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Analysis of the impact of nonlinear loads on capacitor banks for reactive power compensation in MV/LV substations

***Abstract**. The influence of nonlinear loads on the selection and exploitation of capacitor banks for reactive power compensation in MV/LV substations has been analyzed in the paper. Frequency and time simulations were performed for a model system to determine the possible negative consequences of compensation or overcompensation.*

***Streszczenie**. W artykule przedstawiono analizę wpływu odbiorników nieliniowych na warunki doboru i eksploatacji baterii kondensatorów do kompensacji mocy biernej, instalowanych po stronie niskiego napięcia w stacjach SN/nN. Badania symulacyjne przeprowadzono dla układu modelowego zarówno w dziedzinie częstotliwości, jak i w dziedzinie czasu. Ich celem było określenie możliwych negatywnych skutków wynikających z zastosowania kompensacji, jak i ewentualnego przekompensowania. (**Analiza wpływu odbiorników nieliniowych na baterie kondensatorów do kompensacji mocy biernej w stacjach SN/nn**).*

Keywords: power networks, distribution transformers, reactive power compensation, nonlinear loads.
Słowa kluczowe: sieci elektroenergetyczne, transformatory rozdzielcze, kompensacja mocy biernej, odbiorniki nieliniowe.

Introduction

The development of feeding power electronic systems caused that a great number of converters started to be installed in electrical devices fed by the low voltage power networks. They share a common property of non-sinusoid input current bringing about the distorted feeding voltage. The distortion of the feeding voltage from the sinusoid course creates hazard for practically all electrical devices. If reactive power capacitors are installed in the system feeding nonlinear loads, then the parallel resonance may occur for the characteristic harmonic of this load's current. In the state of parallel resonance, the impedance of the feeding systems reaches maximum, which may lead to a considerable lowering of the feeding voltage, overloading, and destruction of capacitor banks in unfavorable conditions.

The above mentioned phenomena have been analyzed in the paper in view of magnetizing reactive power compensation of distribution transformers. The objective of the analysis was to assess the influence of nonlinear loads on the selection and exploitation conditions of capacitor banks to be used for reactive power compensation in MV/LV substations.

Magnetizing reactive power compensation of distribution transformers

Nowadays the magnetizing reactive power compensation of transformers is a known and commonly applied solution. The first compensation capacitors were installed in distribution networks already in the 1960s. However due to numerous failures caused by technical shortages of the capacitors, further exploitation of these devices was abandoned. Only in the 1990s, when new solutions were introduced (especially dry capacitors with gaseous insulation), the problem of magnetizing reactive power compensation of low voltage distribution transformers was addressed again.

Transformer's magnetizing reactive power Q_0 can be determined from the formula:

$$Q_0 = \sqrt{\left(\frac{i_0}{100} S_{nT}\right)^2 - \Delta P_{nl}^2} \approx \frac{i_0}{100} S_{nT} \qquad (1)$$

where: S_{nT} – rated power of transformer, ΔP_{nl} – magnetizing active power losses, i_0 – magnetizing current expressed in percents.

Magnetizing reactive power compensation of transformers is to eliminate the network losses constant, which is independent of the transformer's load, and so limits energy losses in medium voltage lines feeding the MV/LV substations. Technically, this is a very simple solution, lying in connecting a capacitor directly to the clams of the secondary low voltage winding. However, economically, this is a complex problem. The analyses [1] revealed that in a majority of cases the magnetizing reactive power compensation was economically inefficient. This does not signify that reactive power compensation should not be used for limiting energy losses in the distribution network. The economic efficiency of magnetizing reactive power compensation in distribution networks can be improved by installing a smaller number of much more powerful capacitor banks, unlike situation described in equation (1). The capacitor banks could be switched on permanently or with the use of contactors in selected MV/LV transformer substations. This issue will be discussed in this paper.

Model of the analyzed system

For determining the influence of nonlinear loads on capacitor banks installed on the low voltage side of MV/LV distribution transformers, the model presented in figure 1 has been analyzed. The assumed model consisted of a medium voltage power system, MV/LV transformer, capacitor banks connected in a triangle, and a low voltage network.

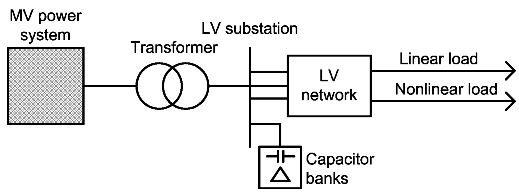

Fig. 1 Model of a low voltage system

The low voltage model network consists of overhead lines feeding loads of a given power and shape of the feeding current. The nonlinear loads are represented by a system of three single-phase rectifiers. Induction-capacity smoothing filters are disposed at their outlet.

The analysis was performed for variants, accounting for various rated powers of transformers and degree of their loading, power of attached capacitor banks and share in nonlinear loads. The most important data of the model system are as follows:

- distribution transformers 15.75/0.4 kV (ΔP_{ll} – power load losses):
  1) S_{nT} = 100 kVA, i_0 = 3.0%, ΔP_{nl} = 240 W, ΔP_{ll} = 1680 W,
  2) S_{nT} = 250 kVA, i_0 = 2.1%, ΔP_{nl} = 460 W, ΔP_{ll} = 3200 W,
  3) S_{nT} = 630 kVA, i_0 = 1.8%, ΔP_{nl} = 900 W, ΔP_{ll} = 6250 W;
- power Q_C of capacitor banks:
  - Q_C = (0, 1, 2, 4, 6, 8, 10)·Q_0;
- degree of transformer's load 15.75 kV/0.4 kV:
  - maximum load: $S_{l\max}$ = 70% S_{nT}, cosφ = 0.90, share of nonlinear load 25% $S_{l\max}$,
  - minimum load: $S_{l\min}$ = 5% S_{nT}, cosφ = 0.95, share of nonlinear load 50% $S_{l\max}$.

As far as the influence of higher harmonics on the elements of the power system is concerned, two basic analytical methods have been applied:

- in the frequency function, thanks to which frequency characteristics of system's impedance can be determined;
- in the time function, thanks to which the results can be obtained in the form of distorted plots of currents and voltages.

Both approaches have their advantages and disadvantages, but both they can be used equally well. In the analysis of the frequency function the changed parameters of equivalent circuits for higher harmonics are relatively easy to account for. Moreover, it allows for efficient detecting of possible resonance frequencies. The analysis of the time function leads to the results in the form of time plots, which visually illustrate phenomena taking place in the analyzed system. This approach, however, requires spectral analysis (mostly Fourier transform) of time signals at its further stages.

The experiments were conducted with the use of a simulation software EMTP-ATP, thanks to which the numerical analyses could be performed both in the frequency and time domains. Recommendations presented in [2] have been taken into account.

Results of analysis in frequency domain

Exemplary results of analysis of the frequency function in the form of plots of system's impedance viewed from the LV switching substation busbars are presented in figure 2. Maximum impedance can be observed in the course of frequency characteristics. This point corresponds with the resonance frequency of the system. If this frequency harmonic exists in the load current plot, then conditions for the resonance occur, which consequently results, among others, in the increase of current in the capacitor bank. It should be noted that the resonance point has not been observed in systems without installed capacitor bank, and the impedance was much lower than in the reactive power compensation systems.

The analysis revealed that the increased power of the added capacitor bank causes shifting of resonance frequency towards lower harmonics, and also lowering of maximum value of system's impedance.

Results of analysis in time domain

In the analysis of the frequency function it is not possible to directly determine the resonance risk level for the elements of the power system. For this purpose, all the analyzed variants were analyzed in the time function, and the obtained time plots were subjected to harmonic analysis with the use of Fourier series. Exemplary time plots and spectra of higher harmonics of feeding voltage, load current on the transformer's low voltage side and current in the capacitor bank have been presented in figures 3, 4 and 5.

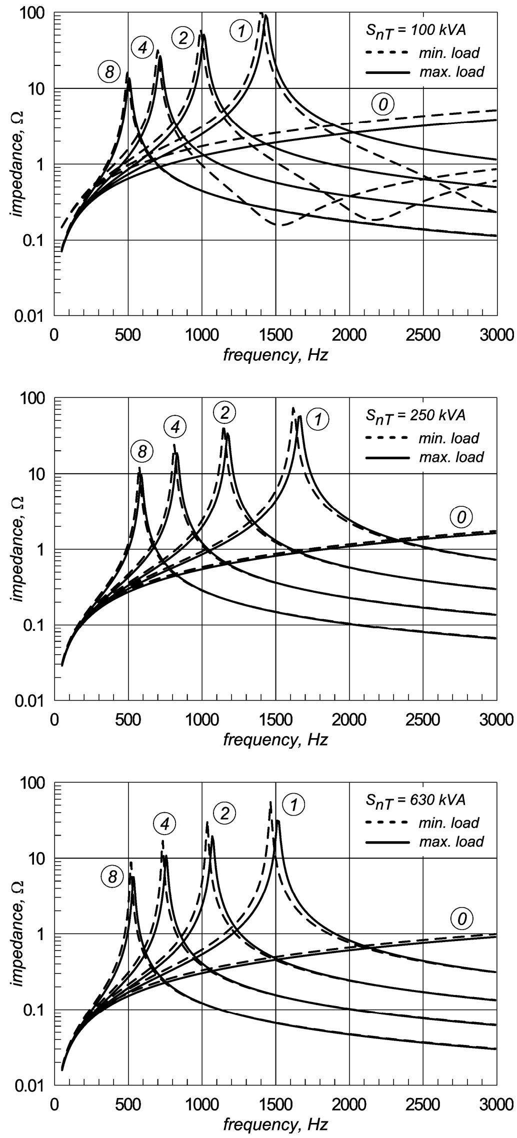

Fig. 2 Impedance of system in the frequency function: *0* – Q_c = 0, *1* – Q_c = 1 p.u., *2* – Q_c = 2 p.u., *4* – Q_c = 4 p.u., *8* – Q_c = 8 p.u.

The following parameters were determined for all the analyzed variants:

- THD_U – total harmonic distortion of feeding voltage,
- THD_I – total harmonic distortion of current in transformer's secondary winding,
- K – coefficient of additional losses in a transformer due to current distortion [3, 4, 5],
- K_H – coefficient of load losses increase in a transformer due to current distortion [3, 4, 5]
- $\Delta\Delta P_{ll}$ – difference of load losses due to compensation,
- I_C/I_n – current of capacitor bank versus rated current.

The dependences of these parameters on power of compensation banks for the analyzed variants have been presented in figure 6.

The performed analyses reveal that magnetizing reactive power compensation of transformers feeding nonlinear loads is a complex issue. In the lack of compensation, the nonlinear loads do not create any significant hazard from the resonance point of view. Otherwise, various negative phenomena may occur.

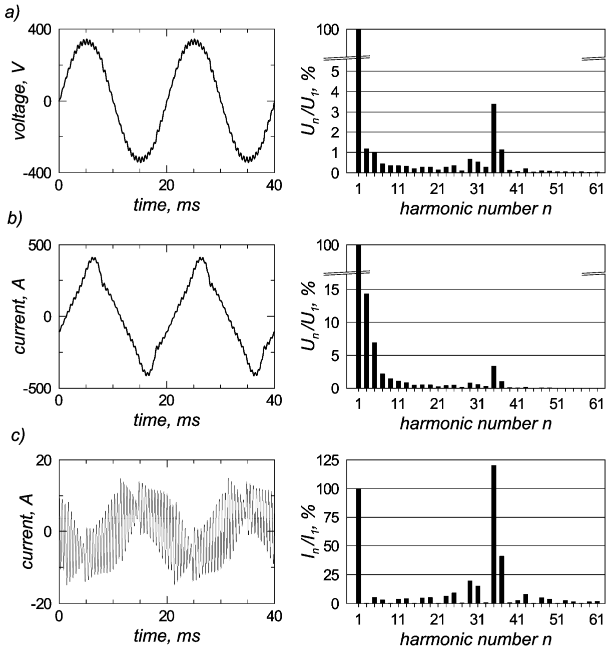

Fig. 3. Plots of voltages, currents and their frequency spectra for transformer's maximum load 250 kVA and power of capacitor banks Q_C = 1 p.u.: a) feeding voltage, b) current of transformer's secondary side, c) current in capacitor

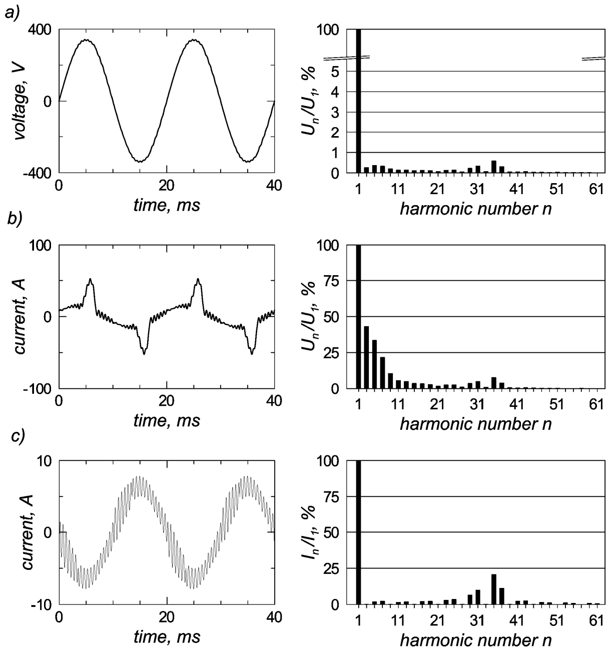

Fig. 4. Plots of voltages, currents and their frequency spectra for transformer's minimum load 250 kVA and power of capacitor banks Q_C = 1 p.u.: a) feeding voltage, b) current of transformer's secondary side, c) current in capacitor

One of them is the possibility of considerable (over 8%) distortion of the feeding voltage (fig. 6a). This happens when considerable overcompensation takes place, for a capacitor bank power Q_C = 8 p.u. for transformers of 100 kVA and 630 kVA, and Q_C = 10 p.u. for transformer of 250 kVA. It should be noted that the voltage distortion gets smoothed, when the power of the capacitor bank is still increased.

Another problem lies in increasing the current distortion on transformer's secondary side (rys. 6b) as a result of applied compensation. Further consequences lie in the increase of additional losses (fig. 6c) and load losses (fig. 6d), frequently leading to a significant losses increase in the transformer itself, even at Q_C = 1 p.u. (fig. 6e). These losses contribute to poorer efficiency of compensation in the presence of nonlinear loads.

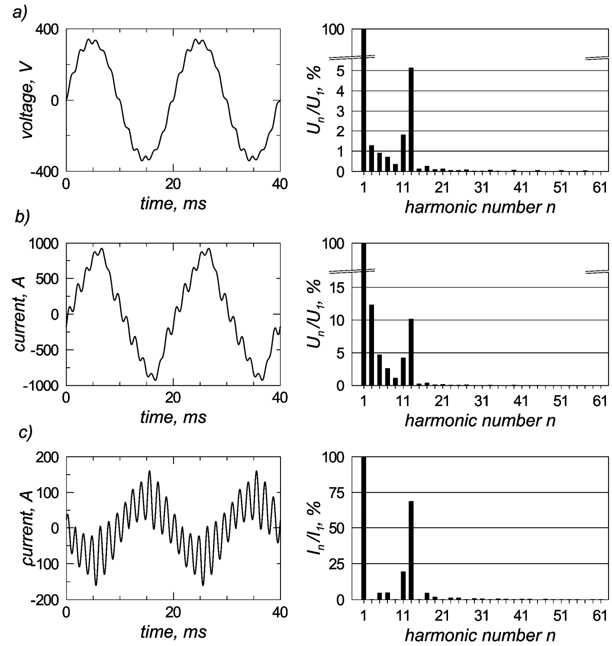

Fig. 5 Plots of voltages, currents and their frequency spectra for transformer's maximum load 630 kVA and power of capacitor banks Q_C = 6 p.u.: a) feeding voltage, b) current of transformer's secondary side, c) current in capacitor

Another factor is the possible current overloading of capacitors. Having assumed that the admissible current overloading equals to 130% of rated current I_n, the capacitor bank of Q_C = 1 p.u. can be damaged in the case of transformers of 250 kVA and 630 kVA (fig. 6f). It should be noted that overcompensation is advantageous here as it contributes to the lowering of compensator's overloading.

Conclusions

The capacitor banks for reactive power compensation in nonlinear load conditions are connected with the occurrence of a number of negative phenomena. However, no detailed or uniform criteria for the selection of capacitor banks for this type of work can be given. Nonetheless care should be taken when talking about reactive power compensation in places where considerable quantities of distorted power are expected. In such situations the calculation analysis should account for the character of the nonlinear load and parameters of the feeding system. If the results of the analysis confirm that the capacitor bank is endangered, some remediation means can be considered or the concept of using capacitors abandoned. From the point of view of the installed capacitor bank exploitation, the control of the transformer's nonlinear load is significant to protect against the capacitors failure.

The analyses revealed that increasing the power of the capacitor bank power over Q_C = 1 p.u. may improve the conditions of capacitor bank's exploitation and smooth other negative effects. This is important owing to the fact that installing more powerful capacitor banks than the transformer's magnetizing rated power, has a positive influence on the efficiency of this type of reactive power compensation in medium voltage distribution substations. This issue, however, will be discussed in another paper.

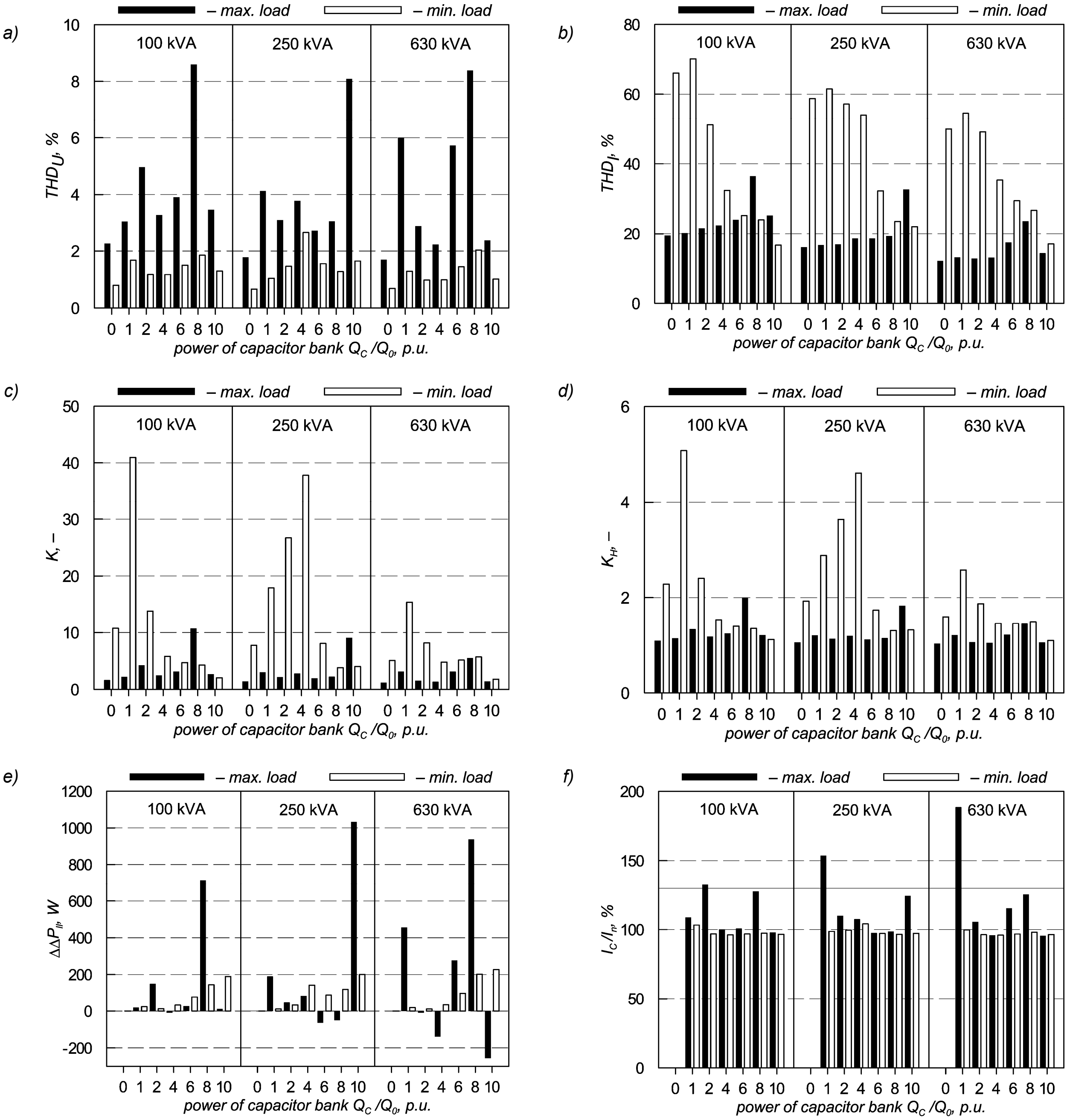

Fig. 6. Results of analysis of a time function: THD_U – coefficient THD of feeding voltage, THD_I – coefficient THD of transformer's secondary side, K – coefficient of additional losses increase in a transformer due to compensation, K_H – coefficient of load losses increase in a transformer due to compensation, $\Delta\Delta P_{ll}$ – change of load losses due to compensation, I_C/I_n – current of capacitor bank versus rated current

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