ZESZYTY NAUKOWE POLITECHNIKI ŚLĄSKIEJ 2000
Seria: ELEKTRYKA z. 171 Nr kol. 1466

Josef LAPČÍK
Departament of Power Electrical and Electronic Engineering
Technical University of Brno

HARMONIC COMPENSATION

Summary. In the paper the problem of switching on the single and multiple capacitor banks is presented, followed by harmonic compensation problems. The role of the power factor correction capacitor banks of a number of switched sections is described, which allows a free flow of harmonics current to circulate between the harmonic source and the filter bank, while practically eliminating these currents and voltages from the rest of the network.

KOMPENSACJA HARMONICZNYCH

Streszczenie. W artykule przedstawiono zagadnienia załączania jedno- i wielosekcyjnej baterii kondensatorów powiązane z problemami kompensacji wyższych harmonicznych. Opisano rolę wielosekcyjnej baterii kondensatorów służącej do poprawy współczynnika mocy umożliwiającej swobodny przepływ prądów wyższych harmonicznych pomiędzy ich źródłem a układem filtrów, praktycznie eliminując te prądy i napięcia z pozostałej części sieci.

1. INTRODUCTION

1.1. Electrical switch-on phenomena

Switching-on a bank of capacitors which is connected in parallel to the network causes transient phenomena resulting from bank charging.

As far as the current is concerned, the oscillating load provokes an overcurrent with an amplitude which is a function of the network and bank characteristics.

At the point of consideration, switching on is equivalent in practical terms to the setting up of a short circuit with short duration.

From the voltage side, the load is followed by the propagation of a shock wave. These transient phenomena depend on network characteristics and on the timing of contact closing or prestrike.

There are two possible cases: a single bank and a bank divided into several capacitors to be switched independently to the supply system.

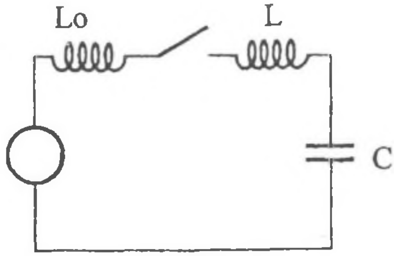


Fig.1 Switching on capacitor circuit
Rys. 1. Załączanie obwodu pojemnościowego

1.2. Single capacitor banks

We will suppose the circuit connection where L ≤ Lo (see fig.1), so that L is thus ignored with respect to Lo in the following calculations.

The switching-on of an isolated bank in a network (wiring diagram with current and voltage curves showing the inrush current and the overvoltages on supply side and load side which follow closing) is shown in Fig. 2.

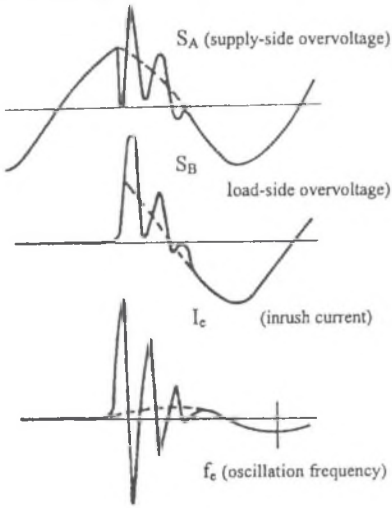


Fig. 2. Switching on simple capacitor bank.
Rys. 2. Załączanie prostej baterii kondensatorów

The inherent oscillation frequency is

$$f_e = \frac{1}{2\pi\sqrt{L_o C}}.$$

The overvoltages supply side and load side are equal to: $S_A = S_B = 2$ p.u.

The closing peak current is given by:

$$I_e = \frac{U\sqrt{2}}{\sqrt{3}}\sqrt{\frac{C}{L_o}} = I_{capa}\sqrt{2}\sqrt{\frac{S_{cc}}{Q}}$$

Scc: short circuit power of the source in MV·A at the connection point
Q: capacitor power rating in Mvar.

1.3. Multiple capacitor banks

We will only consider the case of identical bank units.

L_0: source inductance
l: series link inductance
n: number of steps operating when the n+1th is closed.

The switch-on of one step, made with on line charged capacitors, provokes two superimposed transient phenomena. The first very fast in frequency

$$\frac{1}{2\pi \;\; lC}$$

corresponds to the discharge of the connected capacitor; the second with the slower frequency

$$\frac{1}{2\pi\sqrt{L_o C}}$$

very negligible in relation with to the other (Lo much higher than l) corresponds to the discharge of all the bank units into the network, equalizing the bank potential.

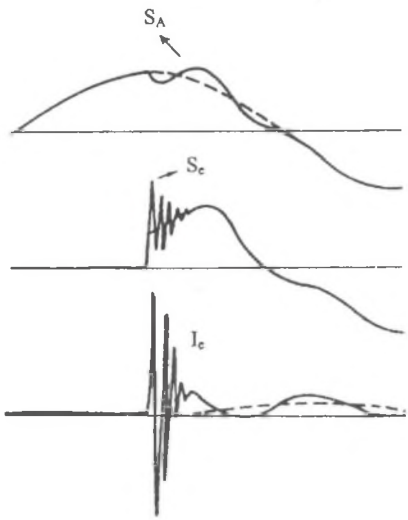


Fig.3. Switch-on of the multiple capacitor bank
Rys. 3. Załączanie wielostopniowej baterii kondensatorów

The switch-on of the n+1th bank of a multiple bank (schematic diagram and current and voltage curves showing inrush current, overvoltages appearing at the switch-on by distinguishing both phenomena) is shown in figure 3.

It should be noted that the overvoltage propagated on the network S_A decreases as the number of banks units in service increases. On the other hand, the inrush current is higher since the number of units is higher.

$$I_e = \frac{n}{n+1}\frac{U\sqrt{2}}{\sqrt{3}}\sqrt{\frac{C}{l}} = I_{capa}\sqrt{2}\frac{n}{n+1}\cdot\frac{f_e}{f}.$$

Inherent oscillation frequency

$$f_e = \frac{1}{2\pi\sqrt{lC}}.$$

Supply side overvoltage:

$$S_A = \frac{2n}{n+1}\ p.u.$$

Capacitor side overvoltage:

$$S_A = \frac{n+2}{n+1}\ p.u.$$

These overvoltages **never exceed** twice the network voltage and generally do not cause problems, all the units being constructed to tolerate this level. On the other hand, the **inrush currents** require appropriate methods to avoid damage to the capacitors and the switchgear.

2. COMPENSATION ON THE TERMINAL OF AN INDUCTION MOTORS

2.1. General

The power factor of a motor is very low at no-load and light load. The reactive current of the motor in such circumstances is small, since the kW consumption is also small, but a number of unloaded motors together constitute a big consumption of a reactive power.
Two good general rules therefore are that unloaded motors are should be switched off, and motors should not be oversized.

It is recommended that **special motors** (stepping, plugging, inching, reversing motors, etc.) should not be compensated.

After applying compensation to a motor, the current to the motor-capacitor combination will be lower than before, assuming the same motor-drive load conditions.

Where the overcurrent protection devices of the motor are located upstream of the motor and capacitor connection, the overcurrent relay setting must be reduced in the ratio: cosφ before compensation/cosφ after comp.

2.2. Self-excitation of an induction motor

When a motor is driving a high-inertia load, the motor without brake will continue to rotate, after the motor supply has been switch off. First one or two cycles after switching off the magnetic field of the rotor will generated emf in the stator windings for a short period and would normally reduce to zero in the case of an uncompen- sated motor.
Compensation capacitor however, constitute a 3-phase load for this decaying emf, which causes capacitive currents to flow through the stator windings. These stator currents will produce a rotating magnetic field in the rotor which acts exactly along the same axis and in the same direction as that of the decaying magnetic field. The almost 90 degrees lagging current taken from the supply in normal circumstances by the unloaded motor, and the almost 90 degrees leading current supplied to the capacitors by the motors acting like a generator, both have the same phase relationship to the terminal voltage.

The rotor flux consequently increases; the stator currents and the voltage at the terminals of the motor also increases (sometimes to dangerous level). This phenomenom is known as self-excitation.
In order to avoid self-excitation as described above, the kvar rating of the capacitor bank must be limited to the following maximum value(kvar): $Q_c \leq 0.9 I_o U_n \sqrt{3}$ where I_o = no-load current of the motor and U_n = phase-to-phase nominal voltage of the motor in kV.

2.3. The effect of harmonics

Equipment which uses power electronic components (frequency convertors, thyris- tor-controlled rectifiers, etc.) considerably increased the problems caused by harmonics in power supply systems.

Harmonics on symmetrical 3-phase power systems are generally odd-numbered:3^{rd}, 5^{th},7^{th}, 9^{th}..., and the magnitude decreases as the order of the harmonic increases. With the advance of power electronics devices and associated non-linear components, even--numbered harmonics are now sometimes encountered.

Capacitors are especially sensitive to harmonic components of the supply voltage due to the fact that capacitive reactance decreases as the frequency increases. In practice, this means that a relatively small percentage of harmonic voltage can cause a significant current to flow in the capacitor circuit.

The presence of harmonic components causes the (normally sinusoidal) wave form of voltage or current to be distorted. Harmonic distortion of the voltage wave frequently produces a peaky wave form, in which the peak walue of the normal sinuso-idal wave is increased.

Several solutions to these problems are available, which aim basically at reducing the distortion of the supply-voltage wave form, between the equipment causing the distortion, and the bank of capacitors in question. This is generally accomplished by shunt connected harmonic filter and/or harmonic-suppression reactors.

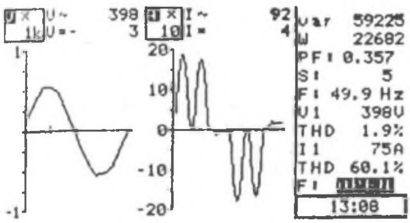
2.4. Measurements

Practical example on harmonic content is presented on the fig.4 and fig.5. Both of them are for GEHO pump motor P = (515 – 720) kW, U = (480 – 690)V, I = (750 – 730)A, n = (823 – 1193) r.p.m.

Motor is supplied from Schorch 1250 kV·A SF6 transformer and A.E.G. 1000 kV·A frequency converter.

Fig. 4 with current and voltage oscillo-grams is for motor running near to the no-load operation and Fig.5 is for middle-load operation and Fig.6 near to the nominal load of the motor.

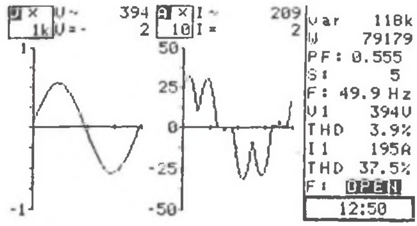
From the harmonic content tables can be seen that similar like for cosφ also for high harmonics content is not recommended to operate motor with low load when average values are significant high. For the motor nominal operation area the 5^{th} and 7^{th} harmonic are specially significant and harmonic compensation filters are recommended.



F (T)	=	50 Hz	F (M)	=	49.9 Hz
V (RMS)	=	393 V	I (RMS)	=	94 A
V 1	=	397 V	I 1	=	77 A
THD (V)	=	2.90%	THD (I)	=	61.90%
W	=	25955	var	=	59070
PF	=	0.386	PHASE	=	THREE

HAR	AVG. VALUES		HAR	AVG. VALUES	
n	Vn %	In %	n	Vn %	In %
DC	0.8	6.72	13	0.28	4.94
2	0.14	0.8	14	0.04	0.36
3	0.1	2.77	15	0.06	1.09
4	0.08	0.67	16	0.04	0.24
5	0.78	62.77	17	0.58	5.99
6	0.05	0.81	18	0.04	0.39
7	1.42	37.4	19	0.19	1.8
8	0.05	0.44	20	0.04	0.3
9	0.12	1.01	21	0.07	0.7
10	0.04	0.28	22	0.04	0.26
11	0.32	5.83	23	0.29	2.47
12	0.04	0.46	24	0.04	0.41
			25	0.29	2.28

Fig. 4. Motor running near no-load
Rys. 4. Małe obciążenie silnika



F (T)	=	50 Hz	F (M)	=	49.9 Hz
V (RMS)	=	393 V	I (RMS)	=	213 A
V 1	=	393 V	I 1	=	198 A
THD (V)	=	4.30%	THD (I)	=	37.20%
W	=	80116	var	=	120 k
PF	=	0.552	PHASE	=	THREE

HAR	AVG. VALUES		HAR	AVG. VALUES	
n	Vn %	In %	n	Vn %	In %
DC	0.79	1.9	13	0.28	0.76
2	0.14	0.23	14	0.06	0.09
3	0.99	1.48	15	0.99	0.86
4	0.06	0.23	16	0.07	0.07
5	2.6	37.98	17	1.65	4.57
6	0.05	0.29	18	0.06	0.11
7	0.38	6.75	19	0.48	0.18
8	0.06	0.07	20	0.06	0.12
9	0.91	0.08	21	1.04	0.55
10	0.08	0.1	22	0.07	0.11
11	1.78	9.42	23	1.31	3.13
12	0.06	0.19	24	0.06	0.04
			25	0.57	0.36

Fig.5. Motor running midle-load
Rys. 5. Średnie obciążenie silnika

F (T)	=	50 Hz	F (M)	=	49.9 Hz
V (RMS)	=	391 V	I (RMS)	=	410 A
V 1	=	391 V	I 1	=	395 A
THD (V)	=	7.90%	THD (I)	=	28.30%
W	=	220k	var	=	168 k
PF	=	0.794	PHASE	=	THREE

HAR	AVG. VALUES		HAR	AVG. VALUES	
n	Vn %	In %	n	Vn %	In %
DC	0.93	1.17	13	2.13	4.53
2	0.09	0.37	14	0.12	0.06
3	0.25	0.87	15	0.22	0.31
4	0.4	0.05	16	0.09	0.09
5	5.49	25.58	17	2.74	5.22
6	0.06	0.04	18	0.1	0.06
7	142	7.71	19	1857	3.06
8	0.13	0.12	20	0.11	0.12
9	0.31	0.25	21	0.26	0.17
10	0.12	0.12	22	0.09	0.07
11	2.99	9.2	23	2.01	3.61
12	0.09	0.13	24	0.12	0.11
			25	1.79	2.31

Fig. 6. Motor running near nominal-load
Rys. 6. Prawie znamionowe obciążenie silnika

3. HARMONIC FILTERS FOR MOTORS SUPPLIED FROM FREQUENCY CONVERTORS

Power-supply authorities generally impose a strick limit on the total harmonic distortion (THD) permitted at the point of power supply to a consumer.

The degree of distortion is measured as the ratio of the rms value of the fundamental frequency wave (50 or 60 Hz). For LV loads supplied through a transformer from a high-voltage service connection, this means that a maximum value of 4 to 5% for voltage THD is permissible at the LV terminals of the transformer. If it is not possible to keep the value demanded, then compensation must be done by the help of the low-voltage L-C series filters. Such filters shunt connected are tuned to resonate at harmonic frequen-cies, to which they present practically zero impedance. Filters connected in this way have the added benefit of contributing to reactive power compensation for the installation. Generally we can say that it is necessary to ensure that interaction between harmonic generating devices and P.F. correction capacitancies does not result in unacceptable levels of voltage and/or current wave-form distortion on the power supply network.

Harmonics on symmetrical 3-phase power system are generally odd-numbered: 3^{rd}, 5^{th}, 7^{th}, 9^{th} and the magnitude decreases as the order of the harmonic increases.

All of these features may be used in various ways to reduce specific harmonics to negligible values – total elimination is not possible.

Capacitors are especially sensitive to harmonic components of the supply voltage due to the fact that capacitive reactance decreases as the frequency increases. In practice, this means that a relatively small percentage of harmonic voltage can cause a significant current to flow in the capacitor circuit.

The presence of harmonic components causes the wave form (normally sinusoidal) of voltage or current to be distorted; the greater the harmonic content, the greater the degree of distortion.

If the natural frequency of the capacitor bank/power-system reactance combination is close to a particular case harmonic, then partial resonance will occur, with amplified values of voltage and current at the harmonic frequency concerned.

In this particular case, the elevated current will cause overheating of the capacitor, with degradation of the dielectric, which may result in its eventual failure.

3.1. Harmonic Compensation (HC) problems

In practice usually three cases can be met in which standard, overdimensioned plus harmonic-suppresioned and overdimensio-ned plus harmonic suppresion equipped capacitor banks should be installed. The paper presented shows the solution for Geho pump motors (Schorch):

type KR5834B,
delta connected, U = (480-690)V,
I = (515-720)kW,
RPM = $(823\text{-}1192)\mathrm{min}^{-1}$,
P = (515 – 720)kW

Motor was supplied from the AEG frequency convertor 1000MV·A, connected to the SF6, 1250kV·A Schorch transformer. After harmonic compensation panels have been damaged by short circuit the suitable supporting documentation was required to clear the HC problems. One of the subjects to be followed is HC calculation about HC configuration and capacitors and reactors sizing. Generally it is required to almost eliminate a harmonic voltage existing across two points A and B in the network a series-connected LCR circuit (Fig.7) tuned to resonate at the harmonic frequency concerned. This will constitute a virtual short-circuit to the current of that harmonic frequency, thereby reducing $V_{AB}(\nu)$ to practical zero.

$$f_{res} = \frac{1}{2\pi\sqrt{RL}}$$

Fig. 7. Elementary harmonic filter
Rys. 7. Elementarny filtr harmonicznych

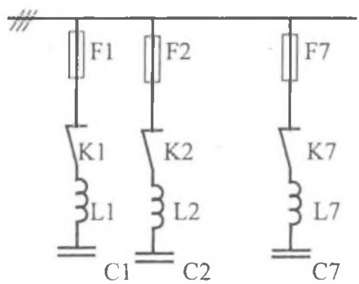


Fig. 8. HC capacitor bank for Schorch motors
Rys. 8. Wielostopniowy filtr harmonicznych dla silników Schorch

The same procedure can be adopted for any number of harmonic frequencies, the individual filters being conneted in parallel to the points A-B. The real solution which was used for Schorch motors supplied from frequency convertors is in the Fig.8.

Calculation is made for the connection according to the fig.9, for transformer voltage $U_S = 0.7$kV and $U_K = 6\%$.

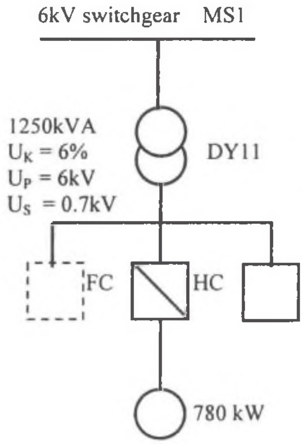


Fig. 9. Schema for calculation
Rys. 9. Schemat do obliczeń

3.2. Calculation of harmonic and reactive power compensation

FC circuit current harmonics

FC load factor:

$$\frac{P_{MOT}}{S_{FC}} = \frac{780}{1000} = 78\%,$$

phase current harmonics content

$$\frac{I_5}{I_1} \cong 0{,}32, \qquad \frac{I_7}{I_1} \cong 0{,}11,$$

$$\frac{I_{11}}{I_1} \cong 0{,}06. \qquad \frac{I_{13}}{I_1} \cong 0{,}03,$$

$$\sum \nu = 0.52.$$

Transformer reactances for 50;250;350;550 and 650 Hz:

$$X_{TR50} = \frac{U_S^2 u_k}{S_{TR}} = \frac{0.7 \times 0.06}{1.25} \cong 24m\Omega.$$

Transformer reactancies for harmonic frequencies

$$L_{TR} = 74.9\mu H,$$

$$X_{TR250} = X_{TR50} \times 5 = 118m\Omega,$$

$$X_{TR350} = 165m\Omega,$$

$$X_{TR550} = 259m\Omega,$$

$$X_{TR650} = 306m\Omega.$$

3.3. Percentage of harmonics which should be compensated:

$$v_5 = \frac{0.32}{0.52} \times 100 \cong 61\% \ldots\ldots\ldots\ldots 4 steps,$$
$$v_7 \cong 21\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2 steps,$$
$$v_{11} \cong 12\% +$$
$$v_{13} \cong 6\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1 steps,$$
$$totaly \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7 steps.$$

Therefore the power factor corrective capacitor should be foreseen to absorb the harmonics calculated above and for the number of steps and frequency point of view. Hence the suggested capacitor steps are specified above as well.

- Motor reactive power absorbtion

According to the Siemens and similar motor's production factories, the reactive power of motors is about 35 to 40% of its active power, thence for the motor used we have:

$0.4 \times 780kW = 312k\,\mathrm{var}$

Reactive power for one step is:

$312k\,\mathrm{var} : 7 = 44.6k\,\mathrm{var} \cong 45k\,\mathrm{var}$

Configuration for power factor correction will be 7 steps, 45 kvar each.

- Step's tune frequency

For the 5th harmonic will be used 4 steps tuned on 235Hz. For the 7th harmonic 2 steps tuned on 330Hz and for the 11 and 13 harmonics 1 step will be used tuned on 600Hz. By manufacturers of the equipments it is not recommended to select resonance branch precisely for desired harmonics because the voltage of capacitors could exceed rated value.

- Steps component calculation

Calculation is made on the base of the next equations and using equivalent circuit on the Fig. 10. For the total harmonic voltage distortion factor THD:

$$U_{TDH} = \frac{\sqrt{U_5^2 + U_7^2 + U_{11}^2 + U_{13}^2}}{U}$$

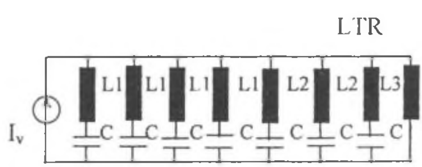


Fig. 10. Equivalent circuit of each harmonics
Rys. 10. Schemat zastępczy dla każdej harmonicznej

When $C = 288\mu F$; $L_{min} = 0.244mH$;
Total current of step 1,2,3,4 = 57A
Total current of step 5 and 6 = 49A
Total current of step 7 = -138A

The results for the 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonics are in the Tab.1.

Table 1

Results for harmonics current calculation

Step No:	***Harmonics current***			
	I_5	I_7	I_{11}	I_{13}
1	42.8	2.5	6.7	0.18
2	42.8	2.5	6.7	0.18
3	42.8	2.5	6.7	0.18
4	42.8	2.5	6.7	0.18
5	-13.2	24.1	17.0	0.44
6	-13.2	24.1	17.0	0.44
7	-6.8	-4.4	-131.8	17.90
TR	105.0	29.2	16.6	3.30
TOTAL	*243.0*	*83.0*	*45.6*	*22.80*

On the base of the calculation can be decided if the harmonic compensation is recommended and if the price of equipment will be suitable. From the calculation presented the using of common filter for 11^{th} and 13^{th} harmonics can be discussed and there is also a danger of overcompensation of the equipment. Also seems to be better divided seven steps of capacitor banks to two parts separately protected by fuses to prevent overcurrents and following damages on the last of the sevens steps where is the highest danger of fault occurance.

Author gratefully acknowledges support under research project No. CEZ: J22/98: 262200010.

REFERENCES

1. IEC standard 56, 1987 Appendix BB

Recenzent: Dr hab. inż. Aleksander Żywiec
Profesor Politechniki Śląskiej

Wpłyneło do Redakcji dnia 20 kwietnia 2000 r.