COMPARISON AMONG DIFFERENT DIAGNOSTIC SYSTEMS FOR MEDIUM VOLTAGE CABLE LINES

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ABSTRACT

The progressive liberalization of the market of electric power gives the user new opportunities in terms of selection of electrical and integrated services providers and motivates electric companies to increase the quality of services offered limiting their costs. In the medium voltage distribution networks, one of the most effective technical drivers to reach a higher level of power quality is the optimization of the cable network operation; this can be achieved through the application of diagnostic tools able of monitoring the conditions of cables and giving necessary indication to extend the expected life of lines, optimize maintenance operations and schedule, thus increasing their productivity. In the specific situation of Italy, where the presence of historic sites, medieval towns and incomparable landscapes are major restraints for the system operator, any preventive maintenance must be well documented and the selection of suitable cable diagnostic systems must be based on the firm belief that the line condition measured is credible, that the diagnostic process has not damaged or aged the tested line and, last but not least, that the system selected can be driven to the site without being blocked into small medieval roads. With this goal in mind, a collaboration between ENEL Distribuzione and CESI has been set up. In particular, a systematic comparison of the most advanced medium voltage cables diagnostic systems available on the market has been carried out, both in laboratory on short cables with simulated defects and in the field on real cables representative of several typical situations: the main results and findings are reported and discussed in this paper.

The work reported in the paper addresses only the methods and systems aimed at identifying the presence and the position of specific weak points in cable lines; we do not consider here the integral methods, aimed at checking the overall conditions of the cable insulation, even if the experience in the application of such integral condition assessment techniques has proven to give irreplaceable information. The techniques experimented in the work documented hereafter are considered as complementary to the integral ones and not replacing them.

N.4 medium voltage cable diagnostic systems were considered in the program. They were selected among the most modern, advanced and representative for the different approaches adopted nowadays. The voltage stress applied to the cables by the different systems tested were: the sinusoidal voltage at power frequency, the sinusoidal voltage with very low frequency (0.1 Hz), the oscillating wave with variable frequency and low damping and the oscillating wave with fixed frequency and high damping.

Systematic laboratory tests were carried out in CESI laboratories on n. 5 medium voltage cables rated 12/20kV insulated with different materials: i.e. paper, EPR and XLPE. Defects were created artificially in the cables or in the joints to check the capabilities of the diagnostic systems to point out, locate and recognize the different types of possible defects.

The cable diagnostic systems considered were also tested in the field on ENEL Distribuzione medium voltage cable network. More than 60 cables were object of this investigation. The lines were selected with the aim of the widest possible representativity in terms of age, insulating media, lengths, lay-down conditions, operation history (electrical and environmental stresses, repairs etc.).

The assessment of the different systems was carried out at the light of a multi-criteria approach, considering both the technical and the economical-management aspects. From the technical point of view we compared the efficiency of the voltage sources, the capability of detecting defects, the precision of the defect locations, the possibility to identify the type of defects and the immunity to external interferences. In terms of economical and management evaluation, we considered the system transportability, the necessary investment as well as the operation and maintenance costs.

Technically speaking we have proven that the overall performance of most of the systems is very much comparable with one another especially if we consider that the continuous development of acquisition and elaboration techniques will narrow the existing performances differences. This also shows that we need to follow with great attention the systems developments to continuously adapt the choices and that much work is still needed in the international community to rationalize this difficult matter.
SURVEY OF HARMONIC DISTORTION IN LV AND MV NETWORKS:
RESULTS AND CORRECTIVE STRATEGIES

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ABSTRACT

Harmonic distortion has become a main concern in electric distribution systems during the last years. Several public utilities are experiencing harmonic problems on their networks and, consequently, many efforts have been devoted to develop methodologies to analyze the problem and to evaluate the behavior and the impact that different appliances have on voltage distortion. Systematic assessment of the distribution networks has been undertaken by many electric companies all over the world and many surveys have been published.

In Europe, the Directive 85/374 recognized to electricity the nature of a commodity and hence the need to guarantee a minimum level of quality standards. Those standards are underway of definition by the various national regulators and penalties will be charged to the companies that do not comply with those standards, making the power quality problems more pressing. At a European level, the technical specification for power quality in the distribution networks, particularly with reference to the limits of voltage distortion, are defined in the European Standard EN 50160 that can be assumed as a reference.

The AEM Torino organized a measurement survey, with several on-site measurements, to monitor the situation of the MV and LV distribution networks with respect to some different power quality aspects. Particularly, during this survey, the phase current and voltage, the active and reactive power, the total harmonic distortion (THD) and the 5th harmonic of voltage and current have been monitored in different locations of the networks. In this paper a summary of the main results of the survey on the situation of the AEM MV and LV distribution systems, mainly with reference to the voltage distortion aspects, is presented. In this framework, the impact of public lighting on the voltage distortion of the LV distribution network is investigated and several remedies are discussed both from the analytical and the experimental point of view.

1. VOLTAGE DISTORTION IN THE AEM MV AND LV DISTRIBUTION NETWORKS

The AEM’s MV distribution system feeds, at present, about the half of the electric loads of the city of Turin (about one million of inhabitants). The MV distribution network is fed by five different HV/MV substations connected, through 220 and 130 kV transmission lines, both to the AEM’s power plants and to the national grid. Three different levels of MV distribution voltages are currently used: 27 kV, 22 kV and 6.3 kV. The 27 kV network is composed by about 250 km of lines (90% underground cables) and feeds about 70 transformers; the 22 kV has about 200 km of cable lines and 400 transformers while the 6.3 kV has about 1900 km of cables and about 2000 transformers. The two voltage levels of 6.3 kV and 27 kV can be traced back to the past history of AEM. During the last years a new, unifying, voltage level of 22 kV has been introduced and a new network has been partially built with the target to substitute the other two distribution networks.

A survey has been undertaken to assess the power quality problems (voltage sags, overvoltages, harmonic distortion) of AEM’s distribution networks. The survey took more than one year to be completed; 20 different measurement sites have been monitored for about one week each. The sites have been chosen in different distribution networks according to the following scheme:

- 2 points in the HV/22 kV substations
- 4 points in the LV network fed by the 22 kV distribution network
- 4 points in the LV network fed by the 6.3 kV distribution network
- 2 points in the 27 kV distribution network
- 3 points in the 22 kV distribution network
- 5 points in the LV network feeding public lighting

Generally, the values of voltage THD were not high and they comply with the European Standard (1). The only exception was in the LV distribution networks characterized by a high public lighting load. The 27 kV network is characterized by lower values of voltage distortion (< 1.8%) (Fig. 1). On the 22 kV network the situation varies considerably and depends on the HV/MV substation feeding the network; the values vary in the range 1-4%. The portion of the 22 kV network fed by the Monterosa substation has been considered with more interest, due to the fact that its load has reached almost its steady state load value. This substation is equipped with two 132 kV/22 kV, 63 MVA transformers but, in its normal state, only one transformer is in service. The voltage distortion of the 22 kV network during a typical week is depicted in Fig. 2 where both the voltage THD and the amplitude of the 5th harmonic voltage are represented. In the LV distribution network fed by the 6.3 kV network the THD is lower and it reaches a maximum of 2.8% (Fig.3) while the 22 kV distribution networks has voltage THD in the range 2-4% (Fig. 4). In Fig. 7 the voltage distortion summary of 8 measurement sites is reported along with the limit on THD and on 5th harmonic.
Fig. 1. Voltage THD and 5th harmonic amplitude at the 27 kV busbars of the La Fenice substation

Fig. 2. Voltage THD and 5th harmonic amplitude at the 22 kV busbars of the Monterosa substation

Fig. 3. Voltage THD and 5th harmonic amplitude at the 400 V busbars of the 29-132 substation

Fig. 4. Voltage THD and 5th harmonic amplitude at the 400 V busbars of the AP-32 substation

Fig. 5. Voltage THD and 5th harmonic amplitude at the 400 V busbars of the AP-92 substation

Fig. 6. Voltage THD and 5th harmonic amplitude at the 400 V busbars of the AL-76 substation
In Fig. 5 and Fig. 6 the voltage distortion of the LV side of two MV/LV substations with a relevant public lighting (PL) load is reported. The substation AP92 is equipped with a 250 kVA transformer and has 82.4 kW of PL load with 137 kvar of lamp capacitors, while the AL76 substation has the transformer of the same rating and a PL load of 93.9 kW with 135 kvar of lamp capacitors.

With reference to Figs. 2, 5 and 6 some considerations can be traced:

- The voltage distortion is mainly due to the 5th harmonic (THD and 5th harmonic are almost coincident) both for the MV and LV side.
- The daily behavior at the LV busbars shows a sudden decrease in the voltage distortion when PL is switched off (at about 7 a.m. in Fig. 5, at 6 a.m. in Fig. 6) and a sudden increase when PL is switched on (at about 5 p.m. in Fig. 6, at 21,30 p.m. in Fig. 6). The increase in THD and 5th harmonic magnitude is about 2.5% for the AP92 substation and about 4% for the AL76 substation.
- The 7th harmonic is always negligible.
- The 3rd harmonic is negligible also at the low voltage busbars.

The correlation between the PL switching on and the increase in voltage distortion motivated the analysis of the harmonic behaviour of the PL lamps (2-5) and the investigation of effective remedies.

2. HARMONIC BEHAVIOR OF PL LAMPS

The PL service is usually carried on with the use of discharge lamps. There are various types of discharge lamps that differ mainly as regards the type of gas used to fill the bulb and the power. The main types of lamps that are used for PL in Turin are:

- sodium gas (Na) with power of 150 and 250 W;
- mercury gas (Hg) with power of 125 and 250 W;
- allogenuri gas (HQI) with power of 100 W.

These types of discharge lamps have been tested in laboratory. The aim was to estimate the main electric parameters of the lamps and, above all, to characterize the harmonic contents of the absorbed current.

The main results are summarized in Tab. 1 in which the lamp power factor (PF), with and without capacitor, the current (not considering the capacitor), with some of its harmonics and the THD are presented. The most relevant harmonics are the 3rd (7.3-12%), the 5th (1.2-3.8%) and the 7th (1.1-2%); higher order harmonics are negligible (<1%). The values slightly depend on the lamp type and power. The current THD is relatively low (about 8–12%).

3. EXPLANATION OF THE LV HARMONIC DISTORTION

To explain the increase of voltage distortion on the LV side of MV/LV transformers, during the switching on periods of the PL loads, the very simple model of Fig. 8 can be used.

The capacitance of the capacitor for PF improvement depends mainly on the lamp type. Sodium and alogenuri gas lamps need higher specific capacitance, varying with their power in the range 125-135 μF/kW. Mercury gas lamps need less capacitance compared to the sodium lamps, in fact their specific capacitance belongs to the range 72-80 μF/kW.

### TABLE 1 - Typical electric parameters for PL lamps

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Na 150 W</th>
<th>Na 250 W</th>
<th>Hg 125 W</th>
<th>Hg 250 W</th>
<th>HQI 100 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitance [μF]</td>
<td>20</td>
<td>31.5</td>
<td>10</td>
<td>18</td>
<td>12.5</td>
</tr>
<tr>
<td>PF with capacitor</td>
<td>0.96</td>
<td>0.96</td>
<td>0.87</td>
<td>0.92</td>
<td>0.93</td>
</tr>
<tr>
<td>PF without capacitor</td>
<td>0.47</td>
<td>0.55</td>
<td>0.51</td>
<td>0.57</td>
<td>0.43</td>
</tr>
<tr>
<td>Lamp current [A]</td>
<td>1.73</td>
<td>2.48</td>
<td>1.24</td>
<td>2.16</td>
<td>1.15</td>
</tr>
<tr>
<td>3rd harmonic current [%]</td>
<td>8.7</td>
<td>12.0</td>
<td>8.2</td>
<td>9.0</td>
<td>7.3</td>
</tr>
<tr>
<td>5th harmonic current [%]</td>
<td>2.2</td>
<td>3.8</td>
<td>1.9</td>
<td>2.5</td>
<td>1.2</td>
</tr>
<tr>
<td>7th harmonic current [%]</td>
<td>1.8</td>
<td>2.0</td>
<td>1.4</td>
<td>1.1</td>
<td>1.3</td>
</tr>
<tr>
<td>Lamp current THD [%]</td>
<td>9.2</td>
<td>12.8</td>
<td>8.6</td>
<td>9.4</td>
<td>7.5</td>
</tr>
</tbody>
</table>

The correlation between the PL switching on and the increase in voltage distortion motivated the analysis of the harmonic behaviour of the PL lamps (2-5) and the investigation of effective remedies.
is under investigation, \( B_K \) is the equivalent admittance of all the PF correction capacitor installed on the lamps and \( I_{1K} \) represents the total current of the lamps. The other loads fed by the same substation, can be included in the Thévenin parameters \( V_{NK} \) and \( X_K \). The generic \( k^{th} \) harmonic voltage phasor at the point P can be expressed as:

\[
V_K = a_k (V_{NK} - j X_K I_{1K})
\]  

(1)

where the first term puts into evidence the influence of the MV network distortion level (and of the other LV loads connected), while the second term takes the contribution of the lamps into account. The two terms in (1) can compensate each other, so that the total distortion due to \( k^{th} \) harmonic can decrease.

The complex coefficients \( a_k \) (amplification factor for the \( k^{th} \) harmonic) is given by:

\[
a_k = \frac{1}{1 - X_K B_K}
\]  

(2)

Introducing the short circuit power \( S_{CC} \) (whose limitation is mainly due the MV/LV transformer reactance) and the reactive power supplied by the capacitors \( Q_C \), both evaluated at the same voltage, \( a_k \) can be expressed as:

\[
a_k = \frac{1}{1 - k^2 Q_C / S_{CC}}\left(1 - \frac{k}{X_K}ight)
\]  

(3)

with:

\[k_R = \frac{S_{CC}}{Q_C}\]

where \( k_R \) is the order of harmonic for which the network and transformer reactance \( X_K \) is equal to the reactance of the capacitors \( B_K^{-1} \) (resonance condition). The coefficient \( a_k \) allows to put the role played by the capacitors into evidence; in fact, if there are no capacitors \( (B_K=0) \) then \( a_k=1 \), otherwise, for the most important harmonics \( (5^{th} \ and \ 7^{th}) \) \( |a_k|>1 \), leading to an amplification of the voltage distortion of the network \( (V_{NK}) \) even without the contribution of the load current \( I_{1K} \).

It should be noted that usually the reactive power \( Q_C \) is lower than the rated power of the transformer and then the amplification factor of the \( 5^{th} \) harmonics is monotonically increasing. The resonance condition occurs for a value of \( Q_C \) almost equal to the transformer rated power, while for a value of \( Q_C \) greater than one half of the transformer power the amplification factor value is greater than 2.

**4. CORRECTIVE STRATEGIES**

The reduction of the voltage distortion on the LV side of the MV/LV substation feeding PL loads can be obtained by different approaches:

a) limitation of the PL load with respect to the rated power of the transformer;

b) reduction of the total capacitance of lamp power factor correction capacitors;

c) addition of capacitors with series reactors at the LV busbars;

d) reduction of the \( 5^{th} \) harmonic in the MV network;

e) increase of the MV/LV transformer rated power.

The proposed remedies have been drawn from the simplified model of Section 3. They have been tested either directly on field and with a laboratory experimental model. Accurate numerical studies have been done using a harmonic power-flow program on a detailed model of the LV distribution system. All the results proved the effectiveness of the proposed remedies.

**a) Limitation of the PL load**

As it has been shown in Section 3, the voltage distortion depends mainly on the reactive power of the lamp power factor correction capacitors. The total capacitor reactive power depends on the total power of the lamps and on the type of lamps (Tab. 1). Chosen, with respect to the voltage distortion without PL load, the maximum amplification factor of the \( 5^{th} \) harmonic, it is possible to evaluate the maximum reactive power of the lamp capacitors. Then, it is possible to compute the maximum rated power of a mix of lamps, taking into account for each different kind of lamp its specific capacitance. Tab. 2 reports the absolute (kW) and relative (%) PL load limits for different transformers (with rated power \( S_N \) and impedance \( Z_{SC} \)) and for different composition of the PL load between mercury and sodium lamps (0, 50%, 100%).

### TABLE 2 - PL load limits

<table>
<thead>
<tr>
<th>( S_N ) [kV]</th>
<th>( Z_{SC} ) [%]</th>
<th>( P_{NAX} = 100% )</th>
<th>( P_{NAX} = 50% )</th>
<th>( P_{NAX} = 0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>max ( P_{TL} ) [kW]</td>
<td>%</td>
<td>max ( P_{TL} ) [kW]</td>
<td>%</td>
<td>max ( P_{TL} ) [kW]</td>
</tr>
<tr>
<td>160</td>
<td>4</td>
<td>24.4</td>
<td>15.3</td>
<td>30.6</td>
</tr>
<tr>
<td>250</td>
<td>4</td>
<td>37.6</td>
<td>15.1</td>
<td>47.2</td>
</tr>
<tr>
<td>400</td>
<td>4</td>
<td>59.4</td>
<td>14.9</td>
<td>74.6</td>
</tr>
<tr>
<td>630</td>
<td>6</td>
<td>60.7</td>
<td>9.6</td>
<td>76.2</td>
</tr>
</tbody>
</table>

The effect of PL load reduction on the voltage distortion has been experimentally tested in the AP92 substation where there are 5 different PL lines, feeding about 15 kW of lamps each.

![Fig. 9 – Phase-neutral voltage THD and 5th harmonic amplitude during the PL load reduction experiment at the AP92 substation](image-url)
Starting without PL load, all the PL lines were switched on (82.4 kW of PL load), then, one line at a time, all lines were switched off. Fig. 9 shows the voltage distortion during the experiment with the corresponding PL loads. It is well evident the sudden reduction of the voltage distortion after switching off each PL line. The experimental values are in good agreement with the values that can be obtained from the simplified model and with the limits of Tab. 2.

b) Reduction of the capacitance of lamp capacitors

The model of Section 3 can also be used to evaluate the amount of reactive power that has to be removed to reduce the voltage distortion. Once the maximum value of the 5th harmonic amplification factor has been fixed, the value of reactive power and hence the number of capacitors to remove can be evaluated. To partially compensate the reduction of power factor correction, the reactive power of the removed lamp capacitors can be installed at the substation LV busbars. To avoid voltage distortion problems, the substation capacitors must be equipped with a series inductor (harmonic block reactor). An appropriate frequency of series resonance is about 180-200 Hz.

c) Addition of capacitors at the LV busbars

Instead of removing capacitors from the lamps, it is possible to add capacitors with harmonic block reactor at the substation LV busbars. It can be proved that adding 1 kvar of capacitors (with series reactor tuned at 190 Hz) is equivalent, in terms of voltage distortion reduction, to the elimination of 1.24 kvar of lamp capacitors. The advantages of this solution are the preservation of power factor correction benefits in the PL lines and the cost reduction obtained by avoiding the expensive removal of each lamp capacitor.

Remedies b) and c) have been tested on the laboratory experimental model. The results showed that the most effective remedy is the substitution of lamp capacitors with substation capacitor equipped with series reactor that reduces the 5th harmonic amplification factor from 1.7 to 1.16. Also the addition of substation capacitors gives good results with an amplification factor of 1.32, and this seems to be the cheapest solution. The removal of lamp capacitors leads to an amplification factor slightly higher (1.43) even if it can be enough to comply with the standard.

d) Reduction of the 5th harmonic in the MV network

The voltage distortion of the LV network can be reduced by decreasing the 5th harmonic of voltage of the MV network, with the same amplification factor for the 5th harmonic. Since the voltage distortion of the MV network is mainly due to the HV/MV transformer reactance, the operation of the HV/MV substation with two transformer in service can be effective. If each transformer feeds a separate MV busbar, the increase of the short circuit power is avoided.

e) Increase of the MV/LV transformer rated power

To reduce the distortion it is also possible to increase the rated power of the MV/LV transformer feeding the LV network for the same value of PL load.

Among all the investigated solutions, the main remedy chosen to reduce the voltage distortion in the AEM LV network due to the PL load was the reduction of PL loads in the existing substations. New planning and design rules, based on the indications of Tab. 2, have also been introduced to limit the maximum PL load allowed for future installations.

5. CONCLUSIONS

The results of the harmonic survey in the AEM MV and LV distribution networks show that there are no significant problems of voltage distortion. The only exception is the increase of voltage distortion in LV distribution networks with a significant public lighting load. The distortion level, in certain cases, could be remarkably high. An analysis of the problem has been presented based on field measurement and on theoretical and experimental models. The proposed models and experimental tests show that the main cause of the voltage distortion can be traced back to the power factor correction capacitors of the lamps, while the current distortion of the lamps plays a negligible role.

Some possible remedies are the PL load reduction with respect to the rated power of the MV/LV transformer or the increase in the rated power of the transformer with fixed PL load, the partial elimination of the lamp capacitors, the addition of capacitors (with series reactor) with or without the corresponding elimination of lamp capacitors. The effectiveness of the proposed remedies has been verified by field tests or laboratory experiments.

6. REFERENCES

1. European Standard EN50160, "Voltage characteristics of electricity supplied by public distribution systems," May 1995