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CRITERIA FOR HARMONIC RESONANCE FREQUENCIES IDENTIFICATION IN HARMONICALLY POLLUTED DISTRIBUTION NETWORKS

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INTRODUCTION

The negative implications generated by the non-sinusoidal regime in power networks operation are well known, and as a consequence this regime must be controlled and limited to an admissible level, imposed by the normative guides, Dugan et al (1), Buta et al (2). Once the presence of the non-sinusoidal regime is identified in the network’s buses, the following question raises naturally: what caused the current and voltage curves distortion: the power source, the load or the network in between the two elements? Xu et al (3), Xu et al (4).

In which concerns the power networks, the harmonic resonance represents a particular kind of physical phenomena that can amplify the harmonic regime generated by some non-linear elements belonging to the consumer. In these conditions, it is possible to consider the electric network as a potential cause for the occurrence of a non-sinusoidal regime in a harmonically polluted network’s buses, regime that can exceed the admissible range, thus endangering the correct and stable operation of the network’s elements.

The paper presents a few practical and analytical criteria for the identification of the harmonic resonance frequencies in a distribution network. The main topics are the harmonic impedance monitoring method, the determination of the frequencies corresponding to the maximum and minimum harmonic impedance, and the analysis of the active power sensitivity to load at low load operation.

In addition to these analytical methods, the paper presents two practical criteria that allow the identification of parallel resonance frequencies: the first is based on the active load’s influence on the harmonic impedance at low active load operation; the second takes into account the change in sign of the difference between the rms values of the harmonic currents (defined for a short interval of time) through the network’s supply transformer, respectively through the capacitors bank placed on the network’s MV buses, Ticula et al (5), Cornoiu et al (6).

A set of rules emerged from the paper, used in a heuristic expert system based on a forward chaining inference engine.

HARMONIC RESONANCE IN HARMONICALLY POLLUTED NETWORKS

The power networks are complex circuits, including inductive and capacitive elements, where oscillation conditions may occur on different frequencies. As a rule in normal operation these resonant circuits are heavily attenuated by the presence of resistive elements found in the network's active loads. During faults or low loads though, the resonant phenomena may amplify, leading to an increased electric stress on the network's elements.

The harmonic resonance may be series or parallel. The series resonance occurs especially when there are non-sinusoidal voltage sources in the network, a very rare situation. A much frequent situation is the current harmonic resonance, caused by the harmonic current sources from the network. E.g.: the parallel resonance may occur in the case of a polluting consumer, at low load, when the reactive power compensation capacitors bank is left connected to the supply bus (figure 1a). The figure 1b presents the equivalent circuit for the *k* harmonic of the network from figure 1a.

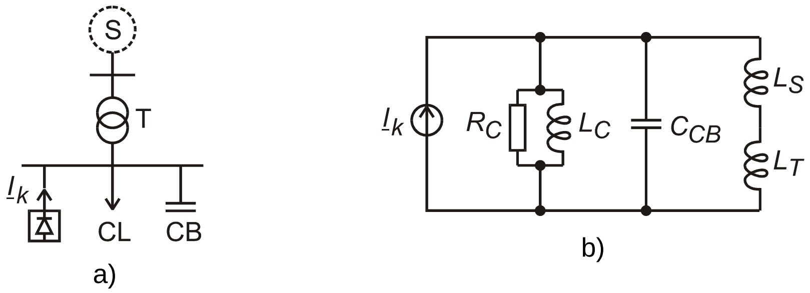


Figure 1. Harmonically polluted network:
a) simplified diagram; b) equivalent circuit for the *k* harmonic.

The symbols from figure 1 have the usual meanings. In addition $\underline{I}_k$ designates the rms value of the *k* harmonic current generated by the non-linear consumer, while CL designates the linear consumer. The harmonic representation of the linear consumer is based upon a frequently used harmonic equivalent scheme, Arrilaga and Arnold (7). The parallel resonance occurs on the *k* harmonic if the following condition is met:

$$k_r \cdot f_0 = \frac{1}{2\pi\sqrt{L_e \cdot C}} \tag{1}$$

where:
C - network's equivalent capacitance,
L_e - circuit's equivalent inductance, $L_e = \frac{L_C \cdot (L_S + L_T)}{L_C + L_S + L_T}$,
L_S - system's inductance,
L_T - transformer's inductance,
f_0 -fundamental frequency at the system's bus bars.
If the consumer runs at low (inductive) load, $L_C >> L_S + L_T$, the equivalent inductance is practically reduced to the following expression: $L_e = L_S + L_T$.

The relation (1) may have another form, Dugan et al (1), when the influence of the reactive power generated by the network's equivalent capacitance is emphasized:

$$k_r^2 = \frac{S_{sc}}{Q_C}\left(1 + \frac{L_S + L_T}{L_C}\right) = \frac{S_{sc}}{Q_C}\left(1 + \frac{Q}{S_{sc}}\right) \tag{2}$$

where:
S_{sc} - supply system's short-circuit power,
Q_C - reactive power delivered on the fundamental by the network's equivalent capacitance,
Q - reactive power absorbed on the fundamental by the network's linear consumers.

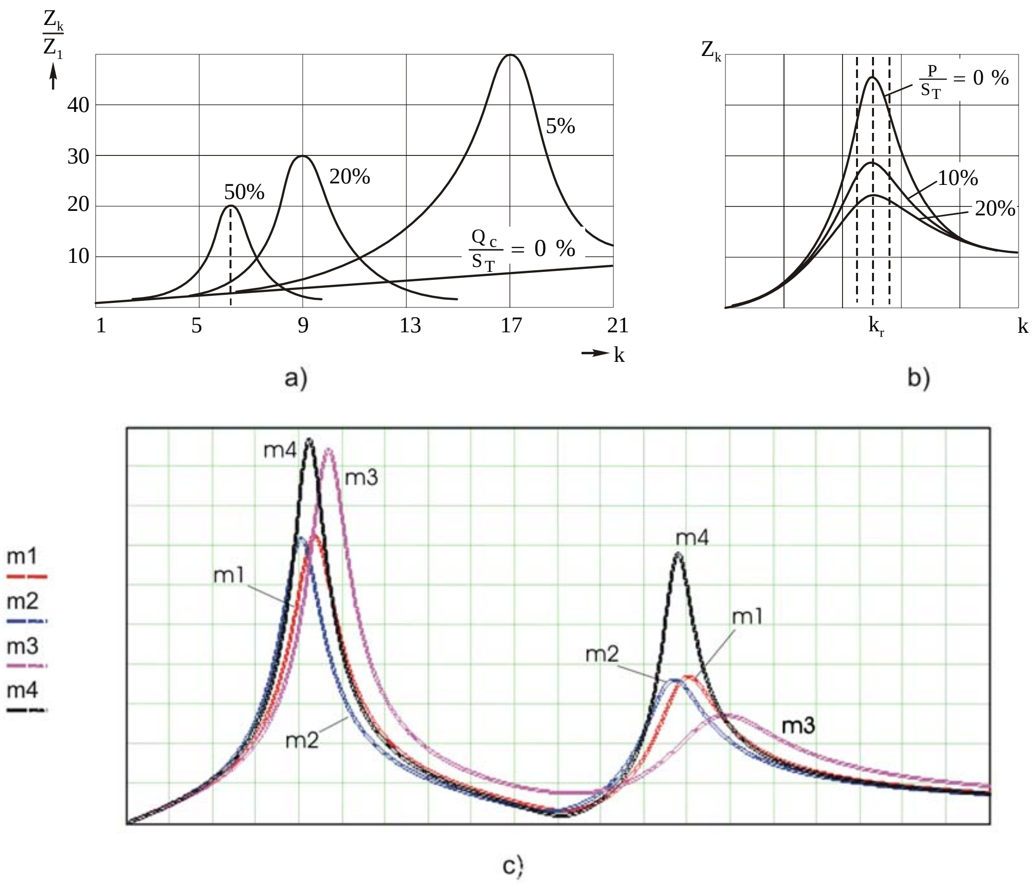
We can see from relation (2) that the increase of the reactive power delivered by the capacitors bank and the decrease of the consumer's inductive load leads to a decrease of the resonance frequency, and the possibility of reaching a dangerous range $(k_r \leq 13)$ occurs.

HARMONIC IMPEDANCE - TYPICAL PARAMETER IN HARMONICALLY POLLUTED NETWORKS

The harmonic impedance is one of the most important parameters used in harmonically polluted networks modeling and analysis. The power flow analysis in these networks is not possible without the study of this parameter and the determination of its response to the disturbances occurred in the network, including harmonic resonance, Buta et al (2), Robert and Deflandre (8).

The network's harmonic impedance variation with the frequency in different buses may give an overview on the poles and zeroes occurrence location, thus indicating the harmonic parallel and series resonance frequencies. The references show that the poles position depends in a great measure on the reactive power compensation degree, thus on the capacitors bank power Q_C, on the systems short-circuit power (as seen in relation 2), and less on the linear consumer's active load P or on the harmonic model used for it, Buta et al (2), Ticula (9). Figure 2 shows the harmonic impedance variation, for the network from figure 1, as seen on the medium voltage transformer bus bars, with:

a) The reactive power compensation degree (the ratio Q_C / S_T , where S_T is the transformer's rated power);
b) The linear consumer's active load P;
c) The linear consumer's modeling, Ticula et al (5).



model 1: $R_c = R_{c0} = ct.;\ X_c = X_{c0} = ct.$ model 3: $R_c = \frac{R_{C0}}{p};\ X_c = \frac{X_{C0}}{p};\ p = 0.1 \cdot k + 0.9$

model 2: $R_c = ct.;\ X_c = \omega_0 \cdot k \cdot L_c$ model 4: $R_c = R_{c0};\ X_s = 0.073 \cdot R_c \cdot k;\ X_p = \frac{R_c \cdot k}{6.7 \cdot (\frac{Q}{P} - 0.74)}$

Figure 2. Harmonic impedance variation with frequency (harmonic rank)
a) capacitors bank influence; b) active load influence; c) linear consumer modeling influence.

Theoretically we can determine the frequency values corresponding to the harmonic resonance by simply monitoring the harmonic impedance values. Additionally, the state estimation can be based upon the harmonic impedance's imaginary value sign. This sign changes when the network's harmonic resonance frequency is reached. In complex networks, the harmonic impedances determination can be based upon the known techniques, Buta et al (2): form the harmonic voltages and currents flow or with the help of the state variables method, Ticula (9), Buta et al (10).

From figure 2b we can see that as the load decreases the harmonic impedance value dramatically increases. More over, this high sensitivity with the active load is present only in the proximity of the harmonic resonance frequency. In conclusion, having a certain distribution network configuration, a certain harmonic current injected in the bus, respectively certain values for the compensation reactive power installed in the capacitors banks, when varying the active load, in dependence to magnitude of the harmonic impedance sensitivity with the active load (that is $\partial Z_k / \partial P$), we can estimate the "distance" (nearness or remoteness) to the harmonic resonance.

If we try to establish dependences $Z_k = \phi(P)$ at Q_C = constant and $k < k_r$, we obtain different curves, as shown in figure 3.

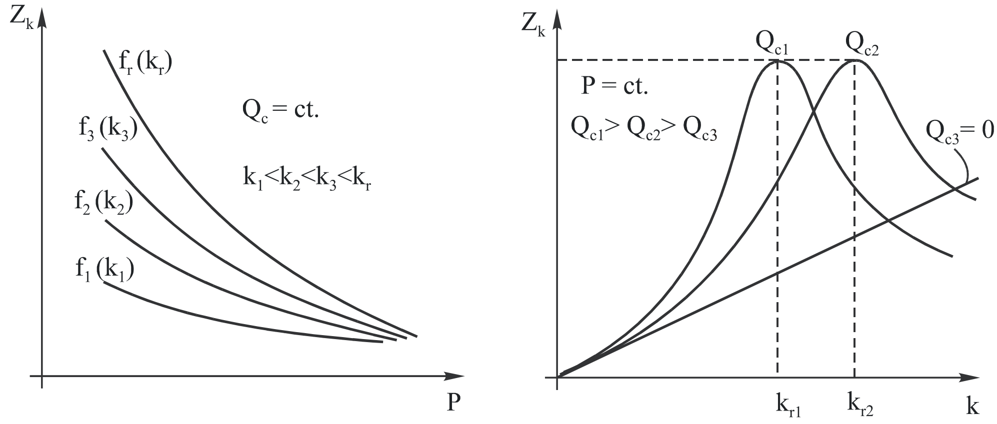


Figure 3. Harmonic impedance variation with:
a) P, at k = constant, $k < k_r$, b) Q_C and P = constant

We can see from figure 3a that having a certain active power value, as we get closer to the resonance frequency (k_r) the response slope absolute value increases; this means that $|\partial Z_k / \partial P|$ increases at k = constant. Certainly, the situation when at the same active power the compensation power variation may lead to a sensitive variation for Z_k at a certain frequency $f(k)$ might occur, without raising the harmonic impedance question, as shown in figure 3b. In conclusion such an indicator as $\partial Z_k / \partial Q_C$ might not be sensitive to the reach of the harmonic resonance operation.

From the above mentioned, in Ticula et al (5) a harmonic resonance frequency identification procedure was developed.

PRACTICAL CRITERIA FOR HARMONIC RESONANCE OPERATION IDENTIFICATION

Unfortunately, the identification procedure form Ticula et al (5) presents some problems, as shown in the following notes:

1. The harmonic impedance estimation is generally difficult, Buta et al (2), Ticula et al (5), Albert and Golovanov (11); There is always the possibility of introducing significant errors;
2. The harmonic impedance's real and imaginary components are practically difficult to obtain, especially at high frequencies, where the reactance's weight factor is significant;
3. The magnitude of the sensitivity $\partial Z_k / \partial P$ is not big enough, in order to always certify the harmonic resonance occurrence;
4. When the active power changes, the reactive power may also change, shifting thus the resonance frequency.

a) In these conditions, from a practical point of view, another quantity must be considered, whose sensitivity can be easily tracked, and which can certify the harmonic impedance evolution with the frequency, with a significant evolution in the proximity of the resonance frequency. This quantity is undoubtedly the harmonic voltage sensitivity $\partial U_k / \partial P$.

We practically consider the critical harmonic voltages, even if these don't exceed the withstand threshold, but are known as causing problems (u_5, u_7, u_{11}, u_{13}, u_{17}), and we check their sensitivity to the active load absorbed in the bus. Based on the network data and the current information about the load, we can determine the harmonic resonance frequencies, validating thus the results obtained from the harmonic voltages sensitivity analysis. If the results don't match the measurements, we check for the presence of significant resistances in the network's equivalent circuit.

b) Another harmonic resonance identification method considers the type of network from figure 1 and the big values of the linear consumer harmonic impedance parameters (R, L) at low load. In this case the current through the parallel equivalent circuit's inductive side flows practically through the system and the supply transformer T, Cornoiu et al (6), Ticula (9).

Monitoring thus the harmonic currents I_{Lk} and I_{ck} at low active load and tracking the sign of the difference $\left(I_{Lk} - I_{Ck}\right)$, we can identify the frequency range where the harmonic resonance occurs, with an error of a two harmonic range. Certainly, the determination precision depends on the ratio between the inductances $L_s + L_T$ and L. At heavy loads, it can reach 20-30%, but at low loads that can occur during the night sag, its value can fall under 5%, Ticula (9).

Based on the criteria mentioned above we present in which follows the task and rules of an expert system destined to insure the identification of harmonic resonance frequencies.

EXPERT SYSTEM TASKS AND RULES

We propose a heuristic expert system, which follows a clear strategy based on a well-defined set of rules, using a forward chaining inference engine. The systems tasks and rules are:

Task 1: Evaluation of the distribution network harmonic pollution. In this purpose we compare the harmonic voltage levels with a certain threshold, in order to eliminate the risk of determination imprecision.

Rule 1: IF the level U_{k0} of the harmonic k_0 exceeds a certain threshold THEN the harmonic k can be taken into account and $D1 = 1$.

Rule 2: IF the level U_{k0} of the harmonic k_0 exceeds a certain value, withstand threshold, THEN the harmonic k can be taken into account and $D2 = 1$.

Rule 3 IF $D1 = 1$ and $D2 = 1$ THEN there is a distortion on harmonic k_0 and it must be taken into account.

Task 2: Determination of the network resonance frequencies using analytical methods (state variables and dependence of Z_k with k).

Rule 1: IF there is a pole in the vicinity of k_0 (k_0 - ε, k_0 + ε), THEN harmonic k is a candidate for the resonance harmonic and $VS = 1$.

Rule 2: IF there is a local maximum of the harmonic impedance Z_k in the vicinity of k_0 (k_0 - ε, k_0 + ε), THEN harmonic k is a candidate for the resonance harmonic and $ZA = 1$.

Rule 3: IF $VS = 1$ and $ZA = 1$ for the harmonic k, THEN harmonic k_0 is a candidate for the resonance harmonic and $C = 1$.

Task 3: Evaluation of harmonic voltage sensitivity with the active power at low active load.

Rule 1: IF sensitivity $\partial U_k / \partial P < 0$ for the harmonic k_0 and active loads $P < P_{threshold}$ THEN k_0 may be a harmonic resonance frequency and $SIGN = 1$.

Rule 2: IF sensitivity $\left|\partial U_k / \partial P\right| < S_{threshold}$ for the harmonic k_0 and active loads $P < P_{threshold}$ THEN the harmonic resonance may occur for k_0 and $VABS = 1$.

Task 4: The first identification test of resonance presence on the harmonic k_0 takes into account the distortion present on harmonic k, its coincidence with the network's characteristic harmonic resonance and the harmonic voltage negative sensitivity with the active power at low load.

Rule 1: IF $D1$ = 1 and C = 1 and $SIGN$ = 1 and $VABS$ = 1 for k_0 THEN the harmonic resonance occurs on harmonic k_0.

Task 5: The second identification test of resonance presence on the harmonic k_0 takes into account the change in sign of the difference between the two harmonic currents - inductive I_L and capacitive I_C - in the range (k_0 - ε, k_0 + ε). But first we must check the variation continuity of these two currents in the vicinity of harmonic k_0.

Rule 1: IF $I_L(k_0-\varepsilon)<I_L(k_0+\varepsilon)$ or $I_L(k_0-\varepsilon)>I_L(k_0+\varepsilon)$ THEN I_L has a monotone variation and $C1$ = 1.

Rule 2: IF $I_C(k_0-\varepsilon)<I_C(k_0+\varepsilon)$ or $I_C(k_0-\varepsilon)>I_C(k_0+\varepsilon)$ THEN I_C has a monotone variation and $C2$ = 1.

Rule 3: IF $\mathrm{sgn}[I_L(k_0-\varepsilon)-I_C(k_0-\varepsilon)]\cdot\mathrm{sgn}[I_L(k_0+\varepsilon)-I_C(k_0+\varepsilon)]=\text{minus}$ THEN DIF = 1.

Rule 4: IF $C1$ = 1 and $C2$ = 1 and DIF = 1 THEN the resonance occurs at frequency f_0 (harmonic k_0).

We can practically use both tests or, when this is not possible, only one. If capacitance C is not concentrated on the station's medium voltage bus bars we can estimate the network's total capacitance as seen in the supply buses, while the harmonic capacitive currents can be evaluated from the bus bars voltage harmonics.

EXPERIMENTAL RESULTS

The experimental determinations took into account an estimation set from the 25 MVA transformer's secondary windings from "Fratelia" substation (figure 4), Ticula (9). These determinations were performed with and without the capacitors bank connected to the 20 kV bus bars. The substation supplies rural and suburban customers mainly through overhead lines, and for this reason the equivalent circuit damping has relatively high values. Throughout the measurements we tried to keep the voltage as constant as possible, and we changed the active power roughly by 2%. This corresponded to a natural load variation in a 10 minutes interval. Figure 5 shows the variation of the phase voltages and currents on the three phases in two operation conditions: with and without the capacitors bank.

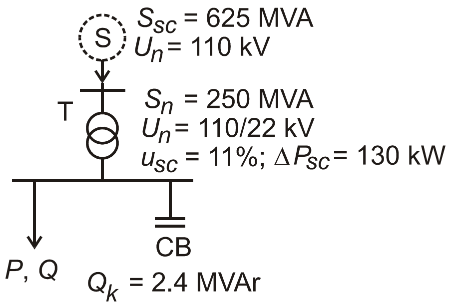


Figure 4. Power supply network

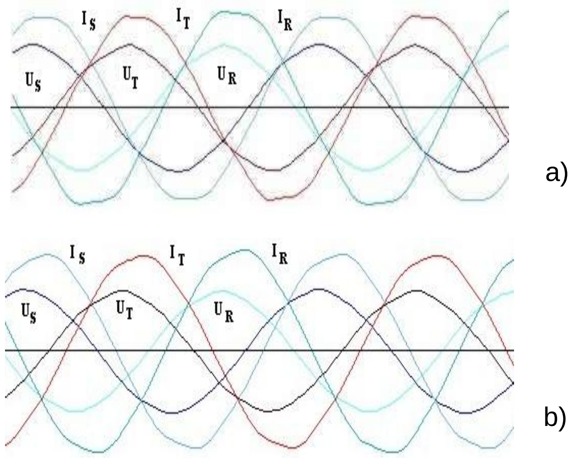


Figure 5. Phase voltages and currents variation in the secondary windings of the transformer from figure 4: a) capacitors bank connected; b) capacitors bank disconnected.

The voltages and currents distortion coefficients values on the three phases and the unbalance factors are presented in table 1.

TABLE 1 - Distortion and unbalance coefficients values, unbalance ratios.

Steady state	δ_U			δ_I			k^-_{nsU}	k^-_{nsI}	r_{nsU}	r_{nsI}
	a	b	c	a	b	c				
without CB	1,49	1,517	1,717	1,82	1,728	1,785	1,47	0,89	0,995	0,980
with CB	1,88	1,87	2,36	2,2	1,74	2,245	1,30	0,92	0,995	0,975

Analyzing the values from table 1 we come to the following conclusions:

- The harmonic operation is weakly felt in the phase voltages and currents curves distortion coefficients; the three phases unbalanced operation is much strongly felt on phase *c* with an increase of 25% in voltages and 12.5% in currents;
- The capacitors bank introduction aggravates the harmonic operation in both voltages and currents; in the absence of the capacitors bank the phase *c* harmonic operation voltage is 14% bigger than phases *a* and *b*;
- The phase voltages unbalance is reduced, the negative unbalance coefficient is 1.47% for voltages, and 0.89% for currents in the absence of compensation; their value becomes 1.3% for voltages and 0.92 for currents in the presence of compensation.

In which concerns the voltage harmonics with the active power we can observe the following:

- In the absence of the capacitors bank the lower harmonics - 5, 7 - are less sensitive to the decrease of the active power absorbed. When the active power decreases by 1.5% the 5th harmonic remains practically unchanged or has an increase of 1.39%, the 7th harmonic increases by 4.5% while the upper harmonics - 17, 19 - decrease by 30.6% respectively 37.5%. So, there is no danger of approaching the harmonic resonance.
- In the presence of the capacitors bank the lower voltage harmonics - 5, 7 - are relatively sensitive to the decrease of the active power absorbed. When the active power decreases by 1.5% the 5th harmonic increases by 4.2%, the 7th harmonic - by 5.5%, the 11th - by 58.33% while the upper harmonics - 17, 19 - remain practically unchanged. The danger of having a harmonic resonance in the vicinity of the 11th harmonic, after the 7th, is obvious. The estimation calculus offered a theoretical harmonic resonance frequency of 420 Hz, that is $k_r = 8.5$.

The mean values of the positive respectively negative sequence harmonic voltages are offered in table 2.

In which concerns the harmonic currents we considered ten frames of the current and voltage curves, in the presence of the capacitors bank, for the network in figure 4, and we obtained the situation from table 3.

Analyzing the data from table 3 we can see that the harmonic currents inequality ratio changes between harmonics 7 and 11, meaning that the harmonic resonance occurs in this range.

We can observe a relatively good concordance between the two practical harmonic resonance identification methods.

TABLE 2 - Positive and negative sequence voltages values in the voltage transformer secondary.

Harmonic order	Sequence	without CB		with CB	
		P = 13 MW	P = 13,4 MW	P = 13 MW	P = 13,4 MW
1	+	60,28	60,32	60,58	60,76
5	-	0,72	0,73	1,006	0,96
7	+	0,44	0,42	0,58	0,55
11	-	0,048	0,048	0,019	0,012
13	+	0,017	0,019	0,035	0,049
17	-	0,020	0,036	0,026	0,029
19	+	0,014	0,016	0,035	0,034

TABLE 3 – Phase and medium values of the inductive and capacitive harmonic currents from "Fratelia" substation.

Harmonic order k	I_{Lk} [A]				I_{Ck} [A]				Remarks
	Phase a	Phase b	Phase c	Medium value	Phase a	Phase b	Phase c	Medium value	
5	5.44	5.28	4.56	5.09	4.23	4.20	5.19	4.77	$I_L>I_C$
7	4.42	4.56	5.07	4.68	4.05	3.36	4.28	3.89	$I_L>I_C$
11	0.12	0.21	0.20	0.17	0.63	1.03	0.55	0.74	$I_L<I_C$
13	0.24	0.16	0.16	0.18	0.28	0.84	0.47	0.53	$I_L<I_C$
17	0.20	0.32	0.16	0.22	0.26	1.22	0.86	0.98	$I_L<I_C$

CONCLUSIONS

The paper presents a few partly original theoretical and practical criteria concerning the harmonic resonance frequencies identification in a harmonically polluted network. The theoretical criterion corresponds to a known phenomenon - the harmonic impedance sensitivity increase with the active power decrease in the network's buses in the vicinity of the harmonic resonance frequencies. The difficulty of determining the harmonic impedance in practice led to a practical criterion that uses the harmonic voltages sensitivity with the active power absorbed. The existence of $\partial U_k / \partial P$ sensitivities of negative sign and high absolute value leads to the conclusion of operation close to the harmonic resonance frequencies. This requires harmonic operation monitoring and the determination of harmonic sensitivities with the active power absorbed. The introduction of this factor extends the application of sensitivity analysis methods in power systems analysis. These methods are frequently met in voltage steadiness problems, synchronous generators dynamics etc. They ease the systemic approach of non-sinusoidal operation.

The change in sign of the difference between the inductive and capacitive harmonic currents is another really useful criterion. The experimental determinations confirm this.

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