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Particularities of Capacitor Bank Overstressing within Detuned Filters

***Abstract**. Detuned filters are frequently used for reactive power compensation in electrical distribution network harmonically polluted. These kinds of filters are series LC circuits formed by filtering inductors and capacitors. The filtering inductor decrease the harmonic voltage at the terminals of the capacitor within the filter, but the value of the fundamental voltage at the terminals of the capacitor will increase. The paper presents a comparative study for two values of tuning frequencies used by the manufacturers of detuned filters.*

***Streszczenie.** Rozstrojone filtry są często używane do kompensacji mocy biernej. Indukcyjności filtru zmniejszają liczbę harmonicznych ale wartość składowej podstawowej napięcia wzrasta na pojemnościach. W artykule analizuje się filtr przy dwóch częstotliwościach strojenia. (**Szczególne cechy przeciążenia pojemności w rozstrojonych filtrach**)*

Keywords: electrical distribution networks, capacitor bank, filtering inductor, detuned filters, harmonic impedance.
Słowa kluczowe: bateria kondensatorów, filtr rozstrojony, iompedancja

Introduction

In the last few years there has been an increase of nonlinear loads in power systems with the development of power electronics. However, all the nonlinear characteristics introduce harmonics.

The harmonic problems caused from the power electronic equipment have become significant: overloading and excessive heating and failure of various electrical equipment, undesired tripping of circuit protections, erroneous operation of control system components, damage of sensitive electronic equipment, and electromagnetic inferences in communication systems. Therefore, the methods for resonant harmonic filter design and optimization becomes very important and major efforts have been focused on in last time [1, 2, 3]. In [4] are proposed different methods for calculating harmonics in measurements obtained from offshore wind farms.

Both active and passive filters can be used to eliminate harmonic currents. However, passive filters are still a better choice for users considering the cost.

Power factor correction is done, in most of the cases, like shunt capacitive compensation both in the utility network and in the consumer network. But for the networks harmonically polluted, parallel resonances can occur due to resonance frequency of the inductance of the network and the capacitance of the compensation capacitor bank. The resonance can conduce to an amplification of existing harmonic conditions by the amplification of equivalent network harmonic impedance. Damages of capacitor banks can occur when the current is 30 % higher than rated current and voltage is 10% higher than rated voltage, as capacitor manufacturers indicate.

In order to avoid this resonance; a filtering reactor must be connected between the network and the compensation capacitor bank. This reactor has to be designed so that the filter reduces the harmonics, but supply the same reactive power on fundamental frequency. This filter is known like detuned filter. The capacitance of capacitor bank is selected to improve the power factor to a certain level, and the inductance of the reactor is calculated so that the tuning frequency of series circuit formed with capacitor bank is lower than the lowest frequency of harmonic currents flowing in the network (usually the 5^{th}).

Depending on the harmonic spectrum, the resonance frequencies for detuned filters designed by the manufacturers are usually: 136 Hz, 177 Hz, 189 Hz, 204 Hz and 215 Hz.

Is already explained in [5] how these frequencies are accomplished using reactors with values for short-circuit voltages of certain percentage at the fundamental frequencies.

In [6] a detuned filter having the resonance frequency of 228 Hz is used to control the line current harmonics and the input power factor of HVDC power supplies.

The value of the resonance frequency of the detuned filter plays an important role not only on the harmonic spectrum of the network, but also on the value of the fundamental voltage across the capacitor terminals within the filter. More the resonance frequency of the detuned filter is lower; more the fundamental voltage across the capacitor terminals is higher.

A mathematical model to calculate the fundamental voltage across the capacitor terminals depending on the value of the fundamental voltage in the network bus and the value of resonance frequency of the filter is presented in the paper.

The paper presents also a comparative study regarding the value of the fundamental voltage across the terminals of the capacitor within detuned filters for two cases of resonant frequency: 189 Hz and 215 Hz. The idea of this comparative study was proposed by the authors after a discussion with the representatives of a large consumer which reported frequently damages of capacitor banks within detuned filters.

Monitoring values for rms voltage in the bus where the filters are installer are presented and simulations for two different resonances frequencies of the filters were done.

Amplification of network harmonic impedance

As is known, as defined in [7], the network harmonic impedance is actually the variation in terms of frequency of the direct sequence component of the impedance seen in a section of that network, section usually considered the point of common coupling (PCC) between the distribution network and the network of a consumer.

In the case of electrical networks harmonically polluted the shunt reactive power compensation must be done with care in order to avoid the amplification of harmonic impedance above certain levels considered dangerous for the compensation capacitor bank or others devices of the network. The harmonic impedance level in a bus depends on the architecture of the network, comprising all the elements: generators, lines, transformers, loads, capacitor banks. The value of harmonic impedance in the compensation bus must be correlated with the existing harmonic conditions in the network (harmonic voltages and currents) because the harmonic impedance amplification conduces to harmonic conditions amplification.

Figure 1 presents an example of harmonic impedance amplification for the cases when the reactive power shunt compensation is done using capacitors (shape b)), and when the compensation is done using detuned filters (shape c)).

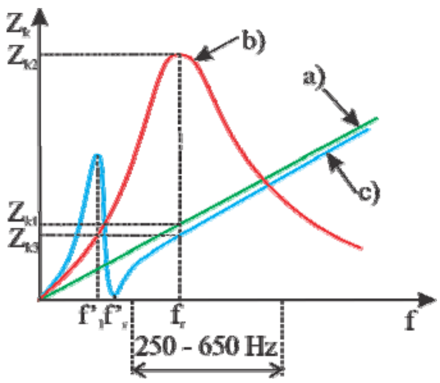


Fig.1. The equivalent harmonic impedance of the distribution network: a) before the compensation; b) compensation using capacitor bank; c) compensation using detuned filter.

The values of the harmonic impedance in the coupling point of the load after the installation of the detuned reactor (Z_{k3}), for values of frequency equal to the frequency of harmonic currents usually present in the network (250–650 Hz), are much lower than in the absence of the reactor (Z_{k2}) and even lower than in the absence of compensation capacitor (Z_{k1}). Maximum harmonic impedance is obtained for a frequency (f'_1) close to the resonance frequency of the detuned filter (f'_r), slightly smaller than this, so outside of the critical area (Figure 1).

The behaviour of the detuned filter is capacitive below its resonance frequency, so, at the fundamental frequency it produces reactive power for power factor correction. Above the resonance frequency, the behaviour of the filter is inductive, so it can't amplifies the existing harmonic conditions.

Voltage determination across the capacitor terminals

In Figure 2 is presented a single phase schema for the detuned filter installed for harmonic distortion mitigation formed by the capacitance C_k and the inductance L_k.

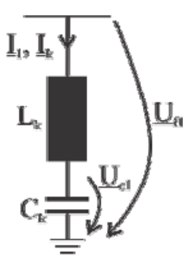


Fig.2. Single phase schema of detuned filter.

Using the following notations:
Q_{f1} – the reactive power necessary for compensation at the fundamental frequency;
C_1 – the capacitance corresponding to the equivalent capacitive reactance of the filter (comprising the capacitor and the reactor) on the fundamental frequency;
Xc_1 – the equivalent capacitive reactance of the filter (comprising the capacitor and the reactor) on the fundamental frequency;
Bc_1 – the equivalent susceptance on the fundamental frequency; it can be determined:

(1) $$Q_{f1} = \frac{U_{f1}^2}{X_{c1}} = B_{c1} \cdot U_{f1}^2 = \omega_1 \cdot C_1 \cdot U_{f1}^2$$

where U_{f1} is the phase voltage of the network for the fundamental frequency, applied to the filter, and ω_1 the fundamental pulsation. It follows:

(2) $$C_1 = \frac{Q_{f1}}{\omega_1 \cdot U_{f1}^2}$$

The two expressions for the equivalent capacitive reactance for the fundamental frequency are equal:

(3) $$X_{c1} = \frac{1}{\omega_1 \cdot C_1} = \frac{1}{\omega_1 \cdot C_k} - \omega_1 \cdot L_k$$

or:

(3') $$\frac{1}{\omega_1 \cdot C_1} = \frac{1}{\omega_1 \cdot C_k} \cdot \left(1 - \omega_1^2 \cdot L_k \cdot C_k\right)$$

and it follows:

(4) $$C_1 = C_k \cdot \frac{1}{1 - \omega_1^2 \cdot L_k \cdot C_k}$$

Using the resonance condition:

(5) $$L_k \cdot C_k = \frac{1}{\omega_k^2}$$

is obtained:

(6) $$C_1 = \frac{C_k}{1 - \frac{\omega_1^2}{\omega_k^2}}$$

respectively:

(7) $$C_k = C_1 \cdot \left(1 - \frac{\omega_1^2}{\omega_k^2}\right)$$

Pulsations ratio is equal to harmonic range ratio:

(8) $$\frac{\omega_1}{\omega_k} = \frac{2 \cdot \pi \cdot f}{2 \cdot \pi \cdot k \cdot f} = \frac{1}{k}$$

It follows:

(9) $$C_1 = C_k \cdot \frac{k^2}{k^2 - 1}$$

respectively:

(10) $$C_k = C_1 \cdot \frac{k^2 - 1}{k^2}$$

Using (3), the voltage drop on the capacitor, Uc_1, can be written depending on C_k:

(11) $$U_{c1} = I_1 \cdot X_{1k} = \frac{I_1}{\omega_1 \cdot C_k}$$

where X_{1k} is the capacitive reactance, on the fundamental frequency, corresponding to the capacitor C_k within the filter.

Expressing now the current on the fundamental frequency, due to the equivalent capacitance of the filter (comprising the capacitor and the reactor) C_1, under the fundamental phase voltage U_{f1}:

(12) $$I_1 = \frac{U_{f1}}{X_1} = \omega_1 \cdot C_1 \cdot U_{f1} = \omega_1 \cdot C_k \cdot \frac{k^2}{k^2 - 1} \cdot U_{f1}$$

And replacing it in the expression (11) is obtained:

(13) $$U_{c1} = U_{f1} \cdot \frac{k^2}{k^2 - 1}$$

Thus, more the resonance frequency of the detuned filter is lower; more the fundamental voltage across the capacitor terminals is higher.

Case study

A. Field monitoring values for fundamental voltage

A large consumer reported frequently damages of capacitor banks within detuned filters. This consumer contains large loads, about hundred of kW, that are turned on and off suddenly. When such a large load turns off, the voltage on the bus where it's supplied increase. At that moment the detuned filters are still connected in order to ensure the power factor correction, and this is a second source of voltage increase until the automatic devices switch off several steps of the filter. So, for a very short time the values for the fundamental voltage can increase significantly. In Figure 3 are presented the values of the voltage recorded in the bus where detuned filters with resonance frequency of 189 Hz are installed. These values of the voltage are recorded across the filter, but across the terminals of the capacitor bank within the filter, the fundamental voltage is slightly higher which can be a cause of the damages of the capacitor banks.

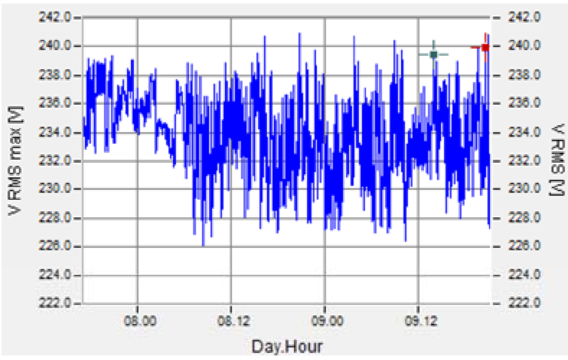


Fig.3. The rms values of the voltage recorded in a bus of a real network.

B. Simulations results for the voltage across capacitor terminals

The electrical network presented in Figure 4 was modelled using MatLab Simulink. For a better simulation of real operating conditions, the detuned filters which are used also for power factor correction are connected to the network in different operating conditions – Table 1.

For the operating conditions described, the detuned filter was successively designed for the resonance frequencies of 189Hz, respectively 215Hz.

Table 1. The operating conditions for the considered network

Regime		P[kW]	Q[kVar]	Q_{filter} [kVar]
1	a	900	700	400
	b	750	600	400
2	a	600	450	200
	b	350	200	200
3	a	550	400	350
	b	400	300	350
4	a	200	150	100
	b	130	100	100
5	a	200	150	400
	b	200	100	400
6	a	150	80	350
	b	100	50	350

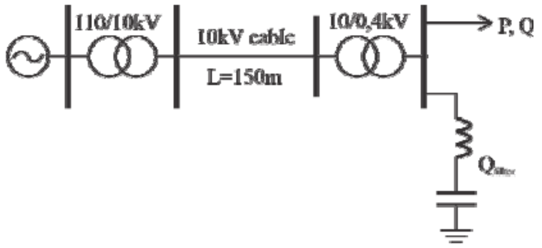
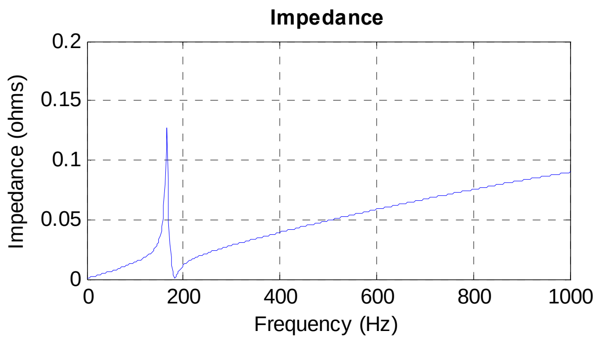
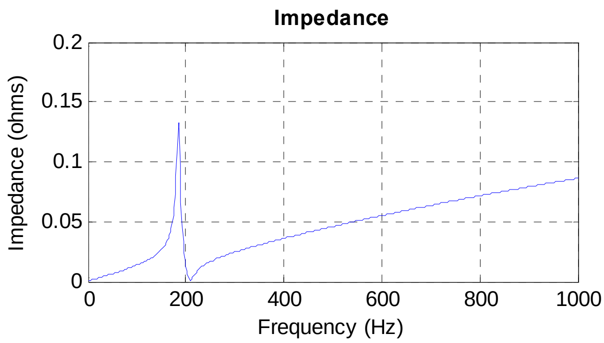


Fig.4. The electrical schema of the modelled network.



a)



b)

Fig.5. The harmonic impedance of the filter seen in the bus for the two tuning frequencies of the filter: a) 189Hz; b) 215Hz.

Table 2. The voltage values in the network bus and across the capacitor terminals

Regime		U_{bus}		U_{cb}	
		189 Hz	215 Hz	189 Hz	215 Hz
1	a	230.9	230.8	249.7	244.8
	b	232.1	232	251	246.1
2	a	231.7	231.7	250.6	245.7
	b	234.5	234.4	253.5	248.6
3	a	233.8	233.7	252.8	247.9
	b	235	234.9	254.1	249.2
4	a	234.1	234.1	253.2	248.3
	b	234.7	234.7	253.8	248.9
5	a	237.3	237.2	256.6	251.6
	b	237.8	237.7	257.1	252.1
6	a	237.5	237.4	256.8	251.8
	b	237.9	237.8	257.2	252.2

Figure 5 presents comparatively the equivalent harmonic impedance of the network obtained using MatLab Simulink for the two cases: a) 189 Hz, b) 215 Hz.

The voltages recorded across the capacitor terminals are presented in Table 2. There is an overvoltage across the terminals of the capacitors within the detuned filter. This overvoltage is higher for lower resonance frequencies of the filter. In most of the cases presented in Table 2 the values of the voltages across the terminals of the capacitor within the detuned filter of 189 Hz exceed the accepted value recommended by the manufacturers which is 253 V for low voltage level (10% increase of rated voltage).

To better highlight the phenomena of increase voltage across the terminals of the capacitor within detuned filters, the results presented in Table 2 are graphical represented in Figure 6.

An alternative solution for power factor correction under nonsinusoidal conditions is SVC (Static VAr Compensator) comprising capacitors and TCR (Thyristor Controlled Reactor).

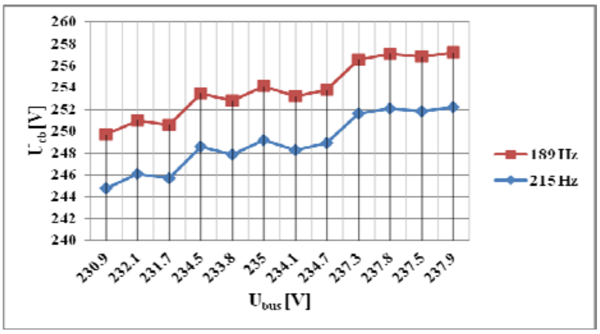


Fig.6. The increase of fundamental voltage across the terminals of the capacitor against the bus voltage for the two studied resonances frequencies of the detuned filter.

Conclusions

The installation of the capacitor bank for shunt reactive power compensation has like negative effect an amplification of the equivalent harmonic impedance of the network for the frequencies close to the resonance frequency. If in the network there are harmonic currents flows on these frequencies, amplification of both harmonic voltages and currents will be produced.

In addition to reducing harmonic voltage across the terminals of capacitors, filtering inductors decrease the overstressing current of the capacitor by the rejection of harmonic currents.

The main disadvantage of detuned filters is the overvoltage on fundamental frequency across the terminals of the capacitors.

The manufacturers of detuned filters propose several resonance frequencies for these filters. The value of the resonance frequency of the detuned filters plays an important role not only on the harmonic spectrum of the network, but also on the value of the fundamental voltage across the capacitor terminals within the filter. More the resonance frequency of the detuned filter is lower; more the fundamental voltage across the capacitor terminals is higher.

An alternative solution for power factor correction under nonsinusoidal conditions is SVC (Static VArCompensator) comprising capacitors and TCR (Thyristor Controlled Reactor).

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