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THE CIRCULATION OF REACTIVE POWER AND THE APPEARANCE OF RESONANCE PHENOMENON AT THE FINAL USER'S PREMISES

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În cadrul lucrării sunt analizate problemele specifice ale marilor consumatori industriali, caracterizaţi de regim nesimetric deformant şi factor de putere sub valoarea factorului de putere neutral. Utilizarea necorespunzătoare a mijloacelor de limitare a perturbaţiilor poate conduce la apariţia fenomenului de supracompensare şi rezonanţe în reţeaua electrică .

Aceste fenomene se constată la utilizatorii actuali moderni în care un mare număr de receptoare sunt comandate utilizând electronic de putere.

Cunoaşterea acestor fenomene şi adoptarea măsurilor necorespunzătoare are un efect important asupra eficienţei economice a utilizatorului şi asupra calităţii energiei electrice.

This paper analyzes the specific problems, faced by major industrial consumers that are characterized by big departures from non-symmetrical conditions and power factors below neutral. The improper usage of the perturbation- limiting means may lead to the appearance of overcompensation and resonance in the electric network.

These phenomena are noticed by current modern users when a big number of receivers that consume large quantities of power are employed.

The knowledge of these phenomena and implementation of proper measures have an important effect upon the economic efficiency of the user and upon the quality of electric energy.

Keywords: reactive power, resonance frequency, filter, electric energy quality, harmonic

1. Introduction

The reactive power flow to the end users of electric energy has been extensively studied by electro-energy specialists, at the national level but more so at the international level. The resonance phenomenon has also been studied and analyzed but, in comparison with the reactive power flow, it is less known by final-users of electric energy.

Materials specialists analyzed the possibility of limiting the warping state and the reactive power flow by the means of compensation limits, such as banks

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of capacitors and individual filters. Their conclusion was that the analysis of the problems related to harmonic distortion corrections can be simultaneously performed with those related to the reactive power compensation.However,the user is charged by the distributor only for the aspect related to the reactive power flow (by failing to observe the power factor) and not also for the network pollution with harmonics.

Through measurements with its own equipment, the consumer is able to identify the problems and consequences which appear as a result of the reactive power flow and of the warping state , so that, eventually, limitation measures of the two phenomena can be taken, and the technologic process can be improved.

The flow of reactive power and the appearance of resonance at the final - user's premises represent an extremely important theme, with great potential for research.In this paper, the specific problems relating to the reactive power flow for a big consumer are analyzed, with an emphasis upon the behavior of the bank of capacitors connected to the supply lines.

If the the bank of capacitors is misused, the consumer may be penalized by overcompensation and network charging with capacitive reactive power.[1]

The overcompensation situation of the reactive power is widely encountered by major consumers with unequal consumption in the three phases, thus requiring the final users to correctly use all the phases and the bank of capacitors.

The bank of capacitors is effective only in the case of usual sinusoidal voltage in the supply lines. Distortion occurs in real cases, absorbing electrical currents; the most common being level 5 harmonic. [1]

Point 5 (below in the present document) describes a study done by sizing a filtering circuit for a level 5 harmonic.

For filter sizing, information regarding active and reactive absorbed power, variation of the power factor, as well as the sinusoidal specter of the absorbed electric energy are necessary.

The analysis of the problems related to the correction of sinusoidal distortion was performed simultaneously with those related to the reactive power compensation.

2. Reactive power flow at a major consumer

The reactive power concept was originally defined for sinusoidal states and was linked to the presence of inductive and capacitive elements in the electrical network. [1]

Although reactive power does not develop useful mechanical work, the transfer of reactive power to the electrical network causes active losses.

Therefore solutions have been sought in order to mitigate the reactive power flow in the electrical network, the power factor being defined and optimal values for it being set. However, in practical cases, failure to watch the reactive power consumption or improper setting of the power factor monitoring can lead to a phenomenon of overcompensation, due to production excess of capacitive reactive power of the bank of capacitors. [1]

The performed analysis was based on a real case of a major consumer, for which theoretical and experimental studies, were conducted in order to highlight the specific problems arising from an industrial consumer, characterized by significant changes in reactive power consumption and, therefore, an important variation of the power factor.

Figure 1 is a schematic diagram of the structure analyzed. Reactive power consumption is controlled by the bank of capacitors, connected to low voltage inels.

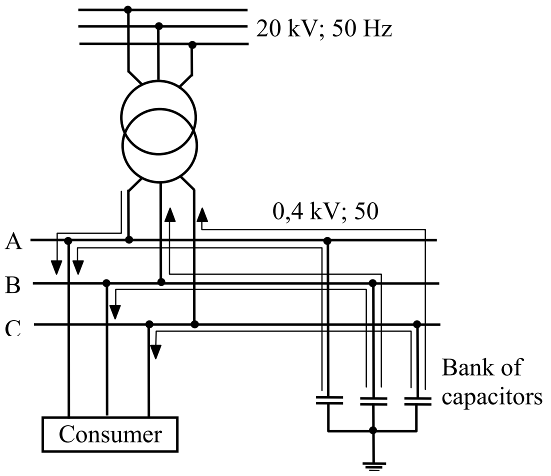


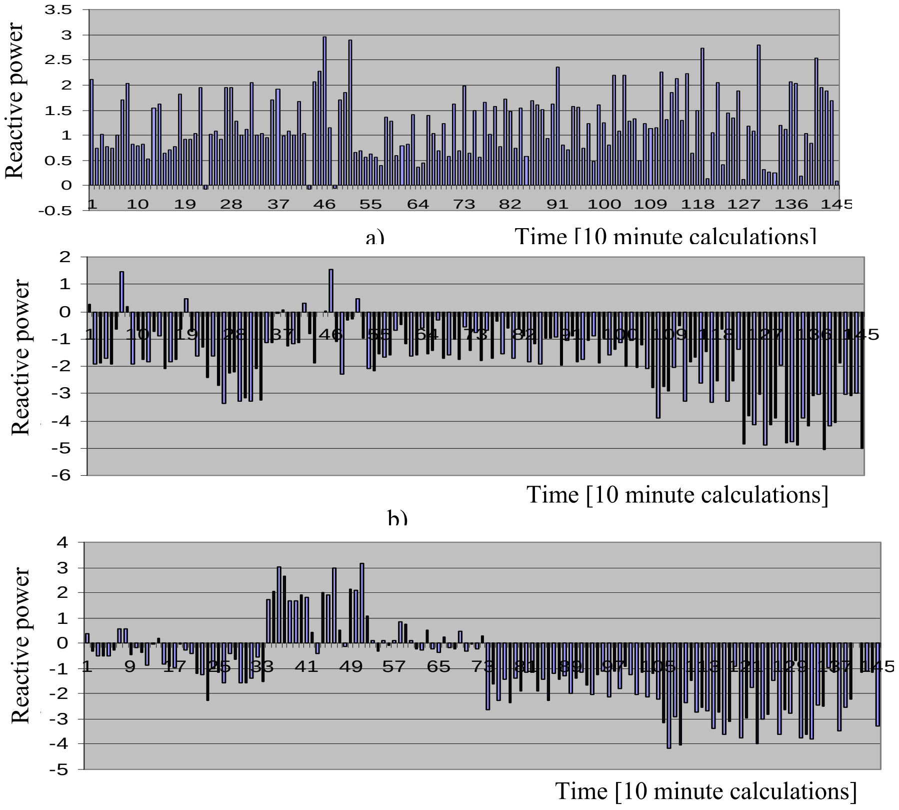
Fig. 1 – Flow of reactive power in the three phases of the analyzed-consumer's network.

Experimental measurements, carried out at the terminals of the MT/JT transformer (Fig. 2), showed a significant unbalanced load of the three phases and a poor operation of the reactive power compensation system (the bank of capacitors is three-phased, with a three-phase connection).

Thus, phase A (Fig. 2 a) is loaded, with an important consumption of reactive power. The bank of capacitors is set on phase A, according to the power factor, and ensures a proper implementation of the power factor imposed on this phase.

Phases B and C (Fig. 2 b) and Fig. 2 c)) have a reduced load (both active power and reactive power), so the connection of the bank of capacitors leads to the appearance of the overcompensation phenomenon at this stage.

Thus, capacitive reactive power is transmitted to the network and the consumer is penalized for capacitive condition operation.This situation of reactive power overcompensation is often encountered by major consumers and requires, from the design phase, implementation of control systems for each phase of the bank of capacitors.Currently, the consumption inequality of the three phases and the usage of the bank of capacitors, with a three phase operation and a control signal based on single phase information, leads to the overcompensation phenomenon.



a)

b)

c)

Fig. 2 – Reactive power on the three phases of the mains transformer
(low tension part)

The improper usage of the bank of capacitors leads to a user’s penalty, even if the user has reactive power compensation devices.

Therefore the mere possession of reactive power compensation devices is insufficient so, save for their correct usage, there is a risk of paying penalties to the distribution operator for deviations from the neutral power factor.

Inadequate administration of users connected to phases B and C, with an insufficient number of inductive consumers and lack of phase control of the bank of capacitors leads to reactive power overcompensation, so the consumer is charged for inserting a capacitive reactive power surplus into the distributor's network.

There are basically two important situations encountered by major consumers regarding the reactive power flow:

- The situation when the user is charged for the inductive reactive power brought into the network, obtaining a power factor less than neutral one, i.e. below 0.92;
- The situation when the user has devices for reactive power compensation, and here we encounter three separate situations:
  - ➢ the user pays for capacitive reactive energy, due to overcompensation (Fig.2);
  - ➢ the user pays a penalty for inductive reactive energy, but also for capacitive reactive energy, in case of overcompensation;
  - ➢ the user complies with the optimal values of the neutral power factor.

Reactive power flow in the electrical network has a significant influence on the voltage level in the electrical network nodes.

The reactive power flow is supplied to the consumers connected in nodes, so that the electricity consumer, through its receivers, has a very important contribution to the reactive power flow.

3. Appearance of resonance phenomenon at large power consumers

The presence of a bank of capacitors in the user's low tension lines, supplied by the means of a MT/JT transformer lead to the possibility of resonance phenomenon on one of the harmonics of the consumer's absorbed electrical energy.

In this respect, it is necessary to calculate both the resonant frequency of the bank of capacitors – transformer's inductance assembly and to evaluate the spectrum of the consumer's absorbed electrical energy.

For the previously analyzed consumer (Fig. 4) the following values are known: $S_{nt} = 0.8$ MVA; $u_{sc} = 6\%$ and $Q_{nB} = 0.150$ MVAr.

The resonance frequency can be calculated by [1]:

$$h_{rez} = \sqrt{\frac{S_{nt}}{u_{sc} \cdot Q_B}} = \sqrt{\frac{0,8}{0,06 \cdot 0,150}} = 9,42 \qquad (1)$$

The resonance frequency is $f_{rez} = 9.42 \cdot 50 = 471$ Hz, complying with value of the level 9 and 10 harmonics.

After determination of this characteristic size and providing there is a deforming state, which is crucial for maintaining the bank of capacitors or deciding on other actions, it is particularly important to continue examining this phenomenon to determine :

- the behavior of the bank of capacitors ;
- other electric power harmonics from the spectrum injected by nonlinear receivers, which may have a higher or lower level rank than the resonance one.

According to the spectral component of the consumer absorbed electric energy, if $h_a < h_{rez}$ and $h_b > h_{rez},$ we have the conventional flow directions of the electric energy harmonics by the bank of capacitors.

The electric energy from the bank of capacitors, for harmonic level h can be calculated by

$$\underline{I}_{hB} = -\frac{X_{hB}}{X_{hT} - X_{hB}} \cdot \underline{I}_h, \tag{2}$$

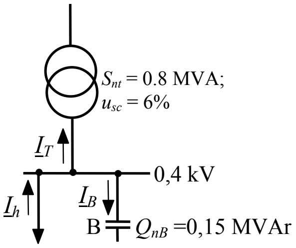


Fig . 3. Bank of capacitors connection to low tension bars

where X_B represents the reactance of the bank of capacitors, and X_T – is the transformer's reactance.

For a harmonic having this level $h_a < h_{rez}$ we have the inequality:

$$X_{1T} \cdot h_a - \frac{X_{1B}}{h_a} < 0, \tag{3}$$

which shows that, for the analyzed harmonic, the reactance of the bank of capacitors is higher than the same frequency transformer.

In equation (3), X_{1T} is the reactance of the transformer, calculated for the fundamental harmonic, and X_{1B} is the reactance of the bank of capacitors, calculated for fundamental harmonic.

The harmonic electric energy, calculated by the user, is mainly transmitted to the electrical network.

The bank of capacitors causes a capacitive current (conventionally, the electric current in the bank of capacitors flows from the bank to the supply lines).

The outcome is that in case of harmonics with lower rank than the resonance one, the prevailing electrical characteristic of the scheme is equal with the one of a capacity and thus the bank of capacitors causes a harmonic current, which flows to the bars, increasing the amplification of the deforming phenomenon.

For a harmonic $h_b > h_{rez}$ we have the inequality:

$$X_{1T} \cdot h_a - \frac{X_{1B}}{h_a} > 0, \tag{4}$$

which shows that for the analyzed harmonic, the reactance of the bank of capacitors is lower than the same frequency transformer reactance.

The conclusion is that the harmonic electric energy produced by the consumer is mainly transmitted to the bank of capacitors, which partially absorbs the harmonic electric currents.

Conventionally, the electric current in the bank of capacitors flows from the supply lines to the capacitor.

The bank of capacitors slightly contributes to the mitigation of the deforming state, because these superior level harmonics generally have low values.

In relation to the fundamental frequency, the behavior of the bank of capacitors corresponds to the purpose for which it was mounted, namely it generates capacitive reactive power, compensating the user's reactive power, because the fundamental frequency and therefore, the level of the fundamental curve is always lower than the resonance level.

In order to ensure the distortion of the system limit, but also to compensate for the reactive power, the supply lines may be fitted with a passive filter, calculated for representative harmonics [2].

4. Sizing a passive filter to the lines of a disruptive user

Utilization of a bank with capacitors within an environment polluted with harmonics may contribute to the amplification of a distorted state, but they may themselves become vulnerable, with high probability of deterioration.

The presence of a deforming state leads to reduction of electric energy quality, within the plant and within the distribution area of the operator, but also at the premises of other consumers connected to the same electrical network.

The measures adopted consist of installation of filters, passive or active, limiting the presence of a deforming state to a tolerable level [3].

In many cases, a simple scheme with a bobbin and a bank of capacitors, mounted in series, is an effective solution for solving problems related to distorting states.

Following the allocation calculations made by electricity distributors, each user knows the limits of disturbance that he may issue, without affecting the power quality for other users connected to the same supply bar [4].

In case deviating emission levels are above the user's quota, measures must be taken to limit harmonic disturbance.Sizing an absorbent filter is based on information of the harmonic source (considered as power source), on power supply network characteristics as well as the permissible amount of the distortion factor. The calculations take into account the probable values, the higher ones of the electrical current harmonics.

Typically, an absorbent filter comprises resonant circuits on harmonics 5, 7, 11 and 13, which are the most important in the industrial power system.

Normally, the even and 3- multiple harmonics are not taken into account, in the view of their limitation by the star - delta transformers.

The problem of 3- multiple harmonics becomes important if the current trend of using the star-star transformers instead of the star – triangle is taken into account.

5. Case study for sizing a level 5 resonance circuit

In many real cases, especially in low and medium voltage networks, level 5 harmonic has the highest value. Since level 3 harmonic is limited by using star-delta transformers or other means, and even level harmonics are not specific to electrical installation wiring, the outcome is that level 5 harmonic has the lowest level in the harmonic spectrum of electricity determined by disruptive users.

In such conditions, in the first stage the harmonic filter may contain a single resonant circuit, sized for level 5 harmonic.The resonance frequency of the circuit is usually chosen to a value slightly lower than the theoretical one. In this way, the electrical current in the resonant circuit does not become capacitive, if small changes of the supply voltage frequency occur.

For the proper sizing of level 5 harmonic resonance, a frequency of 240 Hz was chosen. In this case, in normal operation, there is an overvoltage at the terminals of the bank of capacitors defined by the overvoltage factor, equal to 1.045.The rated voltage at the supply lines is 400 V, thus resulting in a phase voltage U = 231 V. In order to achieve the filtering circuit, capacitors with rated voltage of 440 V (nominal voltage per phase, equal to 254 V) were considered.

The movement of electrical harmonic currents in the filtering scheme is represented in Figure 4.

The sizing of the resonant circuit is made in such a way that the electrical and thermal stress of the capacitors form the circuit might be exceeded. Therefore, the following two conditions must be met [2]:

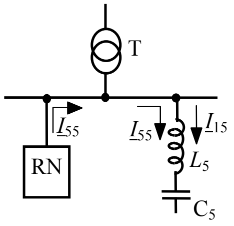


Fig. 4. The flow of the harmonic currents (corresponding to level 5 harmonic)

$$I_{C5} \le k_I \cdot I_{Cr} \; ; \qquad U_{C5} \le k_U \cdot U_r \; , \tag{5}$$

where I_{C5} represents the intensity of the electrical current which flows through the level 5 resonant circuit (causing the thermal stress of the capacitor pertaining toC_5); $k_I = 1.3$ – permissible overload factor of capacitors used in harmonic filter circuits; I_{Cr} – the rated current of the capacitor from level 5 resonant circuit; k_U =1,1 – allowable current growth factor at the terminals of capacitors used in harmonic filter circuits; and U_{Cr} – the rated voltage of the capacitor from level 5 resonant circuit;

The following results [1] are obtained, based upon the sizing conditions (5):

$$C_{5a} \ge \frac{I_{55}}{\omega_1 \cdot \sqrt{k_I^2 \cdot U_{Cr}^2 - a^2 \cdot U^2}} \; ; \qquad C_{5b} \ge \frac{I_{55}}{5 \cdot \omega_1 \cdot \sqrt{k_U^2 \cdot U_{Cr}^2 - a^2 \cdot U^2}} \; , \tag{6}$$

where C_{5a} and C_{5b} are the capacities of the capacitors from level 5 resonant circuit, based upon the two conditions (5), I_{55} – intensity of level 5 electrical current, calculated by the user, which flows through level 5 resonant circuit, $\omega_1 = 2 \cdot \pi \cdot f_1$ – pulsation of the fundamental harmonics, a – factor depending upon the harmonic level.

In relation (6) the hypothesis was that, after the representative filtering of the electric current in the circuit, the tension at the supply bars has a practically sinusoidal shape.

Factor *a* defines the tension growth at the terminals of the capacitors from the filtering circuit (in relation to the supply voltage) and it has the expression:

$$a = \frac{1}{1 - \frac{\omega_1^2}{\omega_5^2}} \tag{7}$$

Based upon calculation (6) it shows that the two values of the capacitor used in level 5 resonant circuit

$$C_{5a} \geq \frac{5{,}5}{100 \cdot \pi \cdot \sqrt{1{,}69 \cdot 65516 - 1{,}09 \cdot 53361}} = 76{,}40\ \mu\text{F}\ ;$$

$$C_{5b} \geq \frac{5{,}5}{5 \cdot 100 \cdot \pi \cdot \sqrt{1{,}21 \cdot 65516 - 1{,}09 \cdot 53361}} = 24{,}11\ \mu\text{F}\ .$$

The three-phased bank of capacitors used in the scheme of the resonant circuit must have the normalized reactive power Q_r

$$Q_r \geq 3 \cdot C_5 \cdot \omega_1 \cdot U_{Cr}^2\ , \quad (8)$$

or

$$Q_{5r} \geq 3 \cdot 76{,}40 \cdot 10^{-6} \cdot 100 \cdot \pi \cdot (254)^2 = 4{,}6$$

.

Given that there is no risk of electrical overload of the bank of capacitors, the bank of capacitors with normal 10 kVAr normalized reactive power can be chosen, which corresponds to a capacity on the phase equal to 76.40 μF.

The inductance of the coil from the filtering circuit is determined from the resonance condition on f_r frequency, close to the one for level 5 harmonic.

$$L_5 = \frac{1}{4 \cdot \pi^2 \cdot f_r^2 \cdot C_5} \tag{9}$$

Thus, the coil in series connection with the bank of capacitors must have the value

$$L_5 = \frac{1}{4 \cdot \pi^2 \cdot (240)^2 \cdot 76{,}40 \cdot 10^{-6}} = 5{,}76\ \text{mH}\ .$$

The electrical current due the fundamental harmonic tension I_{15} which flows through level 5 resonant circuit can be calculated by the formula

$$I_{15} = \frac{U}{\frac{1}{\omega_1 \cdot C_5} - \omega_1 \cdot L_5} = \frac{U \cdot \omega_1 \cdot C_5}{1 - \frac{\omega_1^2}{\omega_5^2}} = a \cdot U \cdot \omega_1 \cdot C_5 \tag{10}$$

and the tension at the terminal of the capacitor is

$$U_{C5} = I_{15} \cdot \frac{1}{\omega_1 \cdot C_5} = a \cdot U \tag{11}$$

For the analyzed circuit the outcome is

$$U_{C5} = 1{,}045 \cdot 231{,}2 = 241{,}6 \text{ V}.$$

the tension at the terminal of the coil L_5 is

$$U_{L5} = \omega_1 \cdot L_5 \cdot a \cdot U \cdot \omega_1 \cdot C_5 = a \cdot \frac{\omega_1^2}{\omega_5^2} \cdot U \tag{12}$$

The outcome for the analyzed circuit is

$$U_{L5} = 1{,}045 \cdot 231{,}2 \cdot \frac{50^2}{240^2} = 10{,}632 \text{ V}.$$

The so sized resonant circuit, causes a reactive power contribution, on the fundamental harmonic, on each phase, obtained from relation

$$Q_{C5} = U_{C5}^2 \cdot \omega_1 \cdot C_5 - \frac{U_{L5}^2}{\omega_1 \cdot L_5} \tag{13}$$

For the analyzed situation, the filter with this size provides a contribution of reactive power Q_5, on the fundamental harmonic:

$$Q_5 = 100 \cdot \pi \cdot 76{,}4 \cdot 10^{-6} \cdot (241{,}6)^2 - \frac{(10{,}63)^2}{100 \cdot \pi \cdot 5{,}76 \cdot 10^{-3}} = 1{,}33 \text{ kVAr}$$

6. Conclusions

The performed analysis revealed that the improper sizing, operation and automation of the bank of capacitors may have undesirable effects on electricity consumers, both by the increase of losses in the circuit of plants and by penalizing fines.

Before installing the bank of capacitors, the existent non-sinusoidal state must be analyzed in detail to assess whether a bank of capacitors can be fitted or the sizing of a filter is necessary, to ensure the necessary reactive power, as well.

In cases of unequal consumption of three phases, a bank of capacitors with control on each phase must be used, thus avoiding the phenomenon of overcompensation of the reactive power, followed by penalties from the distributor.

Sizing the filter resonant circuits involves execution of long-term measurements, in order to determine in detail the frequency spectrum and the amplitudes of the components.

Information regarding active and reactive absorbed powers, variation of the power factor, as well as the harmonic spectrum of the absorbed electric current is required for filter sizing.

In the general case, the analysis of problems of harmonic distortion correction is performed simultaneously with those related to reactive power compensation.

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