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Impact of changes in the impedance and frequency characteristics of certain network elements on the choice of method for passive filter design

***Abstract**. In this article, we discuss difficulties connected with the determination of the parameters of a single-tuned passive filter connected in parallel to a network that supplies power to devices with the impedance and frequency characteristics varying as a function of time or load. Devices of this type are exemplified by a capacitor bank whose steps are composed of capacitors connected in series with inductances. Based on the results of tests conducted at an industrial plant, we demonstrate the impact of a capacitor bank on the current and voltage harmonics in the power network. The harmonics should be taken into account when designing a passive filter. Considering that the operation of a capacitor bank may cause significant changes in voltage distortion, a passive filter designed without regard to such changes may not function properly.*

In the remaining part of the article, we present graphs of selected electrical values recorded at the industrial plant, followed by the simulation results, which confirm the phenomena observed during the test measurements. Our findings concern methods employed in the process of designing a passive filter to be used in a network that includes a capacitor bank. ***(Wpływ zmian charakterystyk impedancyjno-częstotliwościowych wybranych elementów sieci na wybór metody projektowania filtrów pasywnych)***

***Streszczenie.** W artykule przedstawiono problem związany z trudnością w określaniu parametrów rezonansowego filtra pasywnego włączonego równolegle do sieci, w której pracują urządzenia o charakterystyce impedancyjno-częstotliwościowej zmiennej w funkcji czasu lub obciążenia. Reprezentantem grupy wspomnianych urządzeń jest bateria kondensatorów w której stopnie złożone są z kondensatorów szeregowo połączonych z indukcyjnościami. Na przykładzie instalacji przebadanej w zakładzie przemysłowym wykazany zostanie wpływ baterii kondensatorów na wartości harmonicznych prądu i napięcia w sieci zasilającej zakład. Wartości te powinny być uwzględnianie przy projektowaniu filtra pasywnego. W rezultacie znaczących zmian odkształcenia napięcia, jakie może powodować praca baterii kondensatorów, filtr pasywny zaprojektowany bez uwzględnienia tych zmian może pracować nieprawidłowo. W dalszej części artykułu przedstawiono wykresy wybranych wielkości elektrycznych zarejestrowanych w zakładzie przemysłowym, a następnie wyniki symulacji potwierdzające zjawiska zaobserwowane podczas pomiarów. Wnioski dotyczą wybranych metod postępowania podczas projektowania filtra pasywnego w sieci, w której pracuje bateria kondensatorów.*

Keywords: the current and voltage harmonics, nonlinear loads, passive filters, capacitors bank.
Słowa kluczowe: wyższe harmoniczne, obciążenie nieliniowe, filtry pasywne, baterie kondensatorów.

Introduction

Voltage distortions in electricity networks that supply power to non-linear loads are caused, among other things, by the flow of non-sinusoidal currents through the impedance of the power supply system. Loads such as DC drives, rectifiers, inverters, UPSs, servers, etc. draw currents not only at the fundamental frequency but also at harmonic frequencies. These currents cause voltage drops on the impedances of individual elements of the supply circuit in proportion to the impedance values for harmonic frequencies. Harmonic voltages are injected into all the loads powered by the network. This means that each device is fed at both the fundamental frequency and higher harmonics. As the impedances of individual loads as a function of frequency are different, there may appear circuits that attenuate, amplify or have no impact on the level of voltage distortion.

The supply voltage harmonics have an adverse effect on many devices, including transformers, cables, rotating machines, capacitor banks, computer equipment, and protection relays. Transformers, motors, switchgears, and cables may experience increased energy losses leading to an excessive rise in temperature. Induction motors may have problems starting or operating at hypersynchronous speeds. Circuit breakers may fail to interrupt the current due to the malfunctioning of magnetic and electronic triggers. Capacitors may prematurely deteriorate due to excessively loaded dielectric or even explode due to resonance. The time-current characteristics of fuses may change, and protection relays may malfunction, failing to protect the network from overload.

Most of the various methods used for reducing voltage distortions in power networks involve the reduction of harmonic currents on selected non-linear loads or groups of loads. These methods include:

- Use of power units with active current shaping;
- Increasing the impedance that couples the converter to the network;
- Use of a parallel higher-harmonic filter. This can be
  - a passive filter,
  - an active filter,
  - a hybrid filter.

Passive filters

In passive filters, only selected harmonics are filtered out. This follows from the design of the filter, where each LC element is usually responsible for the rejection of one or two adjacent harmonics. Besides eliminating higher harmonics from the power system, passive filters are a source of capacitive reactive power. For this reason, they are used in systems that require not only a reduction in current distortion but also an improvement of the power factor of the fundamental frequency.

Systems in which passive filters are to be installed should be characterized by a low level of load changes.

Active filters

Being controlled power converters, active filters compensate harmonics in a wide frequency range. They also enable a dynamic adaptation to the currently existing levels of harmonics in the filtered circuit.

In active filters, there is no risk of current resonance between individual elements of the filter, which makes them safer to operate than complex, multi-limbed passive filters.

The correct functioning of a properly designed active filter is possible for a wide range of network impedances and supply voltage distortions.

Hybrid filters

The two basic types of filters can be combined into a single device called a hybrid filter. This solution ensures increased efficiency and allows operation over a wide power range.

As we can see, each method for reducing distortions has its advantages and disadvantages.
Some of the disadvantages of passive filters are as follows:

- Their operating efficiency is strongly affected by the source impedance;
- Their operating efficiency is strongly affected by the network impedance;
- The possibility of inadvertent amplification of certain harmonics as a result of resonance between a parallel passive filter and network elements;
- Difficulties in achieving the optimum design of filter parameters for variable network loads;
- A high level of capacitive reactive power during operation.

However, their main advantages, such as:

- simple design;
- lower price than that of an active filter of a similar capacity;
- sufficiently efficient filtration of the selected harmonic

make them technically and economically viable in certain applications.

Network configuration

In many power systems used to feed non-linear and mixed loads, one needs not only to reduce voltage distortions by filtering out harmonics but also to compensate the reactive power of the fundamental frequency.

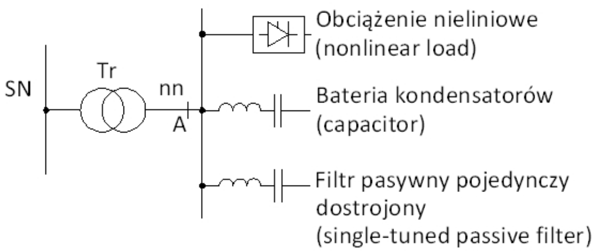


Fig. 1. Fragment of a power supply system

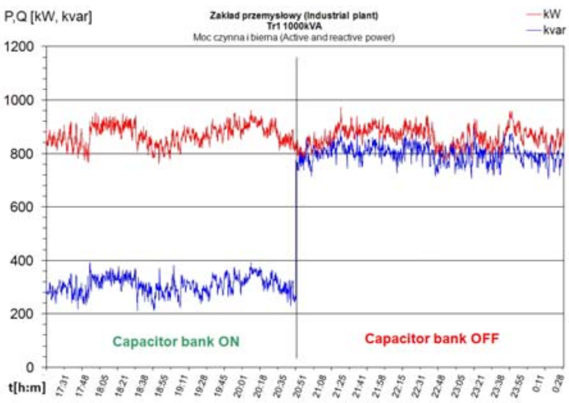


Fig. 2. Active and reactive power graphs with a reactive power compensation unit correspondingly off and on

The graph in Fig. 2 indicates a significant reduction in reactive power and, therefore, also in apparent power (Fig. 3) caused by the connection of a capacitor bank in order to compensate the fundamental reactive power. Apparent power is reduced to a value below the rated power of the transformer feeding the respective fragment of the network. After the reactive power compensation unit is disconnected, the apparent power drawn from the transformer will exceed the designed rated value of the transformer. If no overcurrent or overheat protection is installed or if the protection fails, the transformer will be damaged. In both cases, all loads fed from the transformer will be switched off. If the production process is continuous, its interruption will put the power consumer at risk of considerable financial losses.

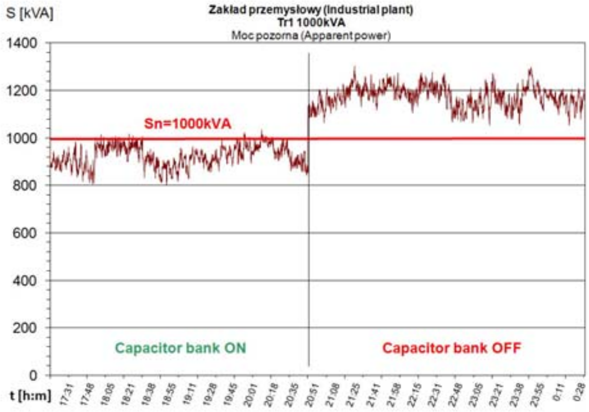


Fig. 3. Apparent power graph with a reactive power compensation unit correspondingly off and on

Problem

In the network system shown in Fig. 1, there is a need to compensate the fundamental reactive power, mainly in order to offload the transformer. Another reason is the need to maintain an appropriate power factor as required by the energy supplier. Aside from the compensation of the fundamental reactive power, it is also necessary to reduce the level of voltage harmonics e.g. by applying a passive filter that would filter out the selected harmonic.
When designing a passive filter for the power system shown in Fig. 1, we can make reference to the values measured in the linear field of the transformer (A).

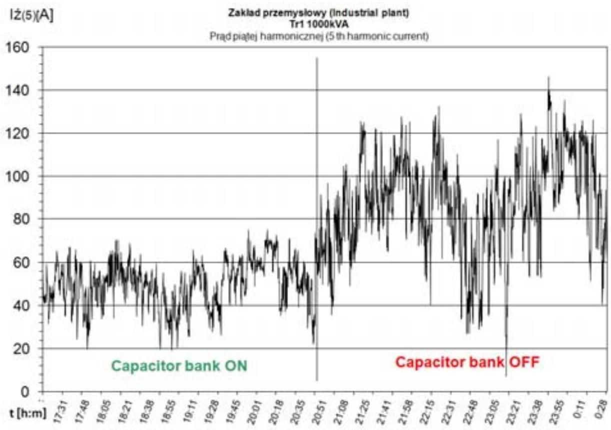


Fig. 4. Graph of a selected voltage harmonic measured at point A with a capacitor bank on and off

The network under consideration supplies power to multiple loads, whose impedances as a function of frequency are not known exactly, especially in view of the fact that in many cases impedance varies as a function of the load on power-consuming devices. The filtering parameters of a passive filter depend on the network impedance, which should be taken into account as accurately as possible. Due to the large number of small volatile loads, their resultant impedance cannot be easily mapped as a function of frequency. In the network, there is a capacitor tank that shifts the phase of the first harmonic current to a value required by the energy supplier. When working in a network with non-linear loads, a capacitor bank is usually equipped with serial inductances tuned to the capacitances of individual capacitor steps. Provided that the resonant frequency of a capacitor bank intended for use in industrial networks with three-phase loads has been selected properly, one can assume that the impedance of a capacitor bank for the 5th harmonic is inductive, and therefore does not significantly affect the value of this harmonic in the transformer and load current.

When conducting a conventional analysis of the 5th harmonic current in the linear field, as illustrated in the first half of Fig. 4, one would adopt the value of 60-70A for the purposes of filter design.

However, after the capacitor bank is disconnected (simulation of the 5th harmonic current in the second half of Fig. 4), one can observe a significant difference in the harmonic current in the linear field as compared to the previous state, when the capacitor bank was connected.

After the capacitor bank is disconnected, the harmonic current in the linear field increases by about 100%, which means that a passive filter designed for a current of 60-70A, characteristic of this network when the capacitor tank is on, would be overloaded also by about 100%.

After the disconnection of the capacitor bank, the filter would become overheated and its components would be damaged (Fig.5).

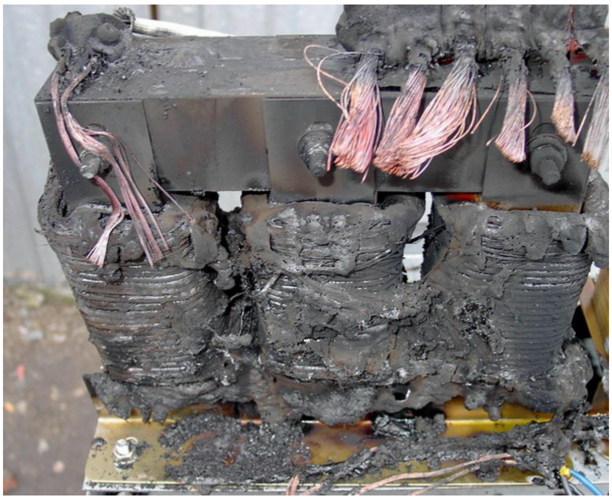
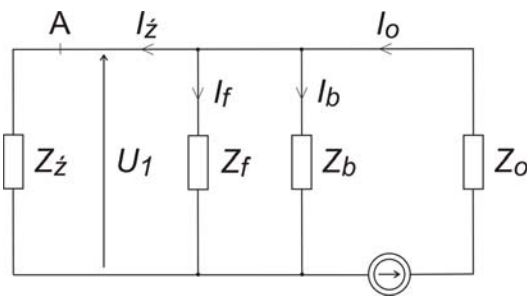


Fig. 5. Photograph of the choke of a passive filter damaged due to an overload caused by the incorrect design of the filter parameters

Dependencies

The harmonics of currents and voltages in a power system that includes a non-linear load, a harmonic filter, and a capacitor bank can be analysed using the model in Fig. 6.



where: $Z_ż$ – power source impedance, Z_f – filter impedance, Z_b – capacitor bank impedance, Z_o – current source impedance.

Fig. 6. Equivalent circuit of a power system for a selected harmonic

In this case, the non-linear load is modelled as the source of current for the selected harmonic. The voltage source, the capacitor bank, and the harmonic filter are modelled as impedance elements. The remaining loads are disregarded due to a very high impedance as compared with the impedance of the voltage source, capacitor bank, and harmonic filter. The harmonic currents in the passive filter, capacitor bank, current source, and the currents fed into the system can be expressed by the following equation:

(1) $$I_o(h) = I_b(h) + I_f(h) + I_ż(h),$$

where:
$I_o(h)$ – the effective (RMS) h-harmonic current produced by the load,
$I_b(h)$ – the effective (RMS) h-harmonic current passing through the capacitor bank,
$I_f(h)$ – the effective (RMS) h-harmonic current passing through the harmonic filter,
$I_ż(h)$ – the effective (RMS) h-harmonic current fed into the power source.

Individual h-harmonic impedances Zo(h), Zb(h), Zf(h), Zż(h) are calculated by the following formulas.

The h-harmonic source of current impedance:

(2) $$Z_o(h) = \sqrt{R_o{}^2 + j(X_{Lo}(h) - X_{Co}(h))^2}$$

The h-harmonic capacitor bank impedance:

(3) $$Z_b(h) = \sqrt{R_b{}^2 + j(X_{Lb}(h) - X_{Cb}(h))^2}$$

The h-harmonic filter impedance:

(4) $$Z_f(h) = \sqrt{R_f{}^2 + j(X_{Lf}(h) - X_{Cf}(h))^2}$$

The power source impedance can be calculated on the basis of the short-circuit conditions:

(5) $$Z_ż(h) = \frac{hcU_n^2}{Sk"},$$

where: U_n – rated voltage of the power supply network, *Sk"* – initial symmetrical short-circuit power, *c* – voltage factor, selected in accordance with Table 1, *h* – selected harmonic.

Table 1. Voltage factor c according to the PN-EN 60909-0:2002 standard specifications

Rated supply voltage U_n	Voltage factor *c* for the calculation of the maximum short-circuit minimum short-circuit current c_{max} [1)]	current c_{min}
Low voltages (100 to 1000 V)	1.05[3)] 1.10[4)]	0.95
Medium voltages (1 kV to 35 kV)	1.10	1.00
High voltages (35 kV to 230 kV[2)])	1.10	1.00

[1)] $c_{max} \cdot U_n$ may not exceed the maximum device voltage U_m;
[2)] If the rated supply voltage is not known, assume that $c_{max} \cdot U_n = U_m$
[3)] or $c_{mim} \cdot U_n = 0{,}9 \cdot U_m$.
[4)] For low voltages with a voltage range of +6%, e.g. for 380 or 400 V. For low voltages with a voltage range of +10%.

$X_C(h)$: capacitive reactance of the h-harmonic

(6) $$X_C(h) = \frac{1}{2\pi fCh}$$

$X_L(h)$: reactance of the h-harmonic for the choke L

(7) $$X_L(h) = 2\pi f L h$$

By reducing the impedance of the power source, capacitor bank, and harmonic filter shown in Fig. 1 to equivalent impedance, we get:

(8) $$\frac{1}{Z_{\dot{z}fb}(h)} = \frac{1}{Z_{\dot{z}}(h)} + \frac{1}{Z_f(h)} + \frac{1}{Z_b(h)}$$

By appropriately transforming the above equation, we get:

(9) $$Z_{\dot{z}fb}(h) = \frac{Z_{\dot{z}}(h)Z_f(h)Z_b(h)}{Z_f(h)Z_b(h) + Z_{\dot{z}}(h)Z_b(h) + Z_{\dot{z}}(h)Z_f(h)}$$

The equivalent h-harmonic impedance in the entire system will be calculated by the following formula:

(10)
$$Z_z(h) = Z_{\dot{z}fb}(h) + Z_o(h) = \frac{Z_{\dot{z}}(h)Z_f(h)Z_b(h)}{Z_f(h)Z_b(h) + Z_{\dot{z}}(h)Z_b(h) + Z_{\dot{z}}(h)Z_f(h)} + Z_o(h)$$

The h-harmonic voltage on the equivalent impedance of the entire system equals:

(11) $$U(h) = I_o(h)Z_z(h)$$

The h-harmonic voltage U_1 on the filter, capacitor tank, and the power source equals:

(12) $$U_1(h) = U(h) - U_o(h) = I_o(h)Z_z(h) - I_o(h)Z_o(h) = I_o(h)(Z_z(h) - Z_o(h)),$$

where:
$U_o(h)$ – h-harmonic voltage on the load.

The h-harmonic current passing through the capacitor bank equals:

(13)
$$I_b(h) = \frac{U_1}{Z_b} = \frac{I_o(h)(Z_z(h) - Z_o(h))}{Z_b} = \frac{I_o(h)\left(\frac{Z_{\dot{z}}(h)Z_f(h)Z_b(h)}{Z_f(h)Z_b(h) + Z_{\dot{z}}(h)Z_b(h) + Z_{\dot{z}}(h)Z_f(h)} + Z_o(h) - Z_o(h)\right)}{Z_b}$$

By inserting the impedance values of individual limbs into the above equation, we get:

$$I_b(h) = \frac{I_o(h)\left(\frac{\frac{hcU_n^2}{Sk''}\sqrt{(R_f^2 + (X_{Lf}h - X_{Cf}h)^2}\sqrt{(R_b^2 + (X_{Lb}h - X_{Cb}h)^2}}{\sqrt{(R_f^2 + (X_{Lf}h - X_{Cf}h)^2}\sqrt{(R_b^2 + (X_{Lb}h - X_{Cb}h)^2} + \frac{hcU_n^2}{Sk''}\sqrt{(R_b^2 + (X_{Lb}h - X_{Cb}h)^2} + \frac{hcU_n^2}{Sk''}\sqrt{(R_f^2 + (X_{Lf}h - X_{Cf}h)^2}}\right)}{\sqrt{(R_b^2 + (X_{Lb}h - X_{Cb}h)^2}}$$

$$I_b(h) = \frac{I_o(h)}{\sqrt{(R_b^2 + (X_{Lb}h - X_{Cb}h)^2}} \bullet$$
$$\left(\frac{\frac{hcU_n^2}{Sk''}\sqrt{(R_f^2 + (X_{Lf}h - X_{Cf}h)^2}\sqrt{(R_b^2 + (X_{Lb}h - X_{Cb}h)^2}}{\sqrt{(R_f^2 + (X_{Lf}h - X_{Cf}h)^2}\sqrt{(R_b^2 + (X_{Lb}h - X_{Cb}h)^2} + \frac{hcU_n^2}{Sk''}\left(\sqrt{(R_b^2 + (X_{Lb}h - X_{Cb}h)^2} + \sqrt{(R_f^2 + (X_{Lf}h - X_{Cf}h)^2}\right)}\right)$$
(15)

The h-harmonic current passing through the harmonic filter equals:

$$I_f(h) = \frac{I_o(h)}{\sqrt{(R_f^2 + (X_{Lf}h - X_{Cf}h)^2}} \bullet$$
$$\left(\frac{\frac{hcU_n^2}{Sk''}\sqrt{(R_f^2 + (X_{Lf}h - X_{Cf}h)^2}\sqrt{(R_b^2 + (X_{Lb}h - X_{Cb}h)^2}}{\sqrt{(R_f^2 + (X_{Lf}h - X_{Cf}h)^2}\sqrt{(R_b^2 + (X_{Lb}h - X_{Cb}h)^2} + \frac{hcU_n^2}{Sk''}\left(\sqrt{(R_b^2 + (X_{Lb}h - X_{Cb}h)^2} + \sqrt{(R_f^2 + (X_{Lf}h - X_{Cf}h)^2}\right)}\right)$$
(16)

Own tests of a capacitor bank

Serial inductances are used in capacitor banks in order to eliminate resonant interaction between the capacitor bank and a network in which harmonic injections are present. This design of capacitor banks is aimed at shaping their impedance as a function of frequency in such a way that, for any harmonics that may occur in the supply voltage, the impedance of the capacitor bank would be inductive. This principle is satisfied in most brand-new capacitor banks.

We have conducted own tests consisting in the measurement of the step of a capacitor bank with a reactive power of 80kvar (400V) connected in series to a three-phase core choke with an inductance of 1.34mH.

Test results:

Fig. 7. Photograph of one of the steps of an example new capacitor bank

Table 2. Measurements of a new capacitor bank with a 80kvar (400V) step in a circuit that includes a choke with an inductance of 1.34mH

Lp.	C1[μF]	C2[μF]	C3[μF]
1	529	530	529

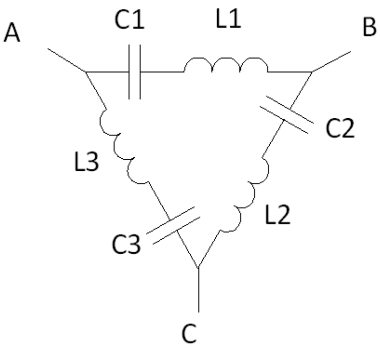


Fig. 8. Connection diagram of the tested capacitor bank and the choke

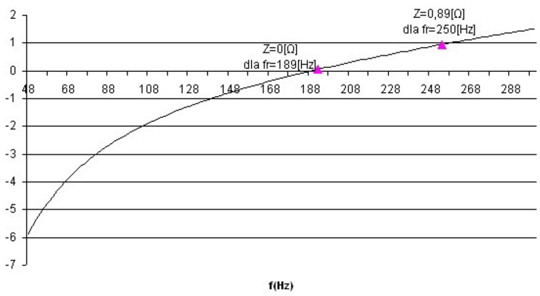


Fig. 9. Z (f) parameter for a 80kvar (400V) step of a brand-new capacitor bank

However, due to various reasons, including the wrong choice of capacitor bank elements and the increasingly inferior quality – caused by savings – of newly introduced types of capacitors and chokes as compared with those manufactured some years ago, it is harder to maintain the required stability of the frequency characteristics of a capacitor bank throughout its useful life. The photograph in Fig. 10 and the curve in Fig. 11 illustrate the parameters of components of a sample capacitor bank after five years of operation. The visible bulge in the shell of the right-hand capacitor in the photograph indicates that the capacitor is damaged, while singes on all the elements point to an explosion of a capacitor from an adjacent step.

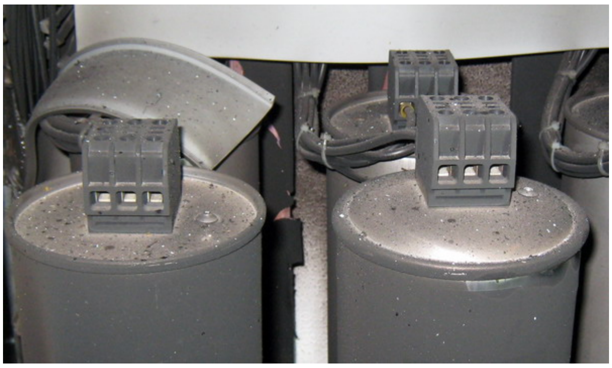


Fig. 10. Photograph of an example capacitor bank step after 5 years of operation

Table 3. Measurements of an old capacitor bank with a 80kvar (400V) step after five years of operation in a circuit that includes a choke with an inductance of 1.34mH

Lp.	C1[μF]	C2[μF]	C3[μF]
1	315	314	315

As follows from the measurements in Table 3, the capacities of the capacitors are lower than their nominal values. After several years of operation, the resonant frequency of the LC step of the capacitor bank increased to 245Hz, which is dangerously close to the 5th harmonic frequency. An increase in the capacitor bank current caused by an inadvertent tuning of its step to a harmonic frequency may result in an overload and damage of the capacitor bank or even in its explosion.

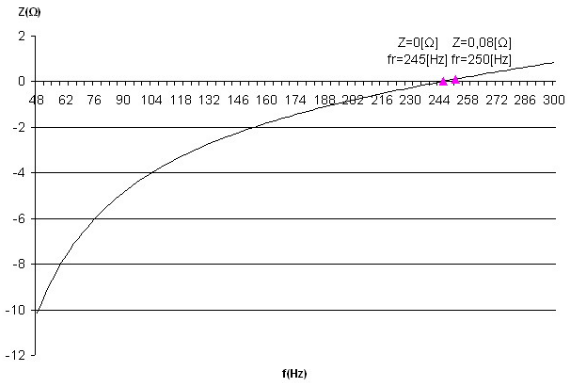


Fig. 11. Z(f) parameter for a 80kvar (400V) step of an old capacitor bank

An analysis of the impedance curve of a new capacitor bank *versus* a worn-out one reveals a shift of the resonance point toward higher frequencies. The result is a significant increase of the harmonic current in the frequency range for which the step of the capacitor bank has inadvertently reached a capacitive impedance. This usually leads to a failure of the step, often accompanies by an explosion of the entire device and a fire.

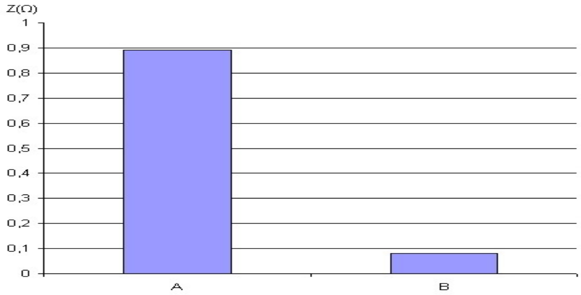


Fig. 12. Comparison graph of 5th harmonic impedance of a new (A) and worn-out (B) step of a capacitor bank

Results of simulation of currents in a capacitor bank and a passive filter

The equivalent circuit in Fig. 3 has been used to prepare a comparison (simulation) of currents in a new and a worn-out capacitor bank for the 1st and 5th harmonics.

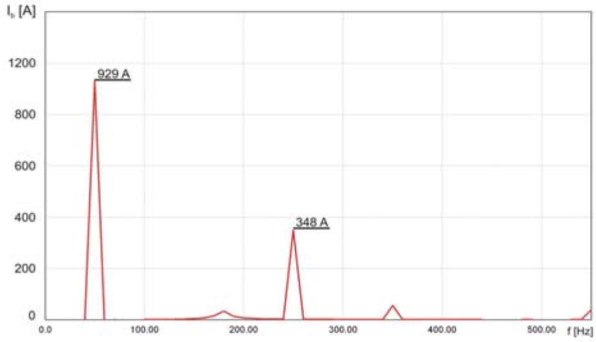


Fig. 13. Simulation of the 1st and 5th harmonic currents in a new capacitor bank

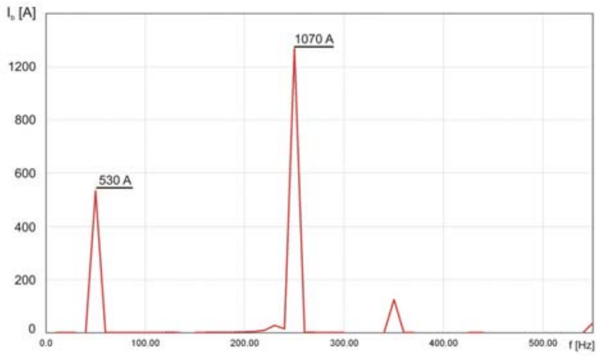


Fig. 14. Simulation of the 1st and 5th harmonic currents in a worn-out capacitor bank

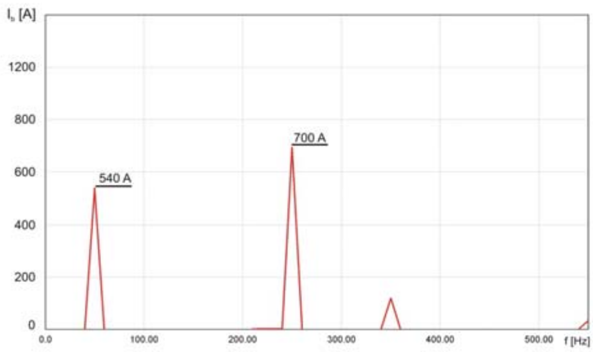


Fig.15. Current I_F in a passive 5th harmonic filter for the 1st and 5th harmonics (simulation) with a worn-out capacitor bank connected to the network

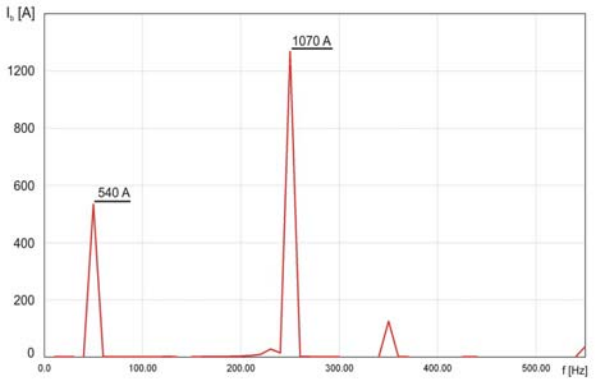


Fig.16. Current I_F in a passive 5th harmonic filter for the 1st and 5th harmonics (simulation) with a worn-out capacitor bank disconnected from the network

The equivalent circuit in Fig. 6 has been used to prepare a comparison (by means of simulation) of the 1st and 5th harmonic currents in a passive filter, with a worn-out capacitor bank on and off.

Problem-solving methods

One can distinguish two groups of methods for solving the problem of the passive filter design in selected parts of a network: non-invasive as opposed to invasive.

Non-invasive methods involve a purely computational determination of the distribution of distorted currents and voltages. They require a lot of data concerning the power supply system in its operating state. Among other things, one must know the impedance of the power system and the transformer, the power frequency characteristics of the capacitor bank, and the impedances of all the major loads for individual frequencies.

Non-invasive methods are based on the theoretical frequency characteristics of the network and power system elements. As such, they cannot take into account either primary or secondary changes in these characteristics. Among primary changes, we include the manufacturing tolerances of chokes and capacitors, the inductance of converters, and the power line parameters. Secondary changes include changes in the above parameters that occur during service life as well as changes resulting from differences in loads, which, as has been argued earlier on, are significant for the correct determination of the resultant network impedance as a function of frequency.

An invasive method will require that measurements and tests of the power system be conducted prior to calculations. This method is aimed at taking into account the characteristics of both the network and its loads through the use of measurement data obtained during tests.

Summary

There are many methods for calculating the distribution of harmonic currents and higher-frequency voltage drops on individual elements of a power supply system. However, in order for these methods to provide reliable results for actual networks, numerous conditions must be met. For example, one needs to know the impedances and frequency characteristics of the network, transformer, and major loads. In order to apply non-invasive methods (i.e. methods based solely on calculation), one must know the impedance characteristics as a function of frequency for all the system elements. These, however, have not yet been conclusively determined for each network element, especially considering the degree of changes in frequency characteristics as a function of load.

Invasive methods eliminate most of the uncertainties with respect to the frequency characteristics of network elements, because thanks to direct measurements and waveform recordings the impedance of many of the elements for harmonic frequencies can be determined with a much greater accuracy. Crucially, this provides the possibility of detecting significant changes in the impedance characteristics of many of the network elements compared to their theoretical parameters or parameters specified by the manufacturer. An example of such an element is a capacitor bank, whose operating parameters undergo significant changes over time. These changes affect both the capacity and the resultant resonance frequencies of the capacitors. When employed to design passive filters, purely computational methods cannot ensure an accurate determination of individual current harmonics in the filter, since they do not take into account the actual impedance and frequency characteristics of the important elements connected to the same network.

Findings

When setting out to design a passive filter of higher harmonics to be used in a power network, one cannot confine oneself to purely computational methods of analysis based on the catalogue values of impedance as a function of frequency for individual elements of the network. While computational methods provide satisfactory results for the static states of networks containing elements with known parameters, their results for dynamic states, for networks that are already in operation diverge from data obtained by invasive methods.

Invasive methods ensure a more accurate determination of the impedance characteristics of network elements, especially in the case of devices that have been in operation for some time already, and whose parameters differ from the parameters of brand-new equipment. The capacitor bank we have examined is a classic example of such a network element. After five years of operation, its impedance for the 5th harmonic decreased almost tenfold. As a consequence, the harmonic current passing through the capacitor bank increased by several times.

A failure to take these findings into considerations leads to an incorrect calculation of the flow of harmonic currents between the passive filter, the power source, the capacitor bank, and the remaining elements of the power system.

This in turn results in an erroneous calculation of the expected values of currents in passive filters. An underestimation of currents when designing a filter may lead to its overload during operation. In the case of passive filters, overloading is particularly dangerous due to their low tolerance to increases in current. This property of passive filters follows from the small overload reserve of capacitors and from the magnetic system parameters of the series inductance of filters.

Conclusion

In the process of designing passive filters, one has to take into consideration capacitor banks, since they are used in most power systems and significantly affect the distribution of harmonic currents in individual elements of the system. After several years of operation, the parameters of capacitor banks differ substantially from the initial parameters of a brand-new capacitor bank, which results in changes in the distribution of harmonic currents both in the capacitor banks themselves and in passive filters. This also means changes in the dependencies assumed for the design of passive filters. A calculation of the parameters of a passive filter based on measurement data and on records of selected values in the actual power system enables one to take into account the currently existing frequency characteristics of many of the network elements. As follows from the case described above, this method of calculation should be used, among others, to determine the effect of capacitor banks on the distribution of higher harmonic currents.

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