RESONANCES IN LV INDUSTRIAL NETWORKS WHEN USING SHUNT CAPACITORS FOR POWER FACTOR CORRECTION

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ABSTRACT

The paper is focused on harmonic resonances in LV industrial and commercial networks. The shunt capacitors used for power factor correction affect directly harmonic currents and voltages in the network and hence cause power losses in induction motors, transformers and capacitors. In the paper practical measurement methods are described for estimating harmonic resonances when power factor correction capacitors are used. The impact of capacitors upon harmonic distortions is discussed. Measurement results of harmonic currents and resonances in industrial LV networks are shown.

INTRODUCTION

Supply voltage quality problems within industrial/commercial LV networks are often discussed regarding disturbances and failures (e.g. voltage disturbances, harmonic distortions, harmonic resonances) [1]–[4]. Still, the harmonic resonance phenomena are frequently not so intense (sharp enough) to cause any breakdown of components other than power factor correction capacitors, but affect supply voltage quality and power losses in the whole LV power system, particularly in induction motors, transformers and capacitors [5]–[8]. Harmonic power losses are usually not estimated because the losses are not measured nor calculated.

Since the 1990s, there has been a steady increase of nonlinear equipment in LV industrial and commercial networks, including electronic loads, adjustable-speed drives, welding converters etc. This has led to a growing presence of harmonic currents and consequently harmonic voltages. Moreover, some industrial loads tend to operate at relatively low power factors. The wide spread procedure for overcoming the problem of low power factor and compensating reactive power is to install controlled shunt capacitor banks on the LV customer side.

Misapplication of power capacitors in today's complicated industrial distribution systems has negative impacts on both the customer (LV equipment, additional losses) and the utility (equipment), including amplification and propagation of harmonics resulting in equipment overheating, additional losses as well as failures of capacitor banks themselves [1]–[5].

A direct indicator of parallel resonance is for example failure (breakdown) of capacitors, when filtering reactors are not used in the capacitor circuit, as could be seen for example in Fig. 1.

Fig. 1. Capacitors breakdown due to parallel resonance in a LV system.

The general requirements upon harmonic voltages and currents have been stated in standards. Still, operating the LV network close to these limit values will be unfavorable for the customer causing extra power losses and consequently extra costs. In addition, heating of equipment and reduction of service time occurs. Moreover, in several cases the limit values of harmonic voltages and currents are exceeded.

As shown in [1], [9], and [10] the predominating harmonics in LV networks are mostly the same in different countries starting from the 5th, followed by the 7th, 3rd, 11th and 13th.

The problems of interest in this study are the following. What is the extent of harmonic currents and voltages during the resonance phenomena? What are the characteristic resonance frequencies in LV industrial networks? What parameters should be measured to estimate the resonance? How sharp is the resonance? How does damping affect the resonance? Does the resonance affect only one harmonic frequency or several?

BASIC PRINCIPLES

In a simplified LV network as seen from the LV side the impedance of the transformer and the capacitance of the capacitor form a parallel circuit having a resonant

frequency at some point. To calculate the resonant frequency one could use the equivalent circuit as shown in Fig. 2 including the inductance and resistance of the transformer, the capacitance of the capacitor battery and the source of harmonic currents, which is in parallel to the circuit.

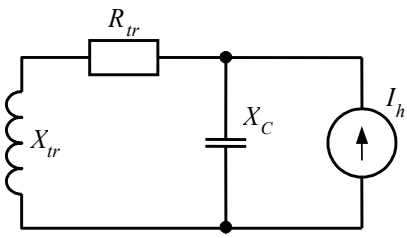

Fig. 2. The parallel circuit including transformer, capacitor and source of harmonic currents.

The resonant frequency in such a parallel circuit can be determined from the transformer inductance L, resistance R and capacitance of the capacitor C as follows, [1]:

$$f_{res} = \frac{1}{2\pi\sqrt{LC}}\sqrt{\frac{L/C - R^2}{L/C}} . \quad (1)$$

The impedance of the parallel circuit at different frequencies one could calculate from, [1]:

$$Z = \frac{R + j\omega L}{1 - \omega^2 LC + j\omega RC} . \quad (2)$$

The resistance R_{tr} and inductance X_{tr} of the transformer at the fundamental frequency one could calculate from well-known equations:

$$R_{tr} = \frac{\Delta P_k \cdot U_{nom}^2}{S_{nom}^2} , \quad (3)$$

$$X_{tr} = \frac{u_k \cdot U_{nom}^2}{S_{nom}} , \quad (4)$$

where ΔP_k – no-load losses of the transformer, (kW);
U_{nom} – nominal line voltage of the transformer primary side, (kV);
S_{nom} – nominal power of the transformer, (kVA);
u_k – short-circuit voltage of the transformer.

In case the resonant frequency of the parallel circuit corresponds to the frequency of the harmonic source the harmonic currents as well as voltages in the circuit will be amplified. Problems will arise if the harmonic currents are relatively high and a controlled multi-step capacitor battery is installed. In this case and assuming that the capacitor battery will be switched step-by-step to achieve the setpoint cosφ value the conditions of resonance appear now and then.

The effect of the capacitor battery upon the resonance frequency is characterized by impedance curves. As an example, the impedance curves $Z(\Omega)=f(h)$ of a LV network are shown in Fig. 3. The maximum value of

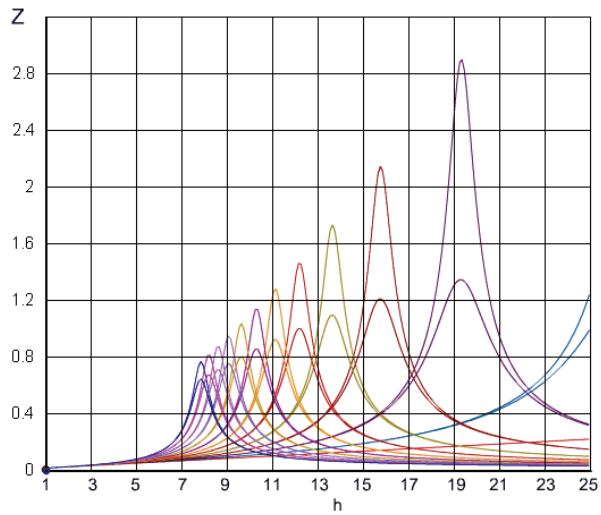

Fig. 3. Impedance curves $Z(\Omega)=f(h)$ of a LV network including a 12-stage capacitor battery.

impedance occurs when $X_{tr}=X_C$. For a battery of capacitors there will be a set of curves, the number of curves is equal to the number of capacitor steps.

In real installations damping by resistances has a great effect upon resonance. Resistance in the capacitor circuit has a damping effect upon the curve. In Fig. 3 the upper curves correspond to no resistance in the capacitor circuit and the lower curves to the resistance $R_C = 0.005\ \Omega$ in the capacitor circuit.

MEASUREMENT OF HARMONIC VOLTAGES AND CURRENTS

In the course of the study measurements of harmonic voltages and currents have been performed in several LV industrial/commercial networks.

Harmonic voltages are mostly within the limits stated by the standard EN 50160. For the 5th harmonic the limit value is 6%, for the 7th – 5%, for the 11th – 3.5% and for the 13th – 3%. It is rather seldom that any of these limit values is exceeded.

Therefore when studying the conditions for resonance it is of little use to measure only voltage harmonics in the LV system and to compare the harmonic voltages with the values stated in the standard EN 50160. Still, if any of these voltage harmonics is above the limit value or close to the limit value there is a risk for resonance and the network should be studied more carefully. Consequently to ascertain the conditions and extent of resonance measurement of harmonic currents in the LV network throughout some time interval is necessary.

The measurements have been performed in the state of the LV system with and without capacitors. The spectrum of harmonic currents of the supplying transformer and the capacitor battery has been recorded. When automatic capacitor battery is used, the capacitors have been switched on and off step by step during the measurements. During

this process the resonant frequency will be shifted along higher or lower harmonic frequencies.

As appears from the measurements in industrial LV networks, resonances at harmonic frequencies h11, h13, and h17 occur quite often resulting in high harmonic currents both in the capacitor battery and transformer. Therefore harmonic currents in the transformer and in the capacitors have been recorded throughout a certain time interval and the spectrum of harmonic currents has been analysed at different capacitor power.

The capacitor battery is mostly operating automatically switching capacitors on/off according to the controller setpoint value of cosφ. The usual setpoint value of cosφ is in the range from 0.98 (inductive) up to 1.00. So the total number of capacitor steps switched on is varying all the time. In addition, the number, type and operating mode of converters installed in the LV system is varying all the time. Hence the resonance in the LV network occurs only shortly during some minutes. For example, a sharp increase of harmonic distortions of the capacitor current is shown in Fig. 4. Total harmonic distortions THD_i of the capacitor current reaches up to 80%.

Resonance condition at harmonic frequency h17 is shown in Fig. 5, where the time-plot of the capacitor current I_{h17} is shown. The resonance occurs during approximately 2 minutes and the current reaches as high as 74% of the fundamental current. The spectrum of harmonic currents in the same LV network is shown in Fig. 6.

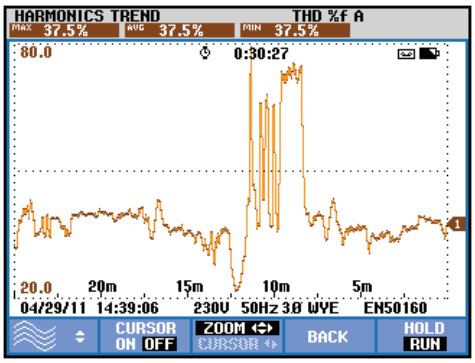

Fig. 4. Total harmonic distortion of the capacitor current, during some interval the THD_i reaches 80%.

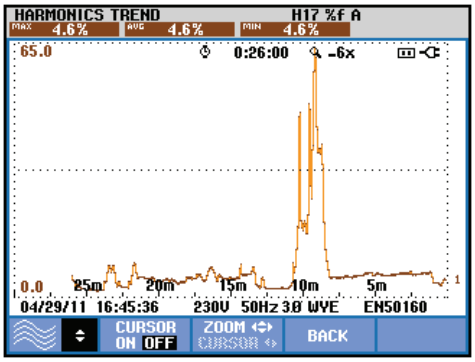

Fig. 5. Parallel resonance at the frequency of the 17th harmonic occurring during some minutes.

As could be seen from Fig. 6, in the course of analyses it is more clear to compare the harmonic currents in the transformer and in the capacitor battery in amperes and not in percent from the fundamental current.

The typical waveforms of voltage and current under resonance conditions at harmonic frequency h11 are shown in Fig. 7.

The intensity of resonance is usually not so very sharp as shown in Fig. 8. The highest harmonic currents in the capacitor are I_{h13}, I_{h11}, and I_{h17} reaching 55–65%.

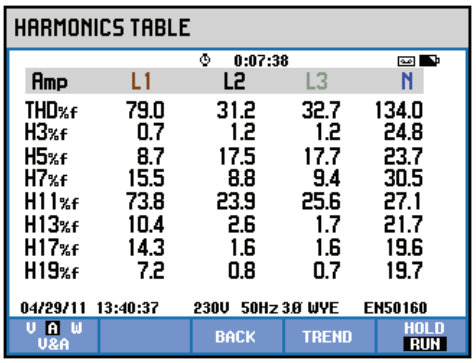

Fig. 6. The resonant condition at harmonic frequency h11; in the columns: L1 – capacitor current; L2 and L3 – transformer currents.

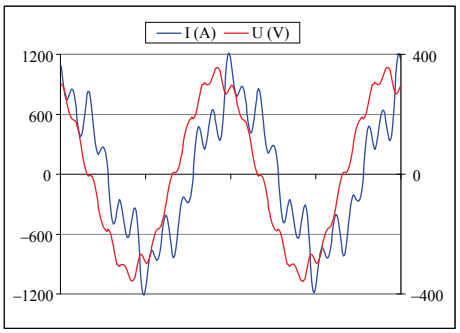

Fig. 7. Typical waveforms of current and voltage of the transformer LV lines in case of resonance at harmonic frequency h11.

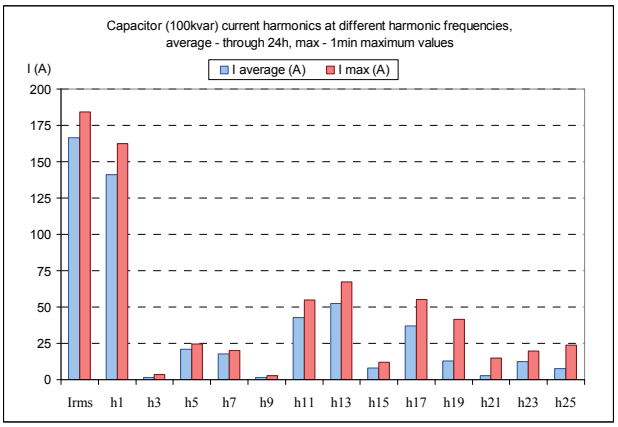

Fig. 8. Harmonic currents in the capacitor connected to the LV network without series reactor.

The intensity and frequency of parallel resonance in a LV network could be seen in Figs. 9 and 10, where the harmonic currents of the capacitor battery and the supply transformer are shown at different capacitor steps. The battery includes 12 steps. Each step is rated 25 kvar and the transformer is rated 1000 kVA 10/0.4 kV.

In this case the most intense resonant situation occurs at the harmonic frequency h11. In the capacitor the current I_{h11} reaches 35% and in the transformer 25% from the fundamental values. The absolute value of these harmonic currents was 145 A and the harmonic currents are nearly equal both in the capacitor and in the transformer.

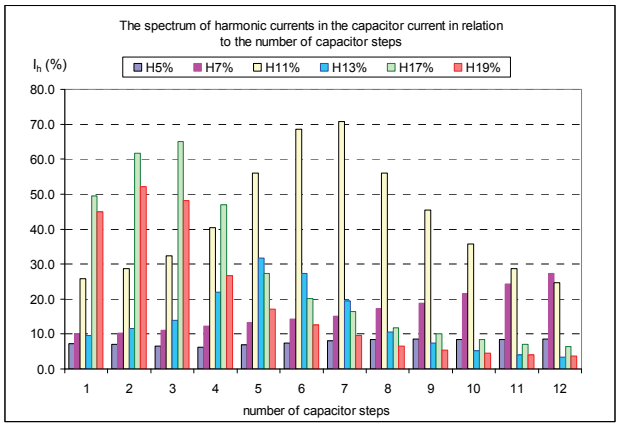

Fig. 9. The spectrum of harmonic currents of the capacitor battery at each capacitor battery step starting from 1 to 12 steps.

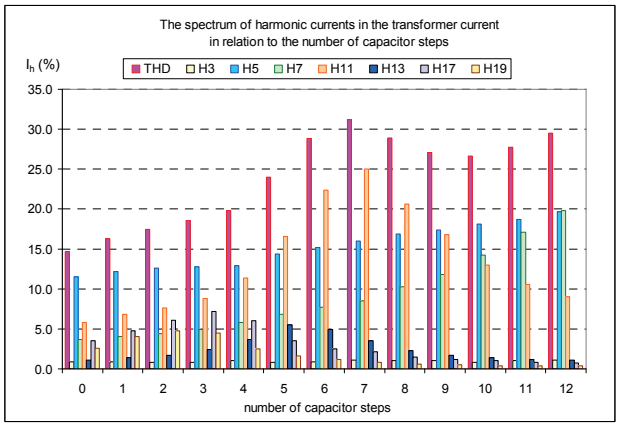

Fig. 10. The spectrum of harmonic currents in the transformer LV lines at each capacitor battery step starting from 0 to 12 steps.

CONCLUSIONS ABOUT HARMONIC RESONANCES IN LV NETWORKS

Parallel resonance appears in LV industrial/commercial networks quite often, particularly in case of powerful nonlinear loads and if the capacitors are not equipped with detuned (filtering) reactors.

In order to detect parallel resonance, harmonic currents have to be recorded both in the transformer current and in the capacitor current. During the measurements the capacitor battery has to be switched on and off step by step. If the harmonic currents are remarkably high both in the transformer current and the capacitor current during some steps or at full load, it is the condition of resonance.

The parallel resonance is usually expected to occur at the 5th harmonic frequency, as the 5th harmonic current is dominating in most cases. Still, measurements show that the resonance often takes place at much higher frequencies, particularly at the 11th or 13th or 17th harmonic frequency.

The harmonic spectrum and harmonic currents are varying rapidly. Therefore monitoring of harmonic currents both in the transformer and capacitor is necessary, with recording intervals preferably from one second up to one minute and the overall measurement duration from one hour to 24 hours depending upon the LV network.

The resonance intensity is not very sharp, therefore the step power rating of LV capacitors in the battery is not critical. Consequently, it does not matter whether the capacitors are smaller or bigger according to their kvar rating, parameters of the transformer and the amount and spectrum of harmonic currents, the type and total power of converters installed (6-pulse or 12-pulse) are affecting the presence of resonance mostly.

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