3-6 [2], IEEE 519 [3]) provide some control of harmonic generation. However, the level of harmonic generation can still be significant and it becomes especially important when the distribution network can exhibit resonance conditions that magnify the harmonic currents and create high voltage distortion levels [4].

Electric utility power quality monitoring campaigns have been done according to EN 50160 recommended standards and also according to a national quality of service regulation, which set different indicators and corresponding minimum levels of quality the electric distributor operator must guarantee to all its clients in the various voltage levels.

In its measurement campaigns the electric utility uses class A (MV bus) and class B (LV bus) equipments. The main power quality parameters are:

- Voltage frequency
- RMS voltage values
- Voltage flicker
- Unbalance of voltage three phase system
- Voltage harmonic distortion

Furthermore, the electric utility measures the magnitude of all voltage dips or sags occurred in the networks, as well as swells and interruptions both in number and duration.

The electric utility has presently identified some problems in its grids, which deserve careful attention, namely those related to the 5^{th} voltage harmonics levels at particular points along the medium and low voltage grids. This paper deals with the problems of analyzing and simulating harmonic phenomena in distribution networks, presenting two case studies, where the 5^{th} voltage harmonics have been monitored both at MV buses of HV/MV substation and at LV side of MV/LV transformer.

Both studies were carried out using the software "DPlan – Análise Harmonica", developed by the Institute of Applied Optimization (IOA) and EDP Distribuição, member of EDP Energias de Portugal [5,6,7].

A. Resonant Harmonic

The resonant frequency for a particular inductance – capacitance combination can be computed from a variety of different formulae depending on what data are available. The basic resonant frequency equation is

$$fr = \frac{1}{2\pi\sqrt{LC}} \qquad (1)$$

Power systems analysts typically do not have L and C readily available, so they commonly compute the resonant harmonic, h_r, based on fundamental frequency impedances and ratings using the following [8]:

$$h_r = \sqrt{\frac{\mathrm{MVA_{SC}}}{\mathrm{Mvar_{cap}}}} \quad (2)$$

where h_r = resonance harmonic
$\mathrm{MVA_{SC}}$ = system short-circuit MVA
$\mathrm{Mvar_{cap}}$ = Mvar rating of capacitor bank

2. Case Study 1: 5th harmonic in a MV busbar of a HV/MV substation

An example is given here for the 5th harmonic monitored in both MV buses of a HV/MV substation, held between April and June 2007 (three months). The period profile of the three phase magnitudes (average values) and the permissible limits by the standard are shown in Figure 1 and in Figure 2.

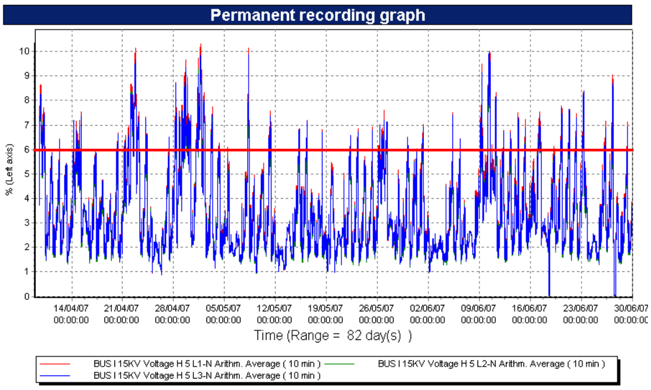

Fig. 1. 5th harmonic in MV busbar # 1

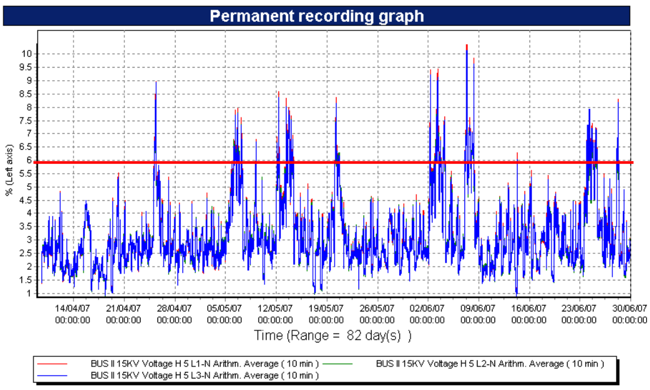

Fig. 2. 5th harmonic in MV busbar # 2

As shown in the Figures above, the values of the 5th harmonics frequently exceeded the limits (6%) defined in standard EN 50160.

From the equation (2) and for the first case study, the resonant harmonic is approximately 4.80, close to the 5th harmonic voltage.

The HV/MV substation topology is illustrated in Figure 3. Two busbars are connected to two transformers and two capacitor banks (CB), one bus for each transformer and capacitor bank.

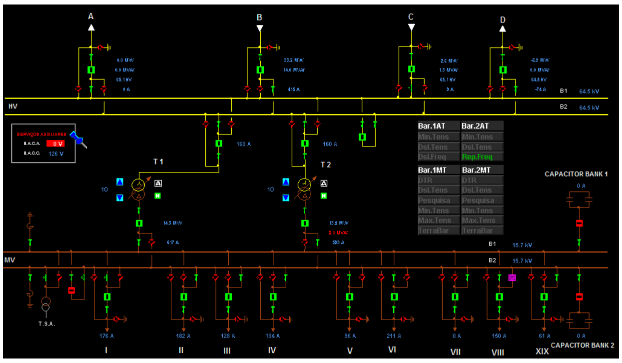

Fig. 3. Substation topology

The worst week profile for the 5th harmonic of the three phase magnitudes (average values) and the permissible limits by the standard for both busbars are shown in Figure 4 and in Figure 5. The CB schedule is represented by two bars. The green colour means the CB is switched on and the red colour means the CB is switched off.

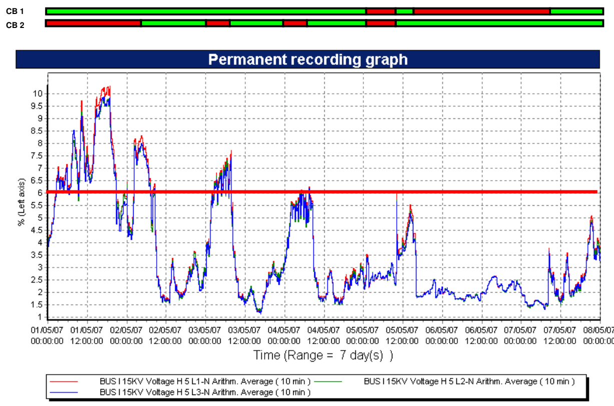

Fig. 4. 5th harmonic in MV busbar # 1

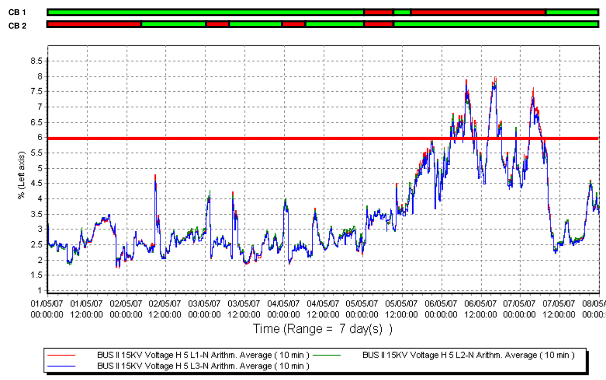

Fig. 5. 5th harmonic in MV busbar # 2

The correlation with the SCADA records shows that the capacitor banks switching has an influence on the 5th harmonic in MV busbar.

The Figure 6 and the Figure 7 presents the load of transformer # 1 and the transformer # 2, respectively, during the same period. Often the transformers were overcompensated.

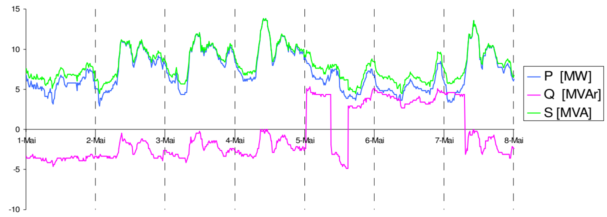

Fig. 6. Load of transformer # 1

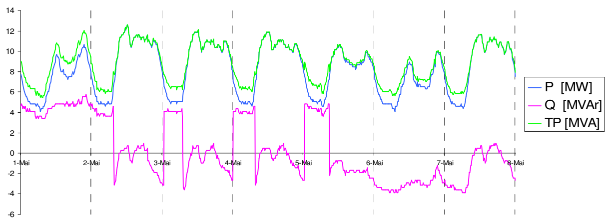

Fig. 7. Load of transformer # 2

The 5th harmonic worst situations happened during the off-peak hours.

A. Simulation

Once the non-linear loads have been estimated and the network has been characterized (for the selected frequencies) based on the monitoring and SCADA data, it is possible to simulate the harmonic behaviour of the system under topology and parameters changes. For example, it is possible to simulate the effect of switching-on capacitor banks, changing tap positions of transformers, connecting busbars and/or reconfiguring the HV or the MV network. Following the example given before, the results of connecting capacitor banks can be simulated by running a power-flow for the 1st May loads and network topology (CB 1 switched on and CB 2 switched off). The results of the simulation are shown in Figure 8 (busbar # 1) and in Figure 9 (busbar # 2).

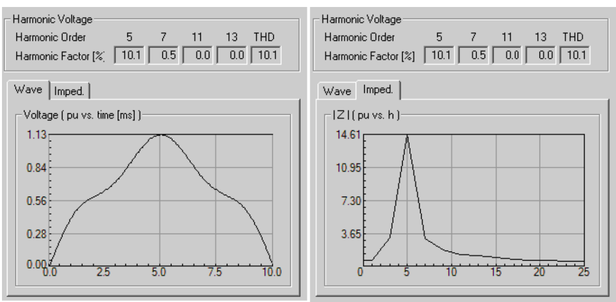

Fig. 8. Harmonic voltage results in MV busbar # 1

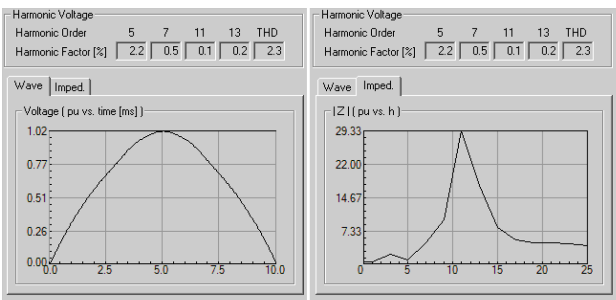

Fig. 9. Harmonic voltage results in MV busbar # 2

The results shown in the Figures above are a good approximation of the harmonic data monitored in both busbars. The impedance curve depicted in Figure 8 shows resonance behaviour for the 5th harmonic. The impedance curve depicted in Figure 9 shows resonance behaviour for the 11th harmonic, which shows that results for this harmonic are very sensitive to system characterization (e.g., tap positions) as well as to component modelling.

The filter function "Harmonic voltage distortion" is shown in Figure 10. The red colour means that harmonic voltage distortion in at least one of the harmonics frequently or THD exceeded the limits defined in standard EN 50160. The yellow colour means the harmonic voltage distortion is between 90% and 100%, and the green colour means the harmonic voltage distortion is below than 90%.

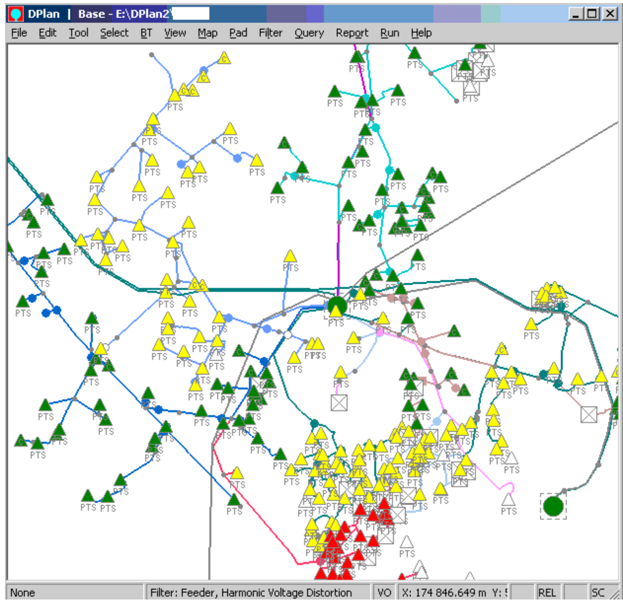

Fig. 10. Filter function "Harmonic voltage distortion"

It is concluded that the increase in the 5th harmonic in MV busbar # 1 happens when the CB 1, connected to busbar # 1, is switched on and the CB 2, connected to busbar # 2, is switched off, coinciding still higher values of 5th harmonic with the periods in which the load is lower (off-peak hours). For another busbar, the conclusion is similar.

B. Proposals

The proposals to reduce the 5th harmonic voltage to regulatory values were changed the schedule of both capacitor banks and decreased the power of the capacitor banks, in 1.60 Mvar (disconnection of 6 elements).

An additional monitoring in the HV/MV substation, held between May and June 2008, has validated the procedures in order to prevent the 5th harmonic voltage, as illustrated in Figure 11 and in Figure 12.

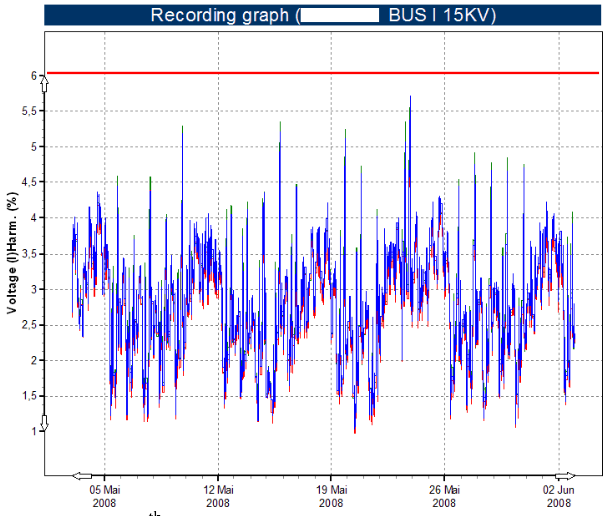

Fig. 11. 5th harmonic in MV busbar # 1, after the proposals put

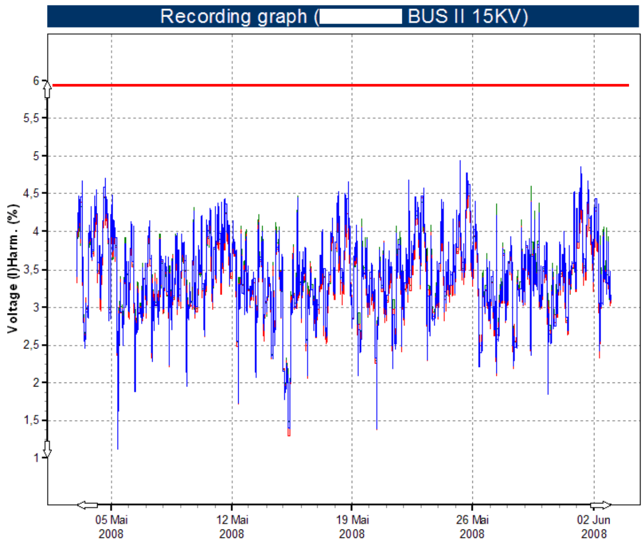

Fig. 12. 5th harmonic in MV busbar # 1, after the proposals put

3. Case study 2: 5th harmonic at LV side of MV/LV transformer

The second case study is about the 5th harmonic monitored at LV side of MV/LV transformer and in MV busbar of an HV/MV substation, held between April and June 2008 (three months). The period profile of the three phase magnitudes (average values) and the permissible limits by the standard are shown in Figure 13 and in Figure 14.

As shown in Figures, the values of the 5th harmonic exceeded the limits (6%) defined in standard EN 50160 at LV side of MV/LV transformer and were close to in the MV busbar.

From the equation (2) and for this second case study, the resonant harmonic in MV busbar is approximately 6.40, which is also close to the 5th harmonic voltage.

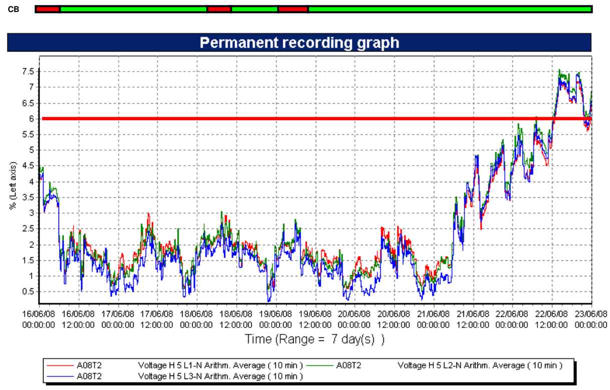

Fig. 13. 5th harmonic at LV side of MV/LV transformer

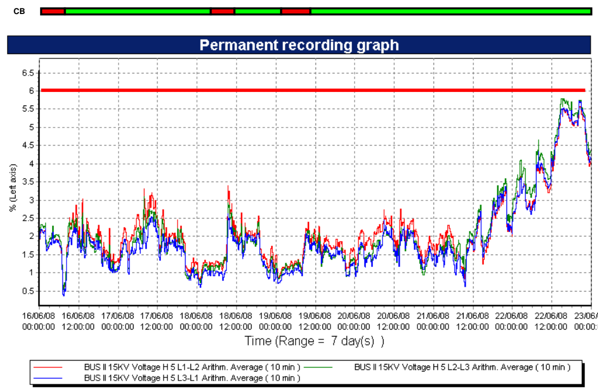

Fig. 14. 5th harmonic in MV busbar

The correlation with the SCADA records shows that the capacitor bank switching has an influence on the 5th harmonic in MV busbar.

Figure 15 presents the load of the HV/MV substation transformer, during the same period. Looking at the same Figure, one notices that at the weekend the load is lower (off-peak hours) and the transformer was overcompensated (CB is switched on).

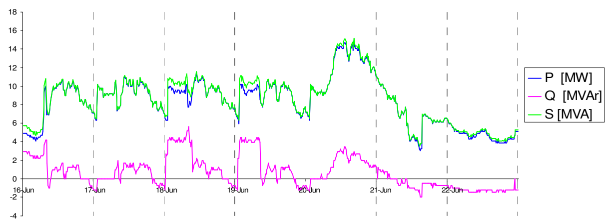

Fig. 15. Load of HV/MV substation transformer

A. *Simulation*

Following the example given before, the results can be simulated by running a power-flow for the 22nd June (Sunday) loads and network topology (CB switched on). The results of the simulation are presented in Figure 16 (LV side of MV/LV transformer) and in Figure 17 (MV busbar).

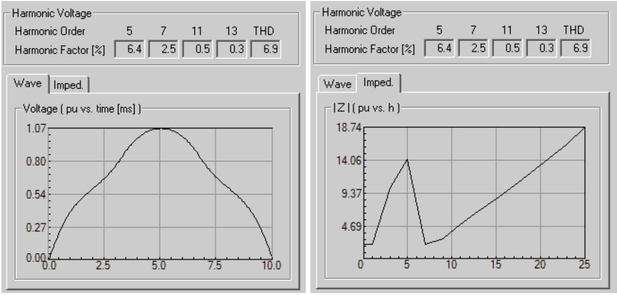

Fig. 16. Harmonic voltage results at LV side of MV/LV transformer

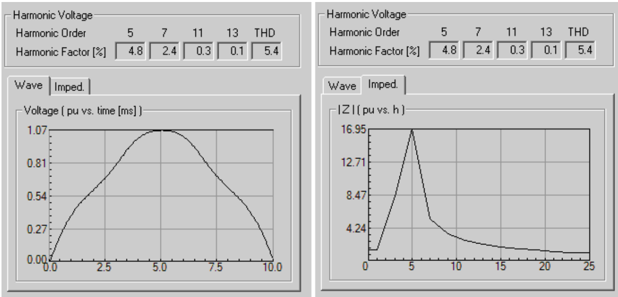

Fig. 17. Harmonic voltage results in MV busbar

The impedance curve depicted in the Figures above shows resonance behaviour for the 5th harmonic

The filter function "Harmonic voltage distortion" for this example is shown in Figure 18.

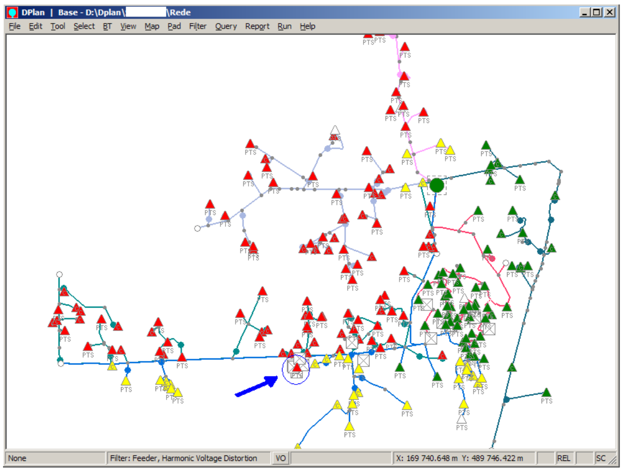

Fig. 18. Filter function "Harmonic voltage distortion"

Following the same example, the results of harmonics voltage of the simulation with change the network topology (CB switched off) is shown in Figure 16 (LV side of MV/LV transformer and MV busbar).

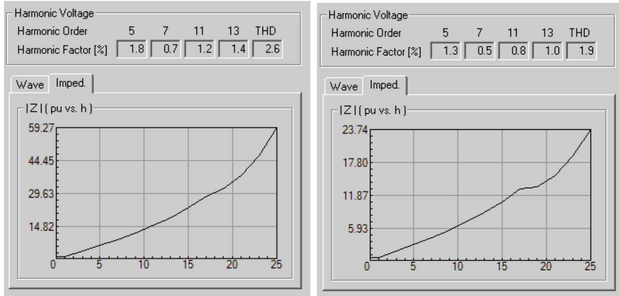

Fig. 16. Harmonic voltage results at LV side of MV/LV transformer (left) and MV busbar (right)

B. Proposal

The proposal to reduce the 5th harmonic voltage to regulatory values was changed the schedule of capacitor bank.

4. Further Information

A. 5th harmonic in a MV busbars

For the first case study, the harmonics voltage spectrum in both MV busbars, from the power quality monitoring, are shown in Figure 17 and in Figure 18.

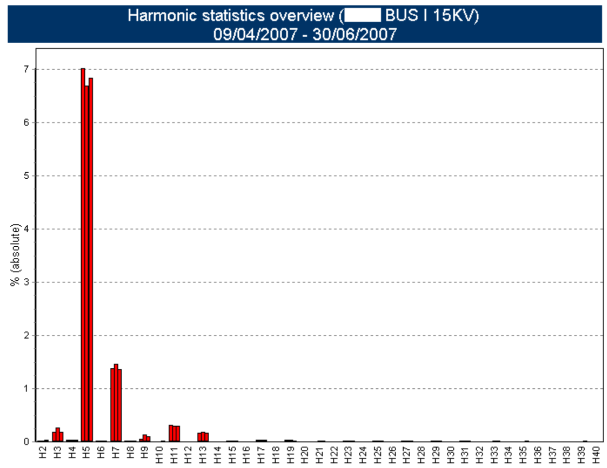

Fig. 17. Harmonic voltage spectrum in MV busbar # 1

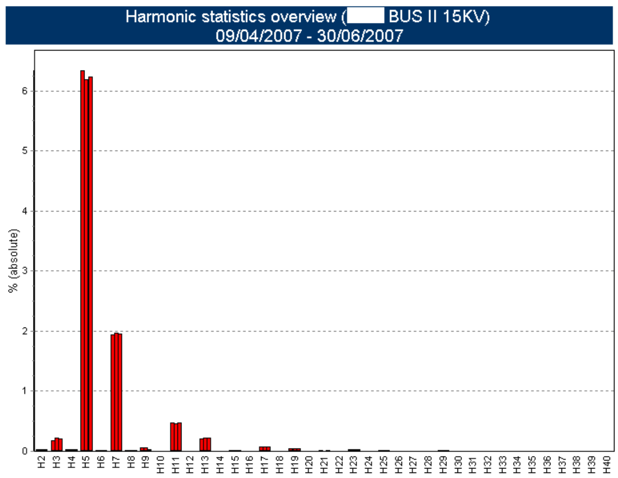

Fig. 18. Harmonic voltage spectrum in MV busbar # 2

In both MV busbars the 5th harmonic is the largest, followed by the 7th, the 11th, the 3rd and the 13th.

The harmonic content is within the normative values for all harmonics, except the 5th harmonic of which exceeded the limit (6%). Therefore, it is concluded that the THD is mainly due to the 5th harmonic.

B. 5th harmonic at LV side of a MV/LV transformer

For the second case study, the harmonic voltage spectrum at LV side of an MV/LV transformer is shown in Figure 19 and in Figure 20 we can see the harmonic voltage spectrum in MV busbar, also from the power quality monitoring.

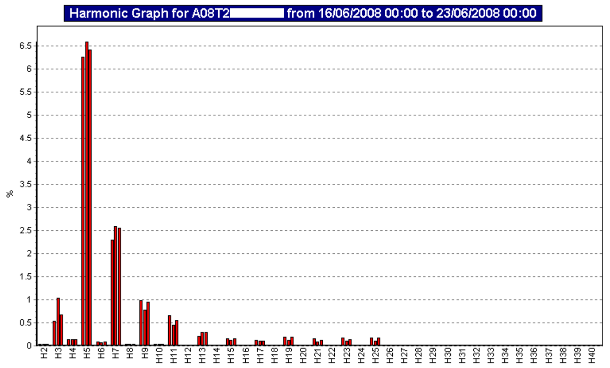

Fig. 19. Harmonic voltage spectrum at LV side of a MV/LV transformer

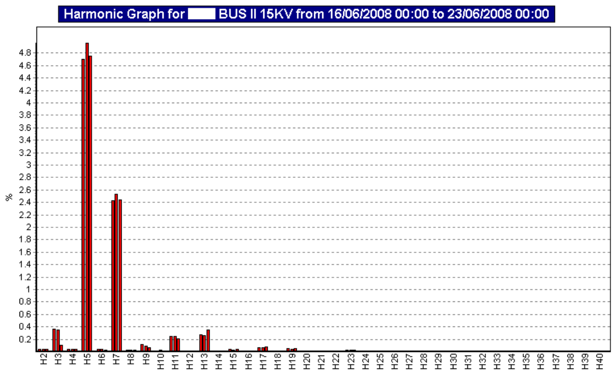

Fig. 20. Harmonic voltage spectrum in MV busbar

The harmonic spectrum is similar in both electric wiring and it has an almost identical distribution in three- phase.

Transformer winding connections have a significant impact on the flow of triplen harmonics currents from single-phase non-linear loads [8].

Measurements have shown that the odd multiples of the third harmonic (h = 3, 9, 15 and 21) are higher at LV side of MV/LV transformer in relation to values measured in the MV busbar of HV/MV substation, which is due to the connection of transformer in the delta (Δ - Yn), which blocks the passage of triplen harmonics upstream.

Also it is concluded that the THD is mainly due to the 5th harmonic, in both electric wiring.

5. Conclusion

Harmonic distortion problem was being caused by resonance created by the substation capacitor banks in the MV busbar. This resonance was magnifying the 5th harmonic component in the currents from all the customers on this system, causing high voltage distortion levels.

In many cases, it may be more economical to control the voltage distortion experienced by all customers by changing the frequency response of the system. This can be accomplished with some changes in capacitor bank on the MV system, particularly by changing the schedule and/or decreasing the power of the capacitor banks.

This paper describes two case studies of solving harmonic resonance problems on distribution networks and reduces harmonic voltage distortion for all customers.

Procedures to prevent high voltage distortion are presented based on the identification of potential resonance conditions in most probable network configurations.

An additional monitoring in an HV/MV substation has validated the procedures in order to prevent harmonic voltage distortion.

Acknowledgement

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