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Technical Note Archive

Power Factor Correction Capacitors: Application and Maintenance

INTRODUCTION

The use of capacitors has long been accepted as the most practical solution to the low power factor problem in power systems. The modern capacitor is a reliable, maintenance free cheap source of VARs needed in inductive circuits to synchronize the voltage and current waveforms. In the past, the application of capacitors was straight-forward; all that was required was a knowledge of KW (or KVA), existing power factor and target power factor.

In recent years, however, this practice has been complicated by the proliferation of non-linear loads, that is, loads that draw non-sinusoidal currents. We will explore this problem and suggest a solution, along with some capacitor maintenance guidelines.

THE SOURCE OF THE PROBLEM

One of the most widely used solid state motor controls is the six-pulse SCR drive. These devices usually employ a group of fast switching silicon-controlled rectifiers to control a motor. Unfortunately, they also represent a non-linear impedance to the power source, drawing a quassi-square wave alternating current. Fig.1 shows the idealized current waveform drawn by the drive.

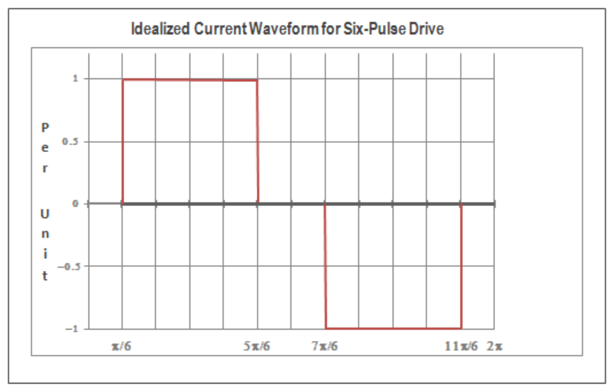


Fig. 1

Fourier analysis of this waveform shows that it can be represented as:

$$i(t) = (2\sqrt{3}\,I/\pi)\ \{\text{Sin } wt - (1/5)\text{ Sin } 5wt - (1/7)\text{ Sin } 7wt + (1/11)\text{ Sin } 11wt + (1/13)\text{ Sin } 13wt + \ldots(2/\sqrt{3})\ [\text{Cos }(n\pi/6)]\ (1/n)\text{ Sin } nwt\}$$

The first term inside the brackets is called the "fundamental" and its frequency is 50 Hz. The subsequent terms are called "harmonics", and their "harmonic order" h is an integral multiple of 60.

A common way of expressing the harmonic order is:

$h = kp \pm 1$

where: h = order of harmonic

k = 1, 2, 3…

p = number of pulses of drive

Also, from the Fourier representation, the theoretical magnitude of each harmonic current is:

$$I_h = I_1/h$$

where: h = magnitude of harmonic current

I_1 = magnitude of fundamental current

For six-pulse drives, for example, the characteristic harmonics are: 5, 7, 11, 13, 17, 19…; the higher order harmonics are not usually troublesome because their magnitude is progressively smaller. Fig. 2 and 3 show the total distortion when one or more harmonics are added to the fundamental. Note that as more harmonic components are added, the total waveform approaches the idealized waveform shown in Fig. 1.

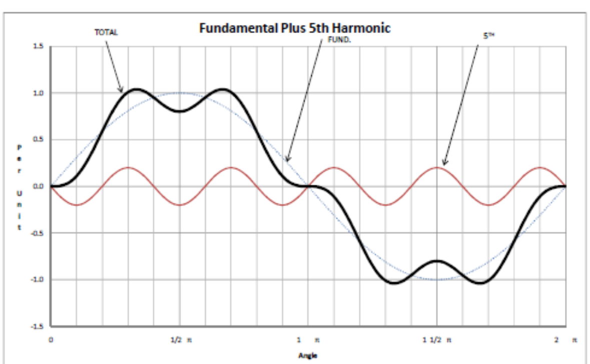


Fig. 2

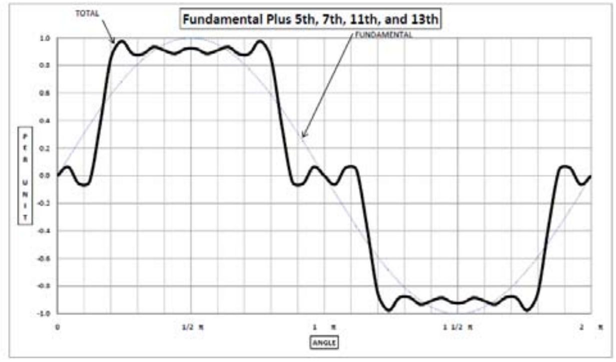
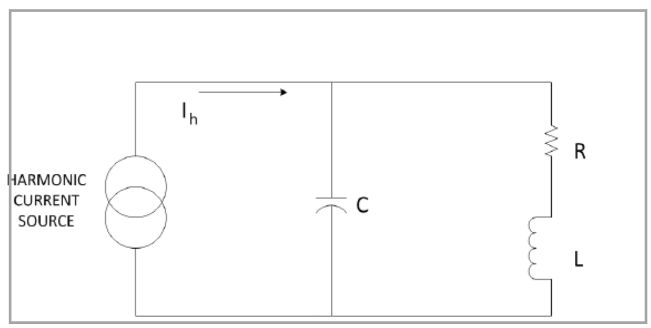


Fig. 3

HARMONIC RESONANCE

When a capacitor bank is added to a power system, it is effectively connected in parallel with the system's impedance, which is primarily inductive. As far as the harmonic source is concerned, it is looking at a capacitor in parallel with an inductor. Fig. 4 shows the model circuit for this system on a per-phase basis.



Fig, 4

Resistor "R" represents the inevitable system losses. The harmonic source is represented as a constant current source, since it behaves as such.

A quick analysis shows that the impedance seen by the harmonic source is:

$$Z = \sqrt{[R^2 + (wL)^2]/[(1 - w^2LC)^2 + (wRC)^2]}$$

where: $w = 2\pi f$ (radians/second)

L= System Inductance

C = Capacitance of Bank

Impedance "Z" attains a maximum value at:

$$w = [1/L] \sqrt{[(L/C) - R^2]}$$

or $$f = [1/2\pi L] \sqrt{[(L/C) - R^2]} \quad \text{(hertz)}$$

At this frequency the system is in resonance (capacitive and inductive reactances are equal) and any harmonic currents matching the resonant frequency will be amplified in the "tank" circuit, the degree of magnification being determined by the system resistance. Fig. 5 is the impedance plot as seen by the harmonic source in Fig. 4 for a typical system consisting of 500KVAR connected to a 1500 KVA, 480 V transformer. Transmission impedances have been neglected for simplicity and resistance has been adjusted to compensate for skin effect at the higher frequencies.

Please note that while impedance magnitudes are dependent on system resistance, resonant frequency is primarily a function of "L" and "C".

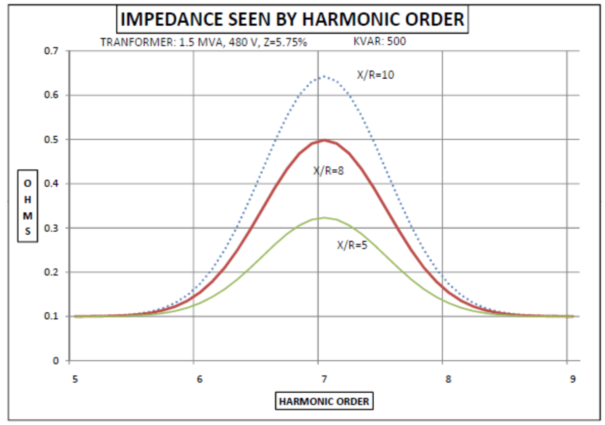


Fig. 5

If we assume the transformer is 80% loaded (at 60 Hz), then the fundamental current is:

$$i_1 = .80 \text{ KVA}/(\text{KV}\sqrt{3}) = (.80)\ 1500/(.48\sqrt{3})$$
$$= 1443 \text{ amp}$$

If we further assume the load is 25% drives, then the generated harmonic currents are:

$$I_h = (.25)\ 1443/h$$

The bus harmonic voltages are:

$$V_h = i_h Z_h$$

The capacitor harmonic currents are:

$$I_h = w_h C V_h$$

Evaluation of the first four harmonics (assuming X/R = 8) yields the following results:

Harmonic Order	Harmonic Impedance	Generated Harmonic Current	Bus Harmonic Voltage	Capacitor Harmonic Current
5	0.088	72	6.34	72
7	0.498	52	25.90	498
11	0.067	33	2.21	55
13	0.048	28	1.34	59

The fundamental capacitor current is:

$I_1 = 500/(\sqrt{3})\ (.48) = 601$ amp

The total RMS capacitor current is then:

$I_c = \sqrt{I_1^2 + I_5^2 + I_7^2 + I_{11}^2 + I_{13}^2}$

$= \sqrt{601^2 + 72^2 + 409^2 + 55^2 + 39^2}$

= 750 amp

$= 1.25\ I_{rated}$

DETUNING THE CIRCUIT

While the previous example is hypothetical, it illustrates how harmonic currrents matching the natural resonance of the "tank" circuit can be greatly magnified and increase voltage distortion. Some of the problems associated with this condition include:

- Unreliable operation of sensitive electronic equipment such as computers
- Premature failure of transformers and UPS systems
- Erratic circuit breaker operations
- Communications interference
- Capacitor failures
- Nuisance fuse operation

The next effective solution to this problem consists of series tuning the capacitor bank to the lowest offending harmonic, usually the 5th. This is done by introducing an inductor in series with the capacitor as shows in Fig, 6.

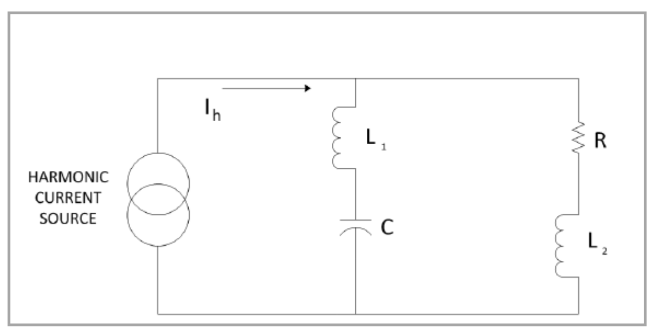


Fig. 6

An analysis shows that the total impedance “Z” for this circuit is:

$Z = [wL_1 - 1/wC]$

$$\sqrt{[R^2 + (wL_2)^2] + \{R^2 + [w(L_1 + L_2) - 1/wC]^2\}}$$

A plot of impedance vs. frequency is shown in Fig, 7; the original impedance (unturned) is shown for comparison:

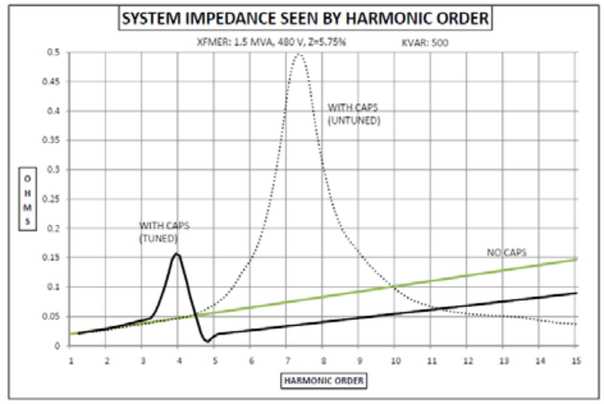


Figure 7

The minimum impedance occurs at the series resonant point near the 5th harmonic, while the peak represents a parallel resonance due to the capacitor and the two inductors. Reevaluation of the first four harmonics leads to the following results:

Harmonic Order	Harmonic Impedance	Generated Harmonic Current	Bus Harmonic Voltage	Capacitor Harmonic Current
5	0.009	72	0.65	56
7	0.034	52	1.77	23
11	0.063	33	2.08	12
13	0.076	28	2.13	9

Where the *capacitor harmonic currents* are calculated as follows:

$$I_h = V_h/Z_f = V_h\, w_h\, C /(w_h^2 LC - 1)$$

(Z_f = filter impedance)

Total RMS capacitor current is now:

$$I_c = \sqrt{602^2 + 56^2 + 23^2 + 12^2 + 9^2}$$
$$= 604 \text{ amp} = 1.005 \text{ x } I_{rated}$$

The capacitor/reactor combination thus act as a trap at the tuned frequency, beyond this point the system looks inductive and can no longer resonate, thus eliminating the problem.

MAINTENANCE

As with other equipment, an inspection program should be adopted by the user. Items to be checked should include:

- Capacitor current
- Capacitor fuses
- Physical appearance
- Ambient temperature
- Ventilation

On a new installation, capacitor currents should be measured with a true RMS meter and the results compared with the capacitor's rated current I_r:

$$I_r = KVAR_r / (\sqrt{3}\ KV_r) \quad \text{(three phase)}$$
$$= KVAR_r / KV_r \quad \text{(single phase)}$$

where $KVAR_r$ and KV_r are the capacitor rated values. If the applied voltage is other than rated, then the measured current I_m will be:

$$I_m = I_r\,(V_a / V_r) \quad (V_a = \text{applied voltage})$$

Due to tolerance, measured current will probably be slightly higher than the rated current. A large discrepancy between rated and measured values is usually an indication of harmonic distortion. Under severe conditions, the capacitor fuses will operate, and unless these are checked periodically, there is no way of knowing that the capacitors are "off" line. For this reason it is a good idea to include "Blown Fuse Indicating Lights" with the equipment. This feature indicates, at a glance, the condition of the fuses.

Occasionally, a combination of harmonic currents, high ambient temperatures and poor ventilation may cause the capacitor to bulge due to high internal pressure. In this case, the capacitor's internal pressure interrupter may operate before the external fuse, thus removing the capacitor from the circuit without warming. This can occur unless the capacitor is equipped with "Loss of KVAR" indication, which monitors continuity between the supply line and the load side of the pressure interrupter.

Under normal conditions, capacitors should operate trouble free for many years. In a harsh environment, however, it is advisable to inspect them on a regular basis.

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