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PROCEDURE FOR CAPACITOR UTILIZATION IMPROVEMENT INTENDED FOR REACTIVE POWER COMPENSATION IN NETWORKS WITH HIGH ORDER HARMONICS

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Abstract: The new solution for dimensioning and forming of capacitor batteries is suggested in the paper. The point is to separate capacitor batteries into the part with fixedly connected power capacitors and part (parts) that, according to need, automatically switches on and off assigned capacitor units and regulates power factor. By applying our idea – choosing such a values for powers of fixedly connected capacitors that $f_r / f \approx 9$, larger amounts are being obtained (approximately four times) for highest admissible values compared to the same one, which are dimensioned in order to avoid series resonance for harmonics of order less than 17. Application of this sollution is useful for eliminating series and parallel resonance risk for current harmonics of order ≥11. Experimental results shows reduction of current and voltage harmonics of order 11 and 13 what confirms proposed solution.

Keywords: Capacitor battery, Harmonics, Power Factor Corection, Reactive Power, Resonance

1 Introduction

Numerous and frequently used electrical devices (electrical motors and other electromagnetical apparatuses) beside active, consume reactive energy as well. When reactive energy spent on magnetizing of transformer is added, a large number of industrial consumers take over approximately the same quantities of active and reactive energy from distributive network, or they would take it over if installed capacitor batteries of considerable power want be available. Capacitor batteries become more frequently used in industrial consumers' networks considering their number and installed powers. Additional reason lies in reaching higher and higher power factor (cosφ) that are demanded from consumers - at first it was mainly the value cosφ = 0,85, then cosφ = 0,90, and nowadays the value cosφ = 0,95 is the most frequent one.

In last 2 – 3 decades, participation of high order harmonics is increased in the consumers' networks due to a more frequent use of electronic power converters. Thanks to the fast development of electronic components and devices, converters of all kinds, regarding power, voltage and frequencies are available on the market. Their use for feeding electrical drives and electro thermal consumers provide energy savings up to 20 – 30 %.

A power converter takes energy from distributive network by regulated rectifier that converts AC into DC voltage. This conversion is followed up by the occurrence of unwanted current harmonics in distributive network and corresponding voltage drops of high order harmonics. Harmonic distortion is caused by non-linear elements connected to the network (motors, saturated transformers, fluorescent lights, electronic devices, etc.). The largest harmonics' source are power converters for regulated drives and other consumers composed of 6 pulse rectifiers (for powers up to 3 MVA) and 12 pulse rectifiers for greater powers, which are at the same time a power generators of high order harmonics. With the appearing of high order harmonics in feed network corresponding problems occur in work of the most consumers: greater power losses in transformers and motors, obstacles in operation of motors, telephone lines, as well as worsening of operation of most devices connected to that network. For the above mentioned reasons, contents of voltage and currents high order harmonics in network is limited by regulations of the international standards [1] as well as by standards of the most industrially developed countries – e. g. IEEE Standard 519 – 1992 [2]. In all these standards the highest admissible values are regulated for some voltage harmonics (HD_U), and also for total distortion of voltage harmonics (THD_U). These standards also regulate the maximum levels of admissible values for some current harmonics (HD_I), and values of current total distortion (THD_I).

Taking into consideration voltage and current harmonics, special problems may occur in networks with capacitors used for power factor correction. Capacitors are not sources of voltage and current high order harmonics, but they can exert influence on multiplication of voltage and current high order harmonics in some parts of the network. Resonance occurrence between capacitor capacities and inductance of some network parts is also possible. Therefore, characteristic resonance occurrences and conditions for their appearance have to be separately analyzed.

2 Resonant circuits in networks with capacitors

Converters and power rectifiers are, among other, current generators of high order harmonics. These currents are spread through distributive and transmission network in an inverse proportion of impendence of these branches. Since sources (electric power plants) and corresponding feeders represent branches with smallest impendence, the largest part of high order harmonics' currents is closed by these paths. But, situation is significantly changed if capacitors are connected in the network. For certain high order harmonics currents, capacitive reactance of capacitor may become equal to an inductive reactance of network seeing from capacitor ends (Fig. 1). In that case parallel resonance occurs for given harmonic. Fig. 1 shows single pole scheme of a typical industrial network fed through its own transformer with non-linear consumer (source of high order harmonics current). Corresponding equivalent circuit is given for high order harmonics. Inductive reactance of sources and transformer (X_t) and capacitor's reactance for power factor correction (X_C) at adequate frequency becomes equal in value, so total parallel circuit reactance formed by them is high. Theoretically it would be of infinite value, if ohm resistances of quoted branches are not taken into consideration, related to resistance values R_P and reactance X_Q represented by active (P) and reactive (Q) consumer loads.

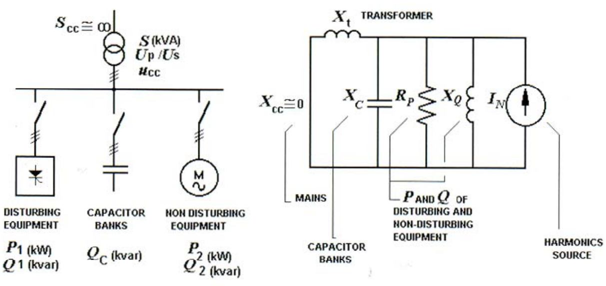

Fig. 1. Consumer network with capacitor battery and non – linear consumer

Currents of high order harmonics that flows through transformer and capacitors (Q_C) could be several times higher than harmonic's currents (I_N) that excite resonant oscillations. That can lead to the overloading, even to the capacitor's damage. Parallel resonance or regimes, which are close to it could be predictable because it is happening due to a non-linear nature of consumers in the network. Therefore it could be avoided by taking appropriate measures or at least decreased in particular cases.

Series resonance may also occur when sources of high order harmonics are located in the network of some other consumer (Fig. 2) and comes from higher voltage network into the network of the monitored consumer. This can be ascertained on the basis of measured values of voltage harmonics on the side of higher voltage of the transformer. In corresponding series circuit for high order harmonics, series resonance may occur for certain harmonic order. This is the case when reactance of transformer ($X_{t\ h}$) and capacitor ($X_{C,\ h}$) has equal values. So, total impedance of series connection ($X_{t,\ h} + X_{C,\ h}$) has low value. Theoretically, that value equals to zero if resistance is not taken into consideration. The consequence is that in the branch where series resonance has occurred, a large current I_{hr} is flowing. Model of high voltage network as well as its parameters are necessary for exact calculation of currents and voltages in series resonant circuit.

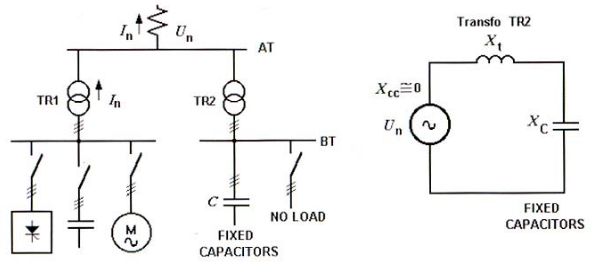

Fig. 2. Consumer network with fixed power capacitor and harmonics coming from higher voltage network

In order to avoid above - mentioned difficulties, procedure is being simplified by exchanging influence of high order harmonics' sources and network, with source of high order harmonics voltage and their value can be proved by measuring. As number and power of sources of high order harmonics in network are variable, the measured values of voltage of some high order harmonics change by hour. Therefore, it is recommended to make calculations with the highest admissible values for voltages of some harmonics in corresponding regulations [1],[2].

To avoid risks of series resonance in branch (X_t + X_C) for low order harmonics, that are as a rule larger, it is necessary to appropriately dimension capacitors in a secondary transformer network. As resonant occurrences are more distinctive when impendence and resistance of consumer are lower, consequently the highest risks for transformer and capacitors are if capacitors are connected to transformer that works in idle motion regime. That is why in literature [3], and often in recommendation of electrical industry companies [4] maximal powers for capacitor connection on low voltage side of transformer 10(20)/0.4kV are being prescribed. In order to emphasize this question maximal admissible powers for fixed capacitor connection into the secondary winding of distributive transformers 10(20)/0.4kV are given in Table 1.

Table 1. Maximal admissible powers for fixedly connected capacitors on secondary busbars of transformers 10(20)/0.4kV, according to the various recommendations

Transformer's rated powers (kVA)	100	160	250	315	400	630	1000	1250	1600
Capacitor's power in kvar according to:									
1. Technical Guide [3]	6	10	15	18	20	28			
2. EDF [4]	7	11	18	22	28	44	50	62	80
3. Proposed sollution [5],[6]	30	50	77	97	124	195	206	257	330

3 Analysis of series resonant circuit

Distributive transformers MV/LV are the most frequent in electric power systems regarding their number and total power. A considerable number of these transformers operate with fixed capacitors for power factor correction, which are connected to a secondary busbars or secondary network. For voltages of high order harmonics coming from high voltage network, transformers and capacitors form series circuit, through which, in certain conditions, significant currents of high order harmonics may flow. In this chapter more detailed calculations and analyses of currents and voltages of high order harmonics in quoted series resonant circuit will be carried out. Recommendations for the highest admissible powers of fixedly connected capacitors (Q_{CF}) are determined in order to avoid series resonance risks with sufficient safety, because voltage harmonics occurances and values could be foreseen only with statistical certainty.

3.1 Series resonance and capacitor dimensioning

The elements of resonant circuit, because of currents and voltages drops of resonant harmonic, bear current overloadings and increased voltages, so total current and voltage values may surpass the highest admissible values. In that regard the capacitors are particularly endangered.

Not loaded MV/LV transformer of reactance X_t with connected capacitor of reactance X_C on low voltage side (Fig. 2), forms series L-C circuit for high order harmonics. For certain voltage harmonic of order $h_r=f_r/f$, series resonance appears in the circuit at resonant frequency f_r.

$$f_r = \frac{1}{2\pi \cdot \sqrt{LC}} = f \cdot \sqrt{\frac{X_C}{X_L}} = f \cdot \sqrt{\frac{S_{nt}}{u_k \cdot Q_C}} \qquad (1)$$

whereas:
L i X_L – inductivity and reactance of transformer,
C i X_C – capacitance and reactance of capacitor,
S_{nt} i u_k – transformer rated power and relative value of the short circuit voltage.

Series circuit formed by transformer of given reactance ($X_t = u_k \cdot U^2/S_{nt}$) and capacitive reactance of capacitor ($X_C=U^2/Q_C$) can be brought into a series resonance, if for corresponding harmonic order $h_r = f_r/t$, following condition is fulfilled:

$$Q_{cr} / S_{nt} = 1 / h_r^{\ 2} \cdot u_k \qquad (2)$$

Corresponding power of capacitors that form resonance circuits are determined for certain condition from the equation (2). The results of these calculations for the values: u_k = 4%, which are above the average for the transformers of powers up to 630 kVA and u_k = 6%, which are the most common one for the transformers of powers above 1000 kVA, as well as for values u_k = 5%, are presented in Table 2.

Table 2: Relative powers of capacitor batteries (Q_{cr}/S_{nt}) that forms resonant circuit with transformer depending on harmonic order (h_r) for various values of transformers' short circuit voltage u_k

Harmonic order	5	7	9	11	13	15	17	19	23
	Q_{cr} / S_{nt}:								
u_k = 4%	1.00	0.510	**0.309**	0.207	0.148	0.111	**0.087**	0.069	0.047
u_k = 5%	0.80	0.408	**0.247**	0.165	0.118	0.089	**0.069**	0.055	0.039
u_k = 6%	0.66	0.340	**0.206**	0.138	0.099	0.074	**0.058**	0.046	0.031
u_k = 7%	0.57	0.290	**0.177**	0.118	0.085	0.063	**0.050**	0.039	0.027

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3.2 Currents and voltages in the series resonance circuit

Resonant harmonic's current value (I_{hr}) is limited only by transformer ohm resistance (r_{thr}) and ohm resistance of the connecting lines (r_{t-c}) between transformer and capacitors, since total circuit reactance is $X_{hr} = X_{thr} - X_{Chr} = 0$. For that reasons it is necessary to take in consideration dependence of transformer ohm resistance to the frequency of the applied voltage. Generally that resistance consists of two components:

– a basic component r, which corresponds to power losses in transformer winding ($P_{cu,1}$) when direct current is flowing through it, and
– an additional resistance r_d that corresponds to the additional power losses in transformer ($P_{d,e}$) coming from leakage field made by losses from eddy currents and hysteresis power losses ($P_{d,H}$) in inactive transformer parts.

Additional power loses in transformer are:

$$P_{d,h} = P_{d,e} \cdot h^2 + P_{d,H} \cdot h \qquad (3)$$

whereas $P_{d,e}$ and $P_{d,H}$ are values of additional power losses from leakage field of the fundamental harmonic. Corresponding values of additional resistance for high order harmonics ($r_{d,h}$), of order $h = f/f_1$, are determined by equation:

$$r_{d,h} = r_{d,e} \cdot h^2 + r_{d,H} \cdot h \qquad (4)$$

whereas $r_{d,e}$ i $r_{d,H}$ are values of corresponding additional resistances for the field of fundamental frequency. Total transformer ohm resistance is:

$$r_{th} = r + r_{d,e} \cdot h^2 + r_{d,H} \cdot h \qquad (5)$$

For the most frequently used distributive transformers 10(20)/0.4kV of powers from 400kVA to 1600kVA, these resistances at frequency $f = f_1 = f_n$, are approximately:

$$r = 1\%, \quad r_{d,e} = r_{d,H} = 0.05\% \qquad (6)$$

Corresponding transformer resistance values r_{th} for given values $r_{d,e}$ i $r_{d,H}$, for some high order harmonics $h = f/f_1$, are calculated according to the equation (5) and presented in Table 3, row r_{th}.

Values of the resonant currents in percents of transformer's rated current (I_h/I_{nt}) are calculated according to equation:

$$I_h / I_{nt}(\%) = 100 \cdot U_h / r_{\Sigma h} \qquad (7)$$

and are presented in Table 3 for the highest admissible values of high order harmonics voltage u_h (%) [4] and ohm resistances r_{th} (%) and $r_{\Sigma h}$ (%) for transformers with $u_k = 4\%$.

Resonant currents flowing through capacitors, which corresponding (resonant) powers of $(Q_C/S_{nt})_{rez}$ are given in Table 2 for transformer with $u_k = 4\%$, are given in percentages of capacitor rated current $(I_{hr}/I_{cn})\%$ and are calculated according to:

$$I_{hr} / I_{cn}(\%) = h^2 \cdot u_k \cdot 100 \cdot U_h / r_{\Sigma h} \qquad (8)$$

They are also presented in Table 3 for given admissible voltage values of quoted harmonics u_h (%). It is obvious from equation (8) that sums of resonant currents (I_{hr}/I_{cn} %), for transformers with $u_k = 6\%$ (or $S_{nt} \geq 1000$ kVA), can be bigger for 50% comparing to the corresponding amounts given in Table 3.

Maximal admissible current contents of high order harmonics is determined on the basis of the criterion that effective current value of the capacitor does not exceed 1.3 I_{Cn}:

$$\sqrt{(\Sigma I_h / I_{cn})^2} = \sqrt{1.30^2 - 1} = 0.833 = 83.3\% \qquad (9)$$

Although criterion (9) relates to the contents of all high order current harmonics, it can be applied with some reduction only to the resonant harmonics current that is dominant in harmonic current spectar of high order harmonics in series resonant circuit. Calculated values of resonant currents are extremely high (as could be seen in Table 3), when voltage harmonics order $h \leq 13$ reach or exceed maximal admissible values. Resonant currents of high order harmonics flowing through capacitor are lower than admissible 83.3%, only to harmonics order $h \geq 17$. On that basis limitations for maximal capacitor powers (Q_C) are determined that could be connected on secondary sides of non-loaded MV/LV transformers.

Table 3: Resonant currents in percent $(I_h/I_{tn})_{rez}\%$ and $(I_h/I_{cn})_{rez}\%$, in series circuit transformer ($u_k = 4\%$, r_{th}) - power capacitor $(Q_C/S_{nt})_{rez}$

Harmonic order		5	7	11	13	17	19	23
$(Q_{cr} / S_{nt})_{rez}$		1.00	0.51	0.207	0.148	0.087	0.069	0.047
r_{th}	(%)	2.50	3.80	7.60	10.10	16.30	20.00	28.60
r_{tc}	(%)	0.50	0.98	2.42	3.33	5.75	7.25	10.62
$r_{\Sigma h}$	(%)	3.00	4.78	10.02	13.43	22.05	27.25	39.22
$u_{h,max}$	[1]	6.0%	5.0%	3.5%	3.0%	2.0 **(1.5%)**	1.5 **(1%)**	1.5 **(1%)**
$(I_h / I_{tn})_{rez}$ %	(7)	300%	105%	34.9%	22.3%	9.1 **(6.8%)**	6.4 **(4.4%)**	3.8 **(2.6%)**
$(I_h / I_{cn})_{rez}$ %	(8)	300%	205%	169%	151%	105 **(78%)**	95 **(64%)**	81 **(54%)**

Remark: Currents for harmonics of order ≥ 17 are calculated for the highest admissible values of voltage harmonics and values decreased for 0.5% (values in brackets), since the voltage harmonics are reduced for at least that amount in resonant conditions.

This can explain estimation shown in [4] that occurrences of series resonance are not dangerous at harmonics order h ≥ 17, as quoted relative relations for powers of fixedly connected capacitors Q_C/S_{nt} in percentages are:

- $Q_C/S_{nt} \leq 7$ %, for transformers $S_{nt} \leq 630$ kVA, ($u_K \leq 4\%$),
- $Q_C/S_{nt} \leq 5$ %, for transformers $S_{nt} > 630$ kVA, ($u_K \leq 6\%$).

They approximately coincide with the values calculated according to equation (2) and given in Table 2 for harmonic of order h = 17.

4 Procedure for increasing of capacitor utilization

4.1 Idea and procedure

According to researches shown in [6], it is estimated that in total it would be possible to get additional 150 – 200 MVAr in consumption centers by increasing utilization of already installed capacitors (by power and by time) at larger consumers in the industry of Serbia. It would be possible by applying the proposed and described procedure. The idea is to permanently connect larger part of a capacitor to a secondary busbar of transformer 10(20)/0.4 kV and to use all 8760 h / per year instead of previously used 2000 – 3000 hours on the average per year. This increases time of capacitor usage for approximately 3 – 4 times. In practice it is realized by splitting capacitor batteries into two parts as shown in Fig.3 [5],[6]:

- a part with capacitor of power Q_{CF} constantly switched on, and
- a part with capacitors automatically switched on and off (Q_C↑↓ - with this part a given power factor cos φ is controlled).

Proposed procedure is practically realized easily and without additional investments. Technical solution for appliance of the procedure is presented in the patent [5] and a study [6].

The solution is based on the idea that provides that addmissible powers of fixedly connected capacitors on a low voltage side of the MV/LV transformer may have for about 4 times higher values comparing to the recomendations [3],[4] as shown in Table 1.

Both criterions are defined with a goal to avoid resonance occurences risks while high order current and voltage harmonics are in the network.

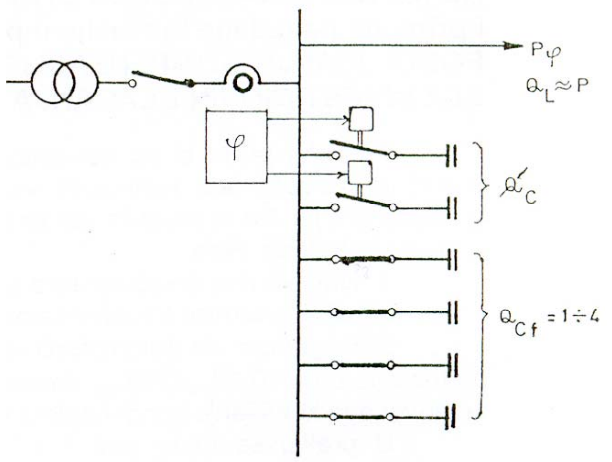

Fig. 3. Capacitor batteries splitted into two parts

That means that non-loaded MV/LV tranformer with permanently connected capacitors on its low voltage side, seeing from the higher voltage side, presents series R–L circuit with minor ohm resistance for high order harmonics currents and enters into resonace, if condition (10) is fulfilled:

$$Q_C = S_{nt} / (h^2 \cdot u_k) \quad (10)$$

Previous equation is derived from (2). In order to avoid occurence of series resonance for harmonics of order less than 17, the powers of capacitors are limited to the values calculated from the equation:

$$Q_C \leq S_{nt} / (289 \cdot u_k) \quad (11)$$

whereas S_{nt} and u_k are rated power and short circuit voltage of transformer. Calculation of the highest admissible values, acording to the equation (11), are given in Table 1 item 1 and 2. By applying our idea [5], [6] - and choosing appropriate values according to the equation (10), for h = 9, i.e. according to equation:

$$Q_C = S_{nt} / (81 \cdot u_k) \quad (12)$$

considerably higher amounts are obtained for powers of fixedly connected capacitors (Table 1, row 3.). Because of that resonant frequency is set on 9x50=450 Hz, but only fictive resonance is in question, since transformers connected in Δ/Y present open circuit for currents of 9th harmonic on a secondary side of the transformer and therefore through capacitors as well. Application of this procedure require certain changes comparing to former practice in structure and operation mode of capacitors units from composition of capacitor's battery.

Calculations and analysis presented in Chapter 4.2. of this paper show that total effective current value of all high order harmonics for capacitors dimensioned in that way, cannot exceed admissible amount if total harmonic voltage distortion is in admissible limits ($THD_u \leq 5\%$).

A several years of checkings in practice on about 300 capacitor batteries [6], confirmed that risk from resonance occurence in networks where capacitors are used according to this procedure is practically nonexistent. It is also important to notice that voltage drops of fixed parts of capacitor's batteries which are dimensioned in this way, are lower than admissible 1,5% when they are switched on, since:

$$\Delta U\% = u_k\% \cdot Q_{FK} / S_{nt} = 100/81 = 1.23\% < 1.5\% \quad (13)$$

This also fulfills the condition that starting currents of the capacitors are < 100 I_{Cn}.

4.2 Voltage and current harmonics in series circuit

It is established (Table 3) that resonant currents considerably exceed the highest admissible amounts for capacitors if voltage harmonics reach the highest admissible values, for harmonic order $h \le 13$. When the highest admissible values are in question for voltage harmonics of order $h \ge 17$, resonant currents that flow through capacitors are somewhat above upper limit of admissible values. But if value of voltage harmonics with the highest admissible values $u_{17,max} = 2\%$ is reduced to $u_{17} = 1.5\%$, which is always the case in resonant conditions, resonant currents that are flowing through capacitors are below upper limit of admissible values – Table 3. As most of the regulations limit level of voltage high order harmonics to $u_h \le 2\%$ [1], only for harmonics order $h \ge 17$, the maximum admissible values for fixedly connected capacitors on transformer secondary busbars are determined from the condition that resonance may appear only for harmonics order $h \ge 17$. At the same time this is an explanation for relatively low admissible power values of fixedly connected capacitors according to some recommendations (Table 1), because according to equation (11), approximately these amounts are obtained.

It will be shown in this work that admissible powers for fixedly connected capacitors can be considerably higher. The idea is that capacitors powers are to be determined according to the equation (12), and current of 9th harmonics are not going to flow through quoted series circuit since Δ/Y connected distributive transformers presents open circuit to them. At the same time impendence of that series circuit for adjacent harmonics order h = 7 and 11 is higher than resonant one. For the complete test and analysis, current values of all relevant harmonics in series circuit formed in that way should be deterimined, more exactly the total harmonic current distortion (THDi) is to be defined. Values of high order harmonics currents in series circuit, transformer (S_{nt}, u_k) – capacitor ($Q_C = S_{nt}/(81u_k)$), in percent ($I_h/I_{C,n}$ %) can be determined according to equation (14) or (15):

$$(I_h / I_{Cn})\% = 100 \cdot (U_h / X_h)/(U_1 / X_C) \quad (14)$$

$$(I_h / I_{Cn})\% = (U_h\% / X_h\%)/(81 \cdot u_k\%) \quad (15)$$

If all impendances are expressed in percent with rated impendence of transformer (Z_n=100%) as a base value:

- reactance of transformer ($X_{t,h}\% = h \cdot u_k\%$)
- reactance of capacitor ($X_{C9}\% = 81 \cdot u_k\%$),

than total impendence of series circuit is $Z_h\% \approx X_h\%$; and:

- $X_h\% = | 81 \cdot u_k\% / h - u_k\% \cdot h | = u_k\% \cdot | 81/h - h |$.

Corresponding current value in percentage units of capacitor rated current is:

$$(I_h / I_{Cn})\% = 81 \cdot u_h\% / |81/h - h| \quad (16)$$

In denominator of the equation (16) the absolute value is taken as to avoid negative values when resonant currents are of capacitive character. It is interesting that values calculated according to the equation (16) do not depend on transfomer's characteristic (S_{nt}, u_k), i.e. currents of high order harmonics have the same amounts only when expressed in percents of capacitor's rated currents (I_h/I_{Cn})%, of corresponding powers $Q_C = S_{nt}/(81u_k)$.

Table 4. Currents values of the most important harmonics through series circuits: non-loaded MV/LV transformers – fixed power capacitors ($Q_C = S_{nt}/81u_k$), in percentage units of capacitor rated current (I_h/I_{Cn})%.

$h = f/f_1$		5	7	11	13	17	19	23	
$r_h = r_1 + h^2 r_d$ %		2.25	3.45	7.05	9.45	15.45	19.05	27.45	
$X_h = \|81u_k/h - u_k h\|$ %		44.80	18.28	14.55	27.08	48.94	58.95	77.91	
$Z_h \approx X_h$ %		44.80	18.28	14.55	27.08	48.94	58.95	77.91	
THD_u %	U_h %	$(I_h/I_{Cn})\%$							$\sqrt{\Sigma I^2_h} = THDi$
2.45	1.0	7.23	17.72	22.27	11.96	6.62	5.50	4.16	33.12
3.68	1.5	10.85	26.58	33.40	17.94	9.93	8.24	6.24	49.67
4.90	2.0	14.46	35.45	44.54	23.93	13.24	10.99	8.32	66.23
6.12	2.5	18.07	44.30	56.67	29.90	16.55	13.75	10.40	82.80
7.35	3.0	21.69	53.17	66.80	35.89	19.86	16.49	12.48	99.35

According to the quoted equation (16) currents calculation of all relevant high order harmonics is carried out, h = 5, 7, 11, 13, 17, 19 and 23. For corresponding MV/LV transformers of all rated powers and short circuit voltage values (S_{nt}, u_k) these calculations results are given in Table 4.

Total contents (i.e. effective value) of current of all high order harmonics is determined by equation:

$$THDi = \sqrt{\sum_h I_h / I_1^2} \text{ , h = 5, 7,…,23} \quad (17)$$

The calculations results show that at voltage harmonics $u_5 = u_7 = \ldots u_{19} = u_{23} = 2\%$, total current harmonic distortion is 66.23% which is lower than admissible level. Corresponding total harmonic voltage distortion (THDu) is:

$$THDu = \sqrt{\Sigma (U_h / U_1)^2} \text{ , h = 5, 7,…,23} \quad (18)$$

reach the amount of 4.90%, which is somewhat below allowed 5%.

At voltage distortion about 5%, current distortion can be higher than quoted one (66.23%) if contents of voltage harmonic of 7th and 11th order are higher than the average. So, in case that voltage harmonic values are u_7=3%, u_{11}=2.5%, and all other voltages harmonics are 1.5% each, harmonic current distortion would reach 81,75% and would not exceed allowed amount. In this case corresponding voltage distortion is:

$$THDu = \sqrt{3^2 + 2.5^2 + 5 \cdot 1.5^2} = 5.15\% > 5\% \quad (19)$$

a bit above permissible limits and with unfavorable harmonic contents for quoted series circuit (high contents of harmonics u_7 and u_{11}).

Above mentioned calculations and analysis show that total current contents of high order harmonics through series circuit, practically cannot exceed admissible amount for capacitors (83%) if voltage distortion is within the permissible limits ($THD_{u,max} \le 5\%$). On that basis, recommendations [5], [6], mentioned in Table 1, item 3, are proposed for common and the most frequently used transformers 10(20)/0.4kV, with powers of 400kVA – 1600 kVA. They are accepted and until now applied on about 300 capacitor batteries in order to increase their utilization. For several years they are proving their efficiency in application at various consumers of Electric Power Industry of Serbia [6]. This shows that by applying of the proposed idea, a maximal permissible powers of fixedly connected capacitors on non-loaded transformers can be increased for about four times comparing to the known recommendations [3],[4].

4.3 Power capacitors $Q_C = S_{nt} / (81 \cdot u_k)$ in network with non-linear consumers

If there are non-linear consumers – sources of high order harmonics in low voltage network with capacitors (Fig. 1) parallel resonance may be excited. In contrast to the linear resonance, it is possible to foreseen risk level, since client exactly knows which non-linear consumers – sources of high order harmonics are being fed through given transformer and knows their powers as well. Therefore the values of current high order harmonics can be estimated or established by measuring.

In addition risks of this resonance are reduced because:

- there are also resistive loads in the network, characterized with R_P on Fig. 1, that reduce currents of paralel resonance
- capacitors of such a large power are rarely connected to the network, so conditions for low order harmonics resonance almost not exist (values Q_{Cr}/S_{nt} in Table 2 for h=5 and 7).

It is demonstrated that usage of battery with capacitor units that are being dimensioned according to our procedure:

$$Q_C = Q_{CF} + (Q_{Ci}\uparrow\downarrow),\ Q_{CF} = (S_{nt}/(81 \cdot u_k) \quad (20)$$

provides avoiding of resonance for harmonic order h ≥ 11, which sometimes might be dangerous, and even cause capacitor's break downs.

That is how more frequent destruction of 3rd or 4th capacitor units is being noticed from capacitor’s battery composition (10·30kvar) for power factor correction of 1000 kVA transformer with u_k=5.8%, that feeds regulated drive of the elevators in the business premises of the Petroleum Industry of Serbia in Novi Sad [6]. Explanation: when the third capacitor is switched on, battery of 90kvar is formed and conditions are made for parallel resonance of 13th harmonic. When the fourth capacitor is switched on, battery of 120 kvar is being formed, so condititons for 11 harmonic resonance are made.

Since low power resistive load is being fed from the quoted transformer (high resistance R_P in Fig. 1), the quasi resonant currents are high, even more if deviation from resonant frequency is lower. Resonant currents of high values caused voltage oscilations of 4 – 5 % that made additional problems to the consumers. By changing capacitor battery into a regime proposed by the procedure for increasing of capacitors utilization, the mentioned problems with voltage alterations and capacitors' destruction disappeared.

It is obvious that parallel resonance occurrences for currents of the 11th and 13th harmonics order are avoided.

It should be noticed that in the working conditions with capacitors of power $Q_C = Q_{CF} = (S_{nt}/(81\cdot u_k)$, voltages of 7th and 11th harmonic are increased to a certain extent (multiplied), but they are several times lower than resonant currents of 11th harmonic. These currents, are previously occured and caused break down of capacitor and even of the contactor for capacitor switching [6].

The results of this analysis are illustrated with the measuring of voltage and current harmonics through capacitor and transformer (supply network) in characteristic working conditions:

- Disconnected capacitors ($Q_C = 0$);
- Connected capacitors $Q_C = 90$kvar ($h_{rez} \approx 11$);
- Connected capacitors $Q_C = 120$kvar ($h_{rez} \approx 13$);
- Connected capacitors $Q_C = Q_{CF} = 180$kvar ($h_{rez} \approx 9$).

It shouldn't be forgotten that with capacitors of power $Q_C = Q_{CF}$, series resonance risks are additionally lowered, which are anyway lower in networks with loaded transformer.

5 Experimental results

Experiments are performed in power station that supplies water pump station in Smederevo (Serbia). Characteristics of transformer are: 10/0.4kV, 630kVA, uk = 4%. Total power capacity of the batteries for reactive power compensation is 200kvar (8 x 25kvar). Measurements, taken from transformer secondary side, are performed with power quality analyzer C.A. 8334 connected to PC for saving data and off-line analysis. Voltage and current harmonics are shown in Fig. 4 (next page) for different values of the connected capacitors (0kvar – all capacitors are switched off, 125kvar, 150kvar, 200kvar).

Harmonic distortion of voltage (THD_U) and current (THD_I) are smallest when capacitors are switched off (Fig. 4a). Distortion is rising when capacitors are switched on and it is at highest value when $Q_C = 125$kvar (Fig. 4b) because of significant increase of 11th voltage and current harmonics ($f_r / f \approx 10.7$). At $Q_C = 150$kvar distortion is reduced (Fig. 4c), while at $Q_C = 200$kvar ($f_r / f \approx 8.5$) is appreciably decreased (Fig. 4d).

6 Conclusion

In this work detailed analysis has been made about series resonance occurrence in the circuit formed by non-loaded transformer ($S_{n,t}$, u_k) and directly connected capacitors (Q_{CF}). Recommendations for the highest admissible values (Q_{CF}) are determined in order to avoid risks of series resonance with sufficient safety, since occurrences and values of voltage harmonics can be foreseen only by statistical confidence.

By applying our idea by choosing values of $Q_{CF} = S_{nt}/(81u_k)$ for powers of directly connected capacitors a large amounts are obtained (approximately for 4 times) comparing to the same one which are dimensioned in order to avoid resonance for harmonics order h<17. That is how resonant frequency is fixed to the 450Hz, but it is fictive resonance since Δ/Y transformers represent open circuit for currents of 9th harmonic on secondary side of transformer, and also through capacitors. This shows that it can be permitted for capacitors of considerably larger powers to be connected to the non-loaded transformers if there is deficiency of reactive energy in medium and high voltage networks. On that basis, the new solution is suggested for dimensioning of capacitor's batteries and capacitor units that form it – Procedure for capacitor utilisation improvement [5]. It should be emphasized that solution with capacitor batteries with minimal power of capacitors switched on $Q_{C,min} = Q_{CF} = (S_{nt}/(81\cdot u_k)$ enables to avoid parallel resonance for current harmonics of order $h \geq 11$ that can exist in considerable amount in network with non-linear loads. Application of this solution has showed also useful for eliminating the risk of parallel resonance for harmonics of 11th and 13th order, which in network with small resistive load can be dangerous.

References:

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[3] Company "Rade Koncar", *Technical Guide*, pp. 876, Zagreb, Yugoslavia, 1980.

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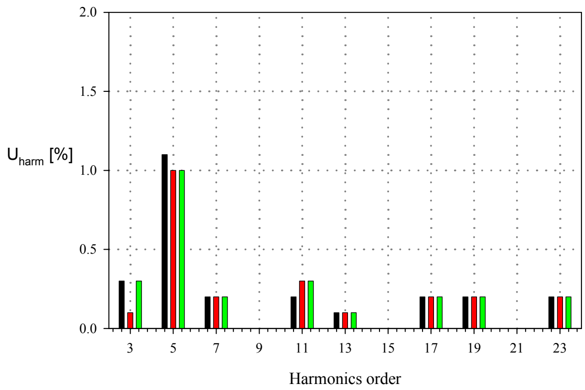
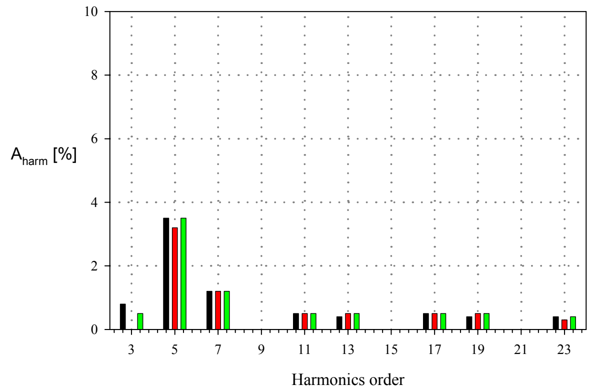
[5] M.Kostic, *Procedure for Capacitor Utilization Improvement on a Secondary Side of MV/LV Transformer in Order to Improve Compensation of Reactive Power* (in Serbian), Patent No. 49030, Serbia & Montenegro, 26.03.2003.

[6] M.Kostic, Improvement of Reactive Power Compensation in Electric Power System of Serbia by Using Existing Capacitors (in Serbian), Institute "Nikola Tesla", Belgrade, Serbia & Montenegro, 2001-2003.

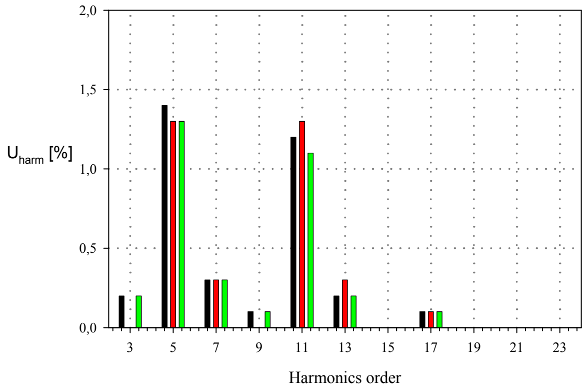


$THD_U = 1\%$, $Q_C = 0$kvar

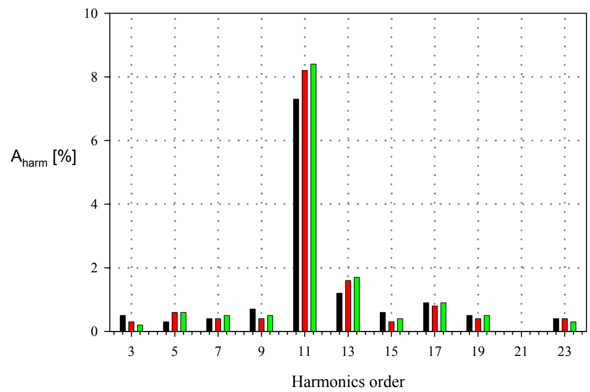


$THD_I = 3.7\%$, $Q_C = 0$kvar

a)

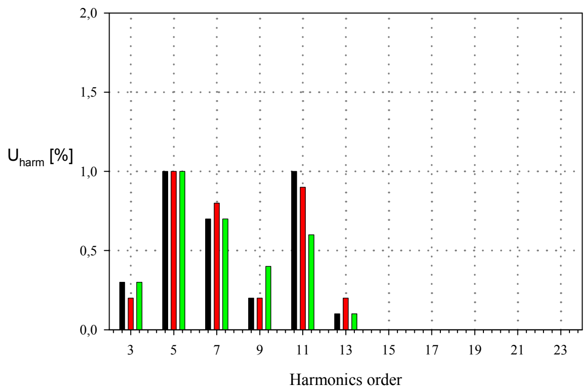


$THD_U = 1.8\%$, $f_r / f \approx 10.7$, $Q_C = 125$kvar

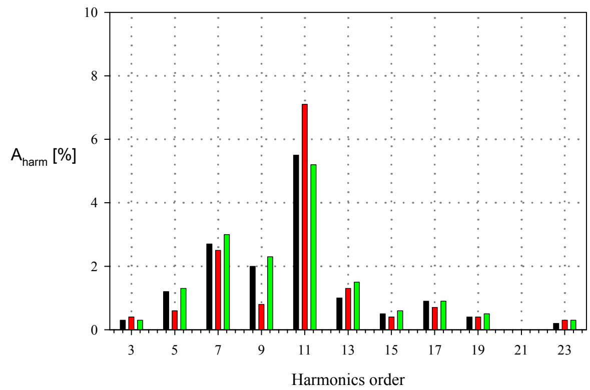


$THD_I = 8\%$, $f_r / f \approx 10.7$, $Q_C = 125$kvar

b)

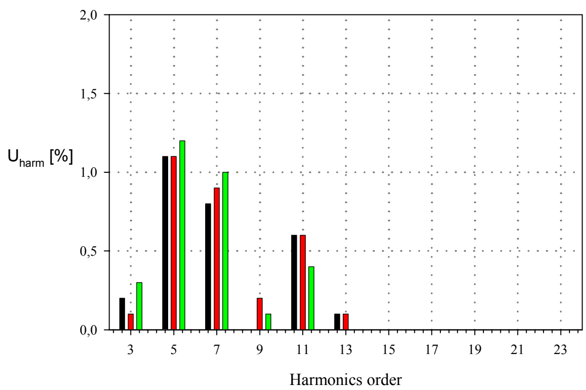


$THD_U = 1.6\%$, $f_r / f \approx 9.8$, $Q_C = 150$kvar

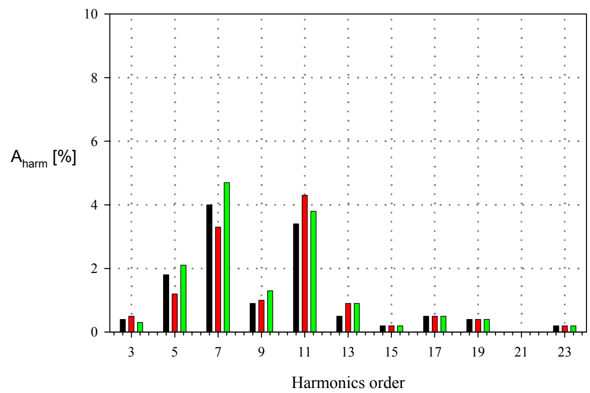


$THD_I = 6.5\%$, $f_r / f \approx 9.8$, $Q_C = 150$kvar

c)



$THD_U = 1.5\%$, $f_r / f \approx 8.5$, $Q_C = 200$kvar



$THD_I = 6\%$, $f_r / f \approx 8.5$, $Q_C = 200$kvar

d)

Fig. 4. Voltage and current harmonics up to 23^{rd} for different values of the capacitors on low voltage side of MV/LV transformer 630kVA, $u_k = 4\%$