ONE OPTIMISED NETWORK EQUIPMENT

Introduction

Harmonic filters consisting of capacitors, reactors and possibly damping resistors remove harmonic current from the network and improve load power factor by contributing capacitive reactive power. The capacitance of the filter bank is determined in part by the reactive power compensation required, and the inductance of the filter reactor is chosen so that the combination is tuned to the desired frequency.

Some applications require harmonic mitigation without any significant reactive power contribution, for example when non-linear loads operate at close to unity power factor and the network cannot accept leading reactive power. Such a situation typically arises when the network impedance is low, implying that relatively small non-linear loads can cause unacceptable harmonic distortion, and any leading reactive power may result in excessive voltage variations when filters are switched.

This note reviews harmonic filtering solutions that draw current only at harmonic frequencies. Steady state and transient performance of a practical installation is described, illustrating a passive filter circuit that is an effective solution of harmonic distortion yet that draws almost no fundamental frequency current, and has no onerous switching requirements.

1 Unity power factor filters

Unity power factor harmonic filters can be active (based on power electronics) or passive. The suitability of either option depends on a variety of factors, including the frequency dependent impedance of the network and the range of harmonic frequencies present.

Active harmonic filters are most efficient when applied in networks with a low frequency dependent impedance (high fault level) and where significant current distortion is only present at relatively low harmonic orders, for example the fifth and seventh harmonics. Compensating higher harmonic orders requires increased switching frequency and hence higher losses. The losses of an active harmonic filter can therefore depend on the harmonic frequencies present, as well as their magnitude.

Passive harmonic filters modify the network impedance in such a manner that current from harmonic sources is diverted into the filter, resulting in lower harmonic voltage distortion. Such filters are most effective in networks with high frequency dependent impedance. Filter configurations are tailored to the application, depending on the nature of harmonic generation. Damped harmonic filters (filters with a damping resistor connected in parallel with the tuning reactor) can be used to mitigate harmonic distortion across a wide range of frequencies. Such filters will remove harmonic current from the network and reduce the impedance at and above the tuned frequency. The losses due to harmonics are proportional to the magnitude of harmonic currents present.

Tuned filters of any configuration produce leading reactive power that can be completely compensated by connecting a shunt reactor of the same reactive power rating in parallel with the filter. The combination will then have a near zero active and reactive power contribution to the network.

2 Harmonic performance

The damped passive unity power factor harmonic filter shown in figure 1 has recently been supplied to a mineral processing plant in Australia. The plant operates in island mode with power supplied from a number of generators. The number of generators in service changes with the plant load. The plant contains linear and non-linear loads.
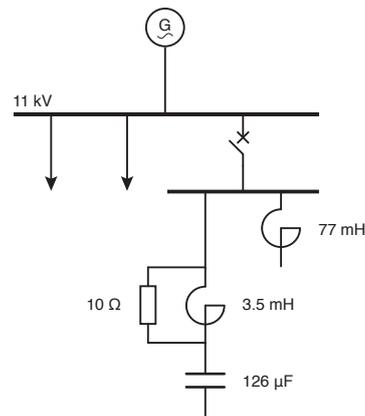

Figure 1: Simplified single line diagram of plant

The non-linear loads have a broad harmonic current spectrum. This results in voltage distortion at characteristic frequencies associated with conventional variable speed drives as well as any number of non-integer and non-characteristic frequencies typically associated with slip energy recovery drives, as is illustrated in figure 2.
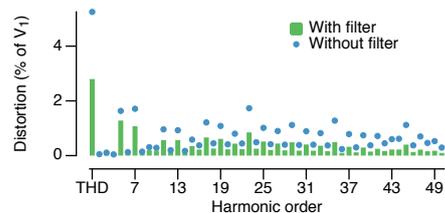

Figure 2: Voltage distortion at the plant 11 kV bus with and without the damped filter connected

The worst case V_{THD} was calculated to be 5.3% and the corresponding spectrum is provided in figure 2 (No filter). The V_{THD} limit accepted by the power plant is 3%. This limit is exceeded at various load levels, including low load levels when a small number of generators are connected.

A conventional passive filter solution with its associated reactive power contribution would not be acceptable as generators would be required to operate outside their capability curve. A filter solution was required that would not contribute any reactive power and would absorb a broad range of harmonics.

A 5 Mvar harmonic filter tuned to 240 Hz with a 10 Ω damping resistor reduces the worst case V_{THD} at the 11 kV bus to 2.8%. The voltage harmonic spectrum with the 5 Mvar damped filter is shown in figure 2. The 5 Mvar damped filter is connected in parallel with a 5 Mvar shunt reactor as shown in figure 1, resulting in an unity power factor filter with a near zero reactive power contribution to the network.

The unity power factor filter has the same effect on the frequency dependent network impedance as a 5 Mvar damped filter without a parallel shunt reactor, illustrated in figure 3, and hence the same harmonic performance.
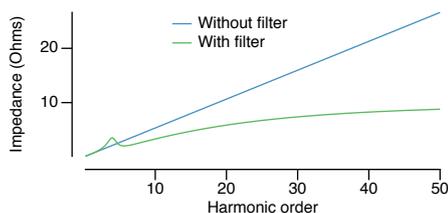

Figure 3: Frequency dependent network impedance at the plant 11 kV bus

Site measurements confirm that the V_{THD} with the filter connected is below the predicted maximum of 2.8%.

3 Transient performance

The transient behaviour of the damped unity power factor filter during energisation and de-energisation was investigated through site measurements and modelling.

3.1 Filter energisation

Current and voltage waveforms were recorded at the 11 kV circuit breaker panel feeding the filter shown in figure 1 during energisation of the harmonic filter. The filter energisation current waveform is shown in figure 4.

The offset is caused by the energisation of the shunt reactor as the current in the reactor cannot change
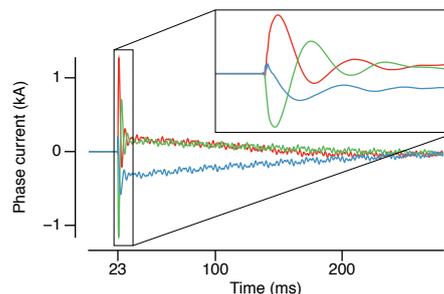

Figure 4: Filter energisation current waveform recorded at the 11 kV circuit breaker

instantaneously. For example in the "blue" phase the supply side voltage is at zero when the breaker closes, a point in the waveform that is associated with the peak value of current.

The current measurements in Figure 4 shows that the unity power factor filter settles to near zero load current approximately 300 ms after energisation.

Figure 5 displays the filter energisation voltage waveform recorded on the plant 11 kV bus, for the period observed in the magnified portion of figure 4.
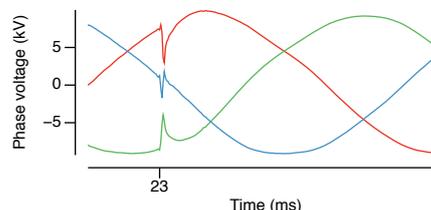

Figure 5: Filter energisation voltage waveform recorded on the plant 11 kV bus

The voltage transient is caused by the energisation of the capacitor bank, and its magnitude and duration is determined largely by the tuning reactor.

3.2 Switching off shunt capacitor banks

Switching off capacitor banks and shunt reactors individually is an onerous task, especially if the neutrals are isolated from ground.

When de-energising ungrounded capacitor banks, the first phase to interrupt will do so when the current reaches zero, hence when the voltage is at its peak. The charge will remain trapped and the bank will retain peak voltage. The instantaneous values of the currents in the other two phases will be equal and opposite, and will reach zero simultaneously a quarter cycle later. If the other two phases interrupt at this time then the maximum recovery voltage will appear

across the first pole a quarter cycle later, with magnitude 2.5 times peak phase voltage. This is because the supply side has reached its maximum value in the opposite polarity to the trapped charge on the capacitor bank. This initial maximum recovery voltage occurs very shortly after the contacts have begun parting and can lead to restriking or reignition in the breaker with possibly destructive voltage multiplication.

3.3 Switching off reactors

When de-energising ungrounded shunt reactors the first phase will interrupt at current zero, usually followed by the other two phases a quarter cycle later. The difference between capacitor and reactor switching is that reactor switching results in oscillation on the load side, and hence a transient recovery voltage across the breaker. The most severe transient recovery voltage will appear across the first pole to clear. The lower recovery voltages experienced by the other two poles will be equal and opposite. The frequency and amplitude of the load side oscillation determine the rate of rise of the recovery voltage and depend on the inductance and stray capacitance of the reactor. These stray capacitances are generally very low resulting in high natural frequencies and steep recovery transients that can be beyond the clearing capabilities of many circuit breakers.

3.4 Switching off a shunt capacitor bank and shunt reactor combination

Switching off a passive unity power factor harmonic filter does not stress the circuit breaker in the same way as switching off a shunt capacitor bank or shunt reactor as described in the previous section. Disconnection from the source does not result in trapped charge or high frequency oscillations on the load side because the capacitor bank still has an inductive load to supply and the reactor still has a reactive power source, in other words it is as if no disconnection has occurred. Energy will continue to oscillate between the filter bank and shunt reactor at the resonant frequency of 50 Hz, gradually dissipating due to the resistance in the circuit. The resulting voltage across the circuit breaker gradually increases to phase voltage as presented in figure 6.
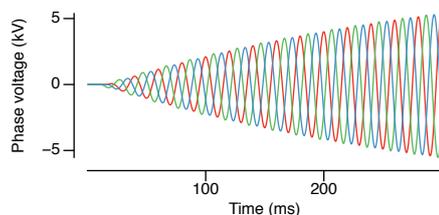
Figure 6: Voltage across the circuit breaker after de-energisation

If a smaller 2.5 Mvar shunt reactor is connected in parallel with the 5 Mvar filter bank then at disconnection the instantaneous values of the filter bank and reactor phase currents are equal and opposite (the capacitor and reactor currents decrease and increase respectively). The resonant frequency of the combination is now 35 Hz as the inductance of the shunt reactor has doubled. The source side oscillates at 50 Hz resulting in the two-frequency voltage waveform illustrated in figure 7 across the circuit breaker.
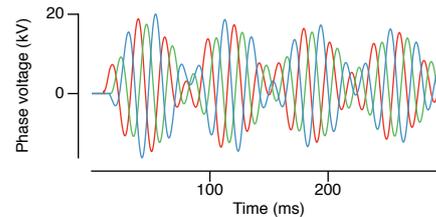
Figure 7: Voltage across the circuit breaker after de-energisation (2.5 Mvar reactor)

Similarly, at disconnection of a 5 Mvar shunt reactor connected in parallel with a 2.5 Mvar filter bank the instantaneous values of the filter bank and reactor phase currents are equal and opposite. The natural frequency of the combination is 71 Hz as the capacitance of the filter bank has halved. The resulting two-frequency voltage waveform across the breaker is shown in figure 8. The energy on the load side dissipates quickly compared to figure 7 due to the smaller filter bank.
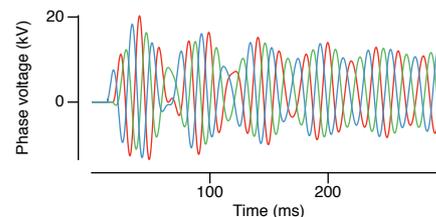
Figure 8: Voltage across the circuit breaker after de-energisation (2.5 Mvar filter bank)

4 Conclusion

Passive unity power factor harmonic filters can be a good solution for networks where little or no reactive power may be supplied to the network. The addition of the shunt reactor does not affect the harmonic performance of the filter, has negligible effect on the switching on inrush current, and the combination has a very smooth switching off load side voltage waveform that does not stress the circuit breaker.