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BENEFITS OF HARMONIC FILTERING (Example)

PURPOSE

The purpose of this discussion is to provide insight into why harmonic filters work and how they accomplish a reduction of harmonic distortion. It is hoped that this discussion will help in better understanding the benefits and limitations of applying harmonic filters. A simple system is used to illustrate these points.

THE PLANT AND SYSTEM

A 3985 kVA load with a 0.7 Power Factor (PF) produces 5th and 7th harmonic currents. A 7.5 MVA transformer, with 7.16% impedance, supplies the load at 4,160 volts. Primary service is 13.8 KV from a utility system having a source impedance of 0.052 + j0.187 Ohms. It is desired to correct the PF to better than 95%. A system diagram is shown in Figure 1.

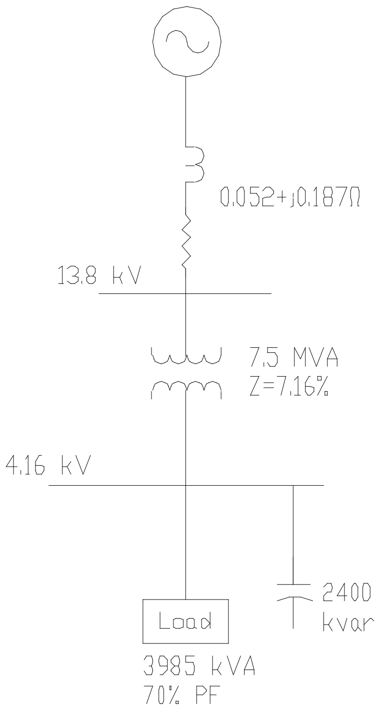

Figure 1 – System Diagram

PRELIMINARY DESIGN

A 2400 kvar capacitor bank is placed on the 4,160 volt secondary to correct the power factor. A frequency scan (Figure 2) shows that the capacitor bank with the transformer and system impedance has a resonant frequency at the 6.3rd harmonic (Case ER1). Harmonic distortion for this is likely to be unacceptable since it is between the 5th and 7th harmonics.

A filter/capacitor bank was designed in order to improve the power factor to above 95% and detune the resonant frequency away from the 5th and 7th harmonics. A capacitor assembly with a three-phase rating of 3000 kvar and 4800 volts was chosen. A reactor of 0.922 millihenries is required to tune the capacitor filter to the 4.7th harmonic (Case ER1F). A case for the original system without capacitors is included (ER1NC) for comparison.

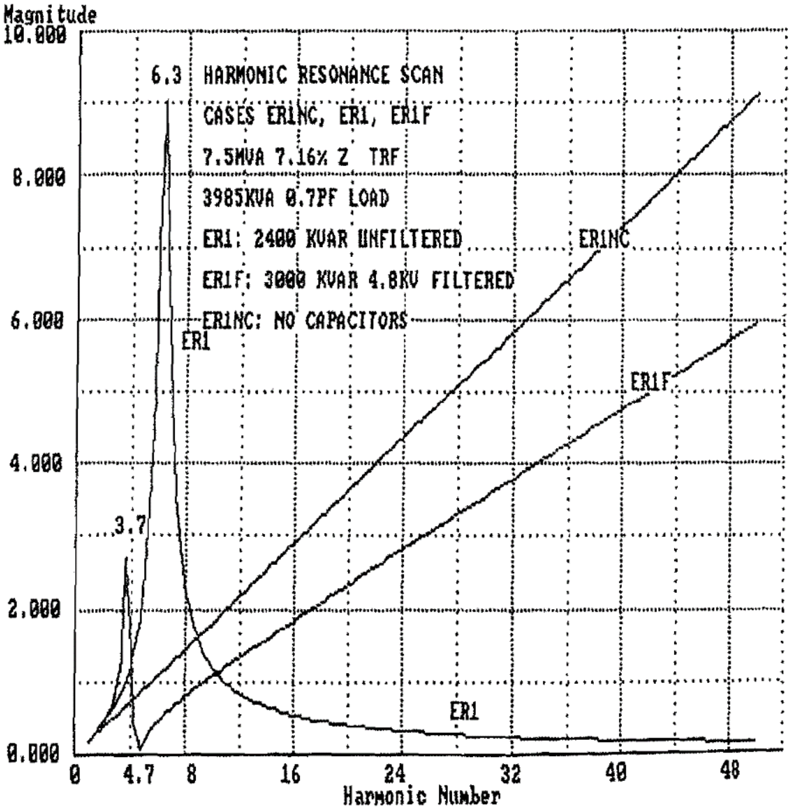

Figure 2 – Harmonic Resonance Scan with Filter Tuned to the 4.7th Harmonic

HARMONIC ANALYSIS

One of the techniques used to analyze a system and detect possible harmonic problems is a harmonic frequency scan. Figure 2 above is an example and shows three scans, one for each of the three configurations for the example system:

ER1NC - No capacitors
ER1 – One unfiltered capacitor bank
ER1F – A filter capacitor replacing the unfiltered bank.

Electrical systems include resistance, inductance, and capacitance. Resistance occurs in all components to some degree. Inductance occurs predominantly in motors, transformers, and reactors. Capacitance occurs primarily in capacitors. The way capacitance and inductance interact gives an electrical system different impedance characteristics at different frequencies.

The impedance of an inductor is considered mathematically as a positive quantity whose value changes with the frequency of interest and is larger at higher frequencies and lower at lower frequencies.

The impedance of a capacitor also changes with the frequency but in an opposite way. That is, the impedance is larger at low frequencies and lower at higher frequencies. The capacitance, mathematically, is considered to be a negative value.

APPLICATION

When inductors and capacitors appear in the same circuit, their values may cancel out at some particular frequency. One example of this is power factor correction, where capacitors are added to the system to partially cancel the effects of the inductance exhibited by motors, which could lead to a poor power factor. The capacitors would be added to improve this power factor.

The effect on the impedance of the inductor and capacitor will depend on how they are connected together, either in series or parallel. Consider the 7.5 MVA transformer supplying power to the bus and the non-filter 2400 kvar power factor correcting capacitor. How are these two components connected? We need to consider both the 60 Hz fundamental source and harmonic sources. We need to consider all harmonics of interest one at a time.

- At 60 Hertz, the transformer and the utility impedance (viewed as an inductor) are combined to make the source impedance. The source and the capacitor bank are series connected. That is, electrical current must pass through the source in order to get to the capacitor.
- For harmonic currents generated by the load, the situation is different. Part of the current from the harmonic source, e.g., the 5th harmonic, will flow into the source, towards the utility, and eventually to neutral, and a different part of the 5th harmonic current will flow into the capacitor to neutral. Therefore, electrically, the source, capacitor, and any other bus loads would be connected in parallel as viewed from the harmonic current source.

Therefore, we must calculate both the series and parallel impedance of the source and capacitor. If we have two impedances, Z_t and Z_c, which vary with frequency, we can express the equivalent series impedance (Z_s) and equivalent parallel impedance (Z_p) as follows:

$$Z_S = Z_t + Z_c$$

The lowest value approaches zero at only one frequency, f_s. (Remember Z_t is positive and Z_c is negative and may have equal magnitudes only at one frequency.)

$$Z_p = \left(\frac{Z_t * Z_c}{Z_t + Z_c} \right)$$

The highest value approaches infinity at only one frequency, f_p. This is the same frequency where Z_s approaches zero. (Assuming the same values for Z_t and Z_c.)

The properties of the parallel circuit near the resonant frequency, f_p, are critical to understanding harmonic resonance problems. Consider the example case ER1. The bus impedance reaches a maximum at the 6.3rd harmonic and has a value at this point of 9.1 ohms, as seen on the "Magnitude" scale. The impedance at the 5th harmonic is 2.5 ohms.

The voltage appearing across any impedance, Z, is

$$\mathbf{V} = I * Z$$

Where:

V is the voltage across the impedance

I is the current through the impedance

Applying this reasoning to the example, suppose there is a total of 100 amps of harmonic current at the 5th harmonic injected into the bus. This current flows into the parallel equivalent impedance, Z_p, of the source and the capacitor at the 5th harmonic and produces a bus harmonic voltage, V_b, of

$$\mathbf{V_b} = 100 \text{ x } 2.5 = 250 \text{ Volts}$$

The impedance of the capacitor at H = 5 is -1.44 ohms. The impedance of the source at H = 5 is .91 ohms. They differ by 0.53 ohms at the 5th harmonic. The harmonic current flowing in the capacitor, I_c, and the source, I_t, can be calculated from

$$I_c = \frac{V_b}{Z_c}, \text{ and } I_t = \frac{V_b}{Z_t}$$

$$I_c = \frac{250}{-1.44} = -172 \text{ amps of 5th harmonic, and}$$

$$I_t = \frac{250}{0.91} = 272 \text{ amps of 5th harmonic.}$$

This demonstrates **harmonic current amplification,** which occurs in parallel resonant circuits. The currents flowing in the capacitor and transformer are greater than the injected harmonic current by a factor of 1.7 and 2.7, respectively. Note that the difference between the two currents is 100 amps, the magnitude of the injected current. If the system resonance were closer to the 5th harmonic (rather than at 6.3), the amplification would be even greater. This demonstrates why capacitor fuses blow and transformers overheat due to harmonics in the system.

The remedy for this harmonic resonance problem is amazingly simple. By replacing the unfiltered capacitor bank with a capacitor bank with a series reactor and tuned to just below the 5th harmonic, e.g., at the 4.7th, the impedance of the series connected combination of capacitor and inductor would approach zero at this frequency point. Since the capacitor impedance, Z_c, is -1.63 ohms at the 4.7th harmonic, we chose a reactor with an impedance of +1.63 ohms at H = 4.7th. At H = 5, the impedance of the filter is

$$\mathbf{Z_f} = -1.54 + 1.74 = 0.20\ \Omega.$$

In the example, the 100 amps of 5th harmonic current injected into the bus would seek the path of lowest impedance, and almost all of the 100 amps would flow to neutral through the filter. Therefore, the 100 amps flowing in the filter impedance, Z_f, would produce a bus harmonic voltage, V_b, of about

$V_b = 100 \text{ x } 0.20 = 20 \text{ volts}$ compared to 247 volts for the unfiltered case.

The filter has accomplished several functions.

1. It eliminated the possibly damaging currents in the capacitor and transformer.
2. It provides a low bus impedance at the filter frequency, which causes the bus harmonic voltage to be very low, thereby reducing bus harmonic voltage distortion.
3. It still provides capacitive compensation to correct the power factor at 60 Hertz.

In Figure 2, the example case ER1F (the filter case) shows a harmonic resonance scan when the filter was tuned to the 4.7th harmonic. Note that the parallel resonance at the 6.3rd resonance no longer exists. A "Notch" in the impedance curve is shown at the 4.7th harmonic due to the low impedance of the filter there. Also, there is a new parallel resonance created near the 3.7th harmonic. A new resonance is always created below the filter tuning point. This new resonance will not cause problems as long as it is located at harmonics where no harmonic current sources exist. This requires care in multi-step filter systems.

The frequency scan Case ER1NC, with no capacitors, shows a straight-line impedance, which increases with frequency. This is just the impedance curve due to the inductance of the transformer and the utility system. Note that the bus impedance above the filter Case ER1F also rises in a straight line but is lower than that of the transformer and the utility system alone and provides some measure of harmonic attenuation at the harmonics above the one filtered.

There are other considerations in the design of harmonic filters. Normally, the filter is not tuned exactly to the offending harmonic but rather to a frequency somewhat below it. For example, 5th harmonic filters are often tuned to the 4.7th harmonic. When several troublesome harmonics are present, the power factor correction filter/capacitor bank may need to be split up into two, three, or more filter stages; one tuned for each of the offending harmonics. In general, it is not a good idea to combine filter banks with unfiltered banks in the same system. The unfiltered capacitors create additional parallel resonances and may become troublesome.

There are trade-offs for the benefits derived from filters. The capacitor voltage rating must be increased, and the capacitor KVAR rating must be increased to offset the KVAR derating due to increased capacitor voltage rating. Equipment costs are increased due to the need for reactors, additional capacitance, and larger enclosures to house the equipment.