ONE OPTIMISED NETWORK EQUIPMENT

Harmonic mitigation in modern networks

Introduction

Significant change has occurred in electricity networks in the last few years: electronic converters are used widely in industrial networks due to the increased flexibility, efficiency and level of control, and are now applied at all levels of the electricity network, from domestic applications such as air conditioning and grid-connected solar photo-voltaic systems, to commercial buildings, large scale renewable energy sources and distribution and transmission utilities.

The harmful effects of harmonics in power systems are clear and range from excessive heating, reduced equipment life expectancy, to loss of supply and destructive failures. Appropriate care and mitigation begins with an understanding of the sources of harmonics. The most common sources of harmonics are described below. An example of how harmonics propagate through an electrical network is presented, then attention turns to what can be done to mitigate excessive harmonics in networks. Practical guidance is given on the measurement of harmonic distortion, and real examples of measurements taken in networks are presented. Finally operating principles and types of harmonic filters are described together with guidelines on the selection of appropriate filters for various applications.

1 Sources of harmonics

Most, but not all network harmonics are caused by electronic loads that are now commonly used in lighting and heating, large industrial applications and transmission networks. We describe some interesting aspects of a number of such loads here, from the thyristor converter to arc furnaces.

1.1 Thyristor converters

The current drawn from the supply network by a thyristor converter is not sinusoidal. Thyristor converters are treated as harmonic current sources because of this non-sinusoidal characteristic. The order of the harmonic fed into the supply depends on the construction of the convertor. A characteristic feature of the converter is its pulse number. The order of harmonics produced by a converter can be approximated by the equation:

$$n = kp \pm 1 \qquad (1)$$

where

n = order of harmonic
p = pulse number
k = 1, 2, 3, ...

Six-pulse converters are in common use and feed harmonics in the order 5, 7, 11, 13 etc. into the supply system as predicted by the above equation. An example of a simple six-pulse converter topology feeding a DC load is presented in figure 1.

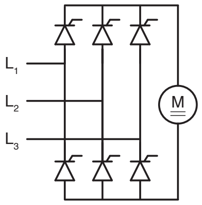

Figure 1: Six-pulse thyristor bridge

If the converter has a twelve-pulse configuration, harmonics of the fifth and seventh order do not appear in general. Twelve-pulse (and higher pulse numbers) are more expensive to manufacture than six-pulse devices and are generally used only for high power applications.

In general we can say that the higher the pulse number, the lower the magnitude of harmonic distortion fed into the supply. Lack of symmetry (as a result of supply system phase unbalance or component mismatches), and specific faults in the converter can cause uncharacteristic harmonic orders such as the second, third and fourth to appear in the supply current.

In the ideal case the magnitude of the harmonic currents produced by the converter is dependent only on the magnitude of the fundamental current and the order of the harmonic concerned according to the following equation:

$$I_n = \frac{I_1}{n} \qquad (2)$$

where

I_1 = fundamental frequency current
n = order of harmonic
I_n = n^{th} harmonic current

Equation 2 assumes that the converter is fed from a strictly symmetrical, stiff three phase network and that the direct current output contains no ripple. In practice the magnitude of the harmonic currents produced is, in addition to order of the harmonic and the magnitude of the fundamental frequency current, also affected by the short-circuit power at the connection point of the converter and the ripple on the direct current. Decrease of the short circuit power (increased network impedance) lengthens the commutation time, in other words the commutation angle increases and the supply side current distortion is reduced.

The circuit inductance is not able to smooth the direct current completely, therefore ripple remains in the DC current. This has the effect of increasing some of the harmonics and decreasing others. Table 1 provides some insight to the difference between the idealised harmonic current magnitudes predicted by equation 2 and typical levels encountered in practice. The differences are mainly caused by the effects of overlap and DC ripple.

Table 1: Converter line side harmonics

Harmonic order, n	I_n/I_1, %	
	Typical	*Idealised*
5	40	20
7	21	14
11	8	9
13	6	7
17	5	6
19	3	5
23	3	4
25	2	4

1.2 Frequency converters

The relationship between fundamental frequency and harmonics fed into the supply network by a frequency converter does not differ materially from what has been stated regarding the thyristor converter. The order of the harmonics is also in accordance with equation 1. There are considerable differences, however, in the harmonic currents fed into the supply system by different types of frequency converters, due to the fact that the fundamental frequency currents taken at the same torque and frequency are of different magnitudes for different frequency converters.

Two different front end topologies are shown in figure 2.

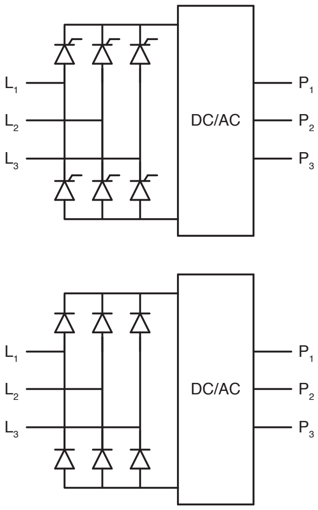

Figure 2: Controlled and fixed converter front ends

The magnitude of the fundamental current at a specific torque and frequency is a function of the frequency converter input circuit, namely whether this is a thyristor bridge or a diode bridge. Since the thyristor bridge also takes reactive power from the supply network, the fundamental current drawn by such a converter is greater than the fundamental current drawn by a diode bridge and consequently the harmonic currents supplied by the thyristor currents are greater than those from a diode bridge.

1.3 Distributed renewable energy sources

Whereas domestic and commercial air conditioning loads are significant users of the frequency converters above, the large scale application of distributed renewable energy sources requires controlled bi-directional power flow. Modern inverters allow for four-quadrant operation, with independent direction of flow of active and reactive power. Furthermore, sophisticated switching control and inverter topologies have enabled development of devices with low harmonic emission and flexible fundamental frequency power control.

The examples in figure 3 demonstrate that independent of the source of energy, a utility interface that transfers power to the network is necessary. Such interfaces are almost always electronic and inject harmonic current into the network. Strict standards apply to the amount of harmonic distortion that can be injected by such devices.

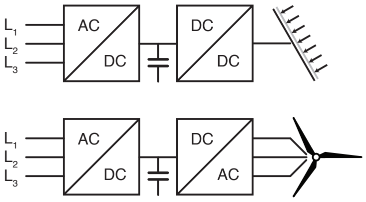

Figure 3: Common distributed generation systems

A large variety of topologies exist for inverters connecting distributed generation systems to the network. Most employ some form of pulse-width modulation and line filters to reconstruct a nearly perfectly sinusoidal voltage waveform to the network, an example of which is illustrated in figure 4.

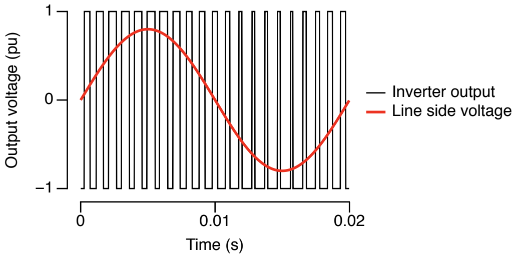

Figure 4: PWM generation and filtering

Reducing the amount of voltage distortion presented to the network requires increased switching frequencies in the inverters with associated increased losses. Most systems strike a balance between acceptable losses and compliance with emission limits. A typical voltage harmonic spectrum at the network connection point is shown in figure 5. Regardless of topology, harmonic contributions are generally characterised by high frequency components, and side-bands around multiples of the switching frequency.

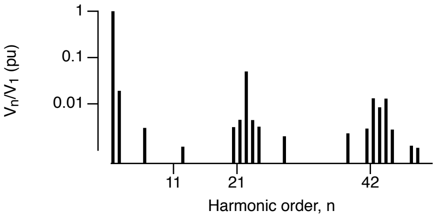

Figure 5: PWM spectrum and limits

Predicting the harmonic contribution of this class of load is made complicated by the fact that changes to the harmonic spectrum can be brought about by changes in the inverter control system, an approach that is often used to circumvent a known problem with harmonic resonance, only to re-appear as a different complication at a different frequency. The combination of large cable networks and the relatively high frequency components generated by these devices, the unpredictable and widely varying spectra result in these devices being a special challenge for harmonic filter design, which is only slightly mitigated by the fact that the devices have relatively low absolute harmonic emissions.

1.4 Thyristor switches

In recent years there has been an increase in the industrial application of thyristors controlling resistive loads. The most general control methods are the so-called integral cycle or burst firing control, and phase control.

The burst firing control thyristors always conduct for one or more complete cycles, after which the ignition pulse is removed, again for one or more cycles.

Figure 6 illustrates some examples for three different degrees of control (the meaning of the parameter "a" is defined in the top set of traces, for example for a ratio of a=0.5, the thyristor conducts for one cycle out of every two.) The bottom figure presents the harmonic current spectrum for each degree of control. It is clear that this type of control results in non-integer (harmonic current at frequencies that are not integer multiples of the fundamental frequency) and sub-harmonics (harmonic current at frequencies lower than the fundamental current.)

In phase control, thyristors are fired during each half cycle and power is controlled by varying the firing angle α depicted in figure 7. The fundamental and lower order current harmonics for various firing angles is shown in the bottom image.

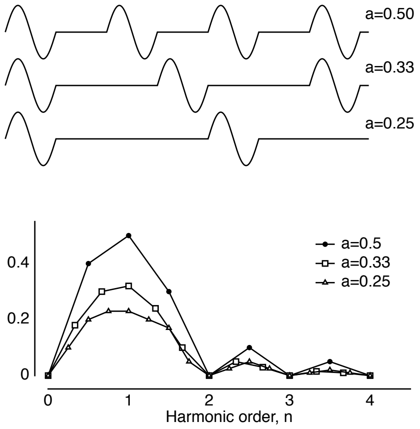

Figure 6: Burst control waveforms and harmonics

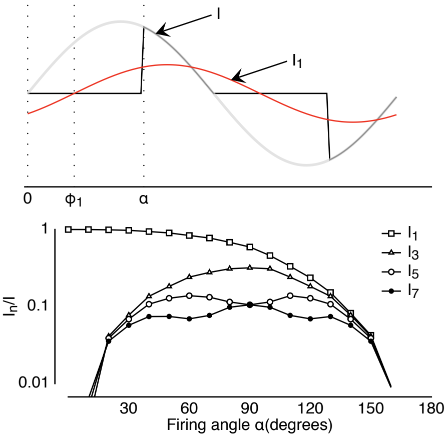

Figure 7: Phase control waveforms and harmonics

In controlling resistive loads by phase control it is observed that the current fed also includes a lagging reactive component. A simple resistive load controller and the amount of reactive power drawn by the controller is shown in figure 8.

1.5 Cyclo-converters

Cyclo-converters are static frequency converters that convert multi-phase fundamental frequency voltage to single or multi-phase voltage at a lower frequency. A characteristic of cyclo-converters is that they operate in most cases without circulating current.

A three-phase cyclo-converter generally consists of three inverse parallel connected three-phase thyristor converters that together provide the output for

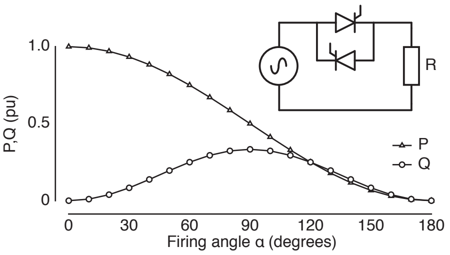

Figure 8: Phase control and reactive power

the lower frequency three phase system. A simple schematic is shown in figure 9.

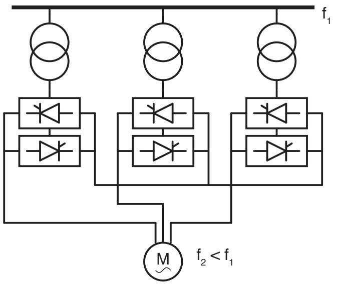

Figure 9: Cyclo-converter schematic

The order of the harmonics in the input current of the cyclo-converter depends on the pulse number (equation 1). In addition to these so-called typical harmonics a three-phase cyclo-converter produces harmonics the order of which depends on the cyclo-converter output frequency as follows:

$$n = (kp \pm 1) \pm 6m\frac{f_2}{f_1} \tag{3}$$

where

n = order of harmonic
p = pulse number
k = 1, 2, 3, ...
m = 0, 1, 2, ...
f_1 = supply network frequency
f_2 = cyclo-converter output frequency

If the output frequency of the cyclo-converter is 3 Hz, for example, there appear components on each side of the fifth harmonic. Additional harmonics will also appear as a function of the output and line frequency.

The cyclo-converter harmonic amplitudes depend on the load, load power factor, degree of firing angle and control mode. In some cases the non-harmonic components may be of greater magnitude than the harmonic components. “Harmonic” is taken to mean integer multiples of the fundamental frequency. Distortion at frequencies such as 268 Hz is non-harmonic per definition.

1.6 Arc furnaces

Since the current drawn by arc furnaces is, particularly in the initial melting phases, appreciably non-sinusoidal, these furnaces are also sources of harmonics. Measurements on different arc furnaces have shown that furnace current includes almost all harmonics. Average and instantaneous harmonic currents are presented in table 2.

Table 2: Average and peak furnace harmonics

Harmonic order, *n*	*% of fundamental current* *Average*	*Maximum*
2	4−9	30
3	6−10	20
4	2−6	15
5	2−10	12
6	2−3	10
7	3−6	8
9	2−5	7

2 Distribution of harmonics

The harmonic producing part of the total load has increased continuously over recent years. Power electronics is being used more extensively in industry for the control of various processes. A consequence of this has been an increase in the harmonic voltages and currents in the supply networks of industrial establishments and electricity undertakings. Harmonics cause additional losses in network components and may disrupt communication and control equipment, causing loss of time, product and equipment.

Capacitance – whether in the form of power factor correction equipment or stray capacitance from cable networks – in networks subject to harmonics may cause harmonic currents and voltages to be amplified. In order to avoid the harmful effects of harmonics it is necessary to be informed of the possibility of their appearance whilst still in the planning phase and if necessary to carry out a network harmonic study. In a network already in use a harmonic analysis will become necessary if, for example, converter power increases considerably. An increase in compensation power also generally makes a harmonic analysis necessary. The better the electrical values of the different network components and their frequency dependent impedance are known the more exact will be the picture of harmonic distribution given by the harmonic study.

For the analysis of harmonics there are now available various software programs that also take into account the frequency dependence of different components, and that can calculate the distribution of harmonics, find possible resonance situations and are of assistance in the electrical design of harmonic filters..

Sources of harmonics are generally represented as constant current sources injecting harmonic current

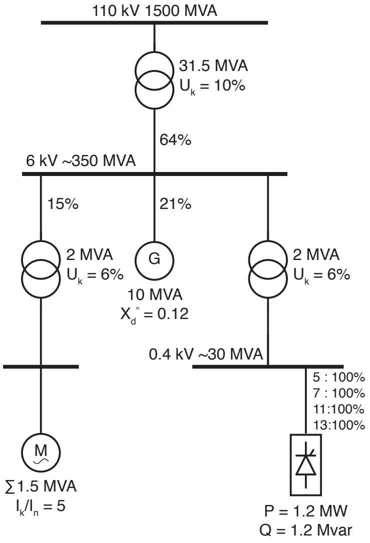

Figure 10: Distribution of harmonics

into the network. Harmonic currents are distributed throughout the different components in the network so that, at any given frequency, the part of the network with the lowest impedance carries relatively the greatest part of the harmonic currents. The impedances used are the short circuit impedances of the various components. Figure 10 shows the distribution in an industrial network. The spectrum of a non-linear load is normalised for reference, and the total harmonic current distortion through various network components as a result of this non-linear load is shown.

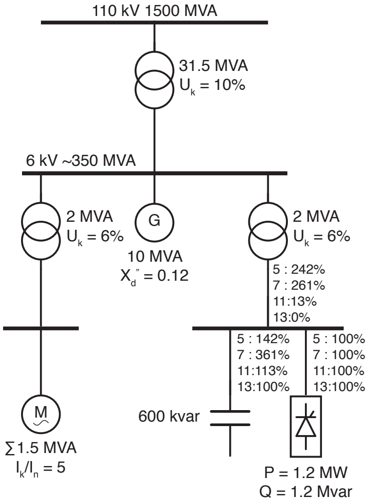

Figure 11: Amplification of harmonics

In figure 11 the new distribution of harmonics is calculated when compensation capacitors are applied to the same busbar as the non-linear load. It is clear that in this case substantial amplification of harmonic current is taking place: for example, for every 1 A of seventh harmonic generated by the non-linear load, 3.6A will flow into the capacitor bank and 2.6 A will flow into the supply transformer feeding that busbar. This is a clear example of harmonic resonance.

In examining what factors affect the network resonance frequency and the distribution of harmonics it is noticed that increase of short circuit power (network inductance decrease) raised the network resonance frequency and a still greater part of the generated harmonics flow into the network. Squirrel cage motors loading the network also increases the resonance frequency, but at the same time damp the resonance.

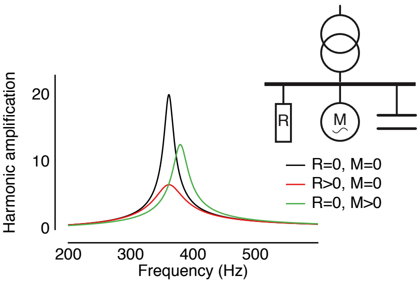

Figure 12: Effect of different loads on resonance

A resistive load does not affect the resonance frequency markedly, but damps the resonance considerably. Raising the degree of reactive power compensation by capacitors reduces the resonance frequency of the network. Figure 12 shows the effect of different loads in damping and shifting the resonance frequency.

3 Measurement of harmonics

Measurement of harmonics in industrial networks and those belonging to electricity utilities is usually carried out by making use of current and voltage transformers that are already part of the network. In some cases, a separate clamp-on current transformer may be used.

For reliable measurement results it is necessary to ascertain whether the voltage and current transformers used in the measurements are capable of reproducing the higher frequencies reliably. In general it may be said that current transformers reproduce reliably harmonics with frequencies of some kilo-herz while the reproduction range of voltage transformers may only be some hundreds of herz.

The following should be considered in all measurements:

1. Take note of the characteristics of the instrument transformers, specifically accuracy class, burden, and construction.

2. Know what network configuration exists. Any number of possible scenarios (fault level, bus configurations, transformer connections and tap position, etc.) may occur and filter designs will be based on the network conditions prevailing when measurements were done.
3. Be aware of the nature of the loads in the network. With modern IGBT inverters the interesting, high frequency and non-integer harmonics may occur outside the range of the measurement device.
4. Plan the analysis process before planning the measurement regime. One normally only gets one go at performing site measurements due to the cost of equipment, travel and access arrangements, so make sure everything you need to measure to construct the model is covered, and that the locations where the measurements are made are consistent with the requirements of the model.
5. Harmonic measurements create a surprisingly large amount of data. Make sure you have a plan for the storage, manipulation, verification and traceability management of the data. For example, measurements over a two week period using 3 second data on three phase of voltage and current on two feeders results in 240 million discrete measurements if all harmonics to the fiftieth are recorded.

Modern measurement equipment can easily provide the voltage and current harmonics phase angles, from which the direction of the harmonic with respect to the network may be determined. In theory it can be said that a part of the network is receiving harmonics when the angle between voltage and current at that frequency is in the range $-90^\circ \ldots +90^\circ$. Correspondingly harmonics are being produced if the phase angle is in the range $+90^\circ \ldots + 270^\circ$.

Care should be taken in interpreting phase angle measurements at harmonic frequencies: current and voltage transformers, depending on technology, burden, and accuracy can have large errors in magnitude and phase and without magnitude and phase calibration harmonic direction measurements can be meaningless.

3.1 Verification of coincidence factors

A critical aspect of model construction is the use of coincidence factors or diversity of distributed harmonic sources. In a wind farm of 100 turbines, the model cannot assume that all turbines are operating at the same level and with the same harmonic generation — some means of taking the load/generation diversity must be incorporated in the model. This is clearly a very important lever that can be used to manipulate the outcome of harmonic studies and the assumptions made in the model must be stated explicitly. The best way to justify the use of a specific diversity factor is to relate its use to existing installations where a model has been set up and calibrated by field measurements.

3.2 Recording existing harmonic levels

It is very important that existing background harmonic distortion be recorded, whether in greenfield or brownfield applications. Most filter design will (or at least should) require post-installation measurements to verify the performance of the equipment. Such measurements are almost meaningless unless the pre-existing harmonic distortion was measured *and* taken into account when the filters were designed.

These measurements should cover a time span of at least a few weeks in order to obtain statistical figures, keeping in mind the requirements of the measurement standards.

3.3 Measurements during commissioning

Apart from the normal tests of voltage rise, reactive power output and verification of the tuned frequency, it is highly recommended to install a transient recorder during energisation of a harmonic filter to capture transient conditions inside the bank and imposed on the network and switching equipment.

Verification of the harmonic performance of the filter is naturally an important test, keeping in mind that the measurement conditions will probably never correspond to the worst case conditions for which the filter design has been made.

3.4 Measurement results

Measurements were carried out of the supply transformer the secondary current in the network shown in figure 13.

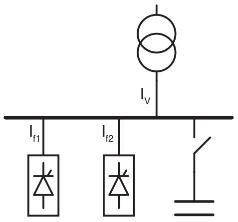

Figure 13: Plant with multiple converter loads

The sources of harmonics were two identical six-pulse thyristor bridges. The firing angles of the two bridges were independent of each other. Table 3 presents the measured harmonic currents in the supply transformer, I_V.

As can be seen from the results of the measurements the fifth harmonic is only 3.4% of the fundamental frequency component, while the expectation from equation 2 is that this component should be approximately 20%. The reason for the low fifth harmonic content is revealed from the voltage waveform on the supply bus as shown in figure 14.

Table 3: Harmonics with independent converters

Harmonic order	I_V//A	I_V//%
1	817	100
5	28	3.4
7	29	3.5
11	57	7
13	32	3.9
17	11	1.3
19	18	2.2
23	18	2.2

It is clear that the control angles (firing angles) of the converter bridges are different — the commutation notches are not aligned. The fifth harmonic currents are therefore not in phase and as can be seen from the vector summation of the harmonics there is substantial cancellation of the fifth harmonic under these specific conditions.

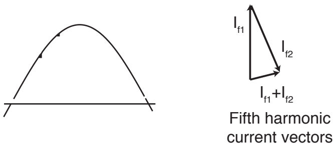

Figure 14: Harmonic summation: independent converters

Regulating the thyristor bridge control angles so that they were almost identical as illustrated in figure 15 resulted in measurement of harmonic currents as reported in table 4. This is much closer to what is expected from equation 2.

Table 4: Harmonics with converters aligned

Harmonic order	I_V/A	I_V/%
1	800	100
5	158	19.9
7	71	8.9
11	51	6.4
13	35	4.4
17	23	2.9
19	16	2.0
23	9	1.1

The harmonic sources of the network in figure 16 are frequency convertors equipped with fixed intermediate circuit voltage (input circuit consisting of uncontrolled diode bridges) with a total power rating of about 1 MVA.

For frequency convertors with diode bridge input circuits the harmonics sum arithmetically since there is no differences between the control angles.

Table 5 presents measurements of harmonics on the low voltage side of the supply transformer. Values are of the same order of magnitude as predicted by equation 2. The table includes the effect of switching two steps of power factor correction in to compensate for reactive power. These non-tuned capacitors clearly cause parallel resonance as can be seen from the increase in current distortion through the supply transformer and increase in harmonic current distortion.

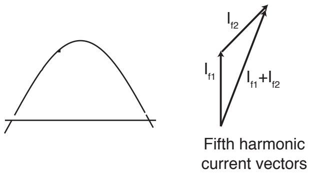

Figure 15: Harmonic summation with converters almost aligned

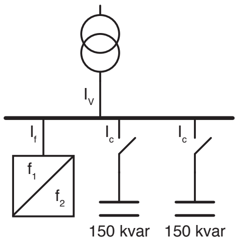

Figure 16: Plant with frequency converters

Table 5: Harmonics with uncontrolled rectifiers

Harmonic		I_V/%	
order	0 kvar	150 kvar	300 kvar
1	100.0	100.0	100.0
5	20.9	26.5	26.9
7	6.9	10.1	23.7
11	5.5	16.8	20.7
13	3.3	15.2	10.5
17	2.6	4.5	2.5
19	1.9	2.9	2.3
V_{THD}/%	4.2	8.3	8.3

Non-linear loads affect the power system, specifically in terms of voltage distortion due to harmonic current generated by the load and passed into the network. Power systems also affect non-linear loads. Voltage distortion on the busbar feeding the converter will result in a different harmonic spectrum drawn by the load than if there was no distortion of the busbar voltage. In figure 17 a simple network is shown that contains an uncontrolled rectifier converter and a fifth harmonic filter.

The results of measurements of the converter current are shown in table 6. It is clear that the presence of the shunt connected filter has a very significant impact

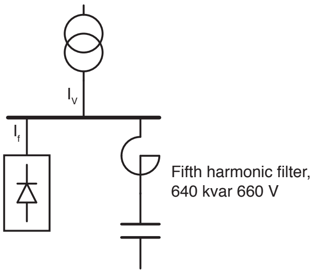

Figure 17: Effect of filter on converter current

Table 6: Effect of filter on converter current

Harmonic order	I_V/% No filter	With filter	*Change* %
1	100	100	0.0
5	31.8	39	22.6
7	4	7.2	80.0
11	10.4	9.5	−8.7
13	2.1	1.9	−9.5
17	5.3	4.9	−7.5
19	1.5	0.8	−46.7

on the converter current, increasing some harmonic current and reducing others.

The measurement results presented above underscore the importance of performing and understanding detailed measurements of harmonic distortion in any facility, before any design work is carried out.

4 Reactive power compensation and harmonics

4.1 Operation principle

The function of a harmonic filter is to remove harmonics appearing in a network and to produce capacitive reactive power at the fundamental frequency. By frequency tuning, filters present a low impedance between phase and star point or between phases, so that the frequency tuned harmonic flows into the filter and does not spread into the feeding network. Harmonic filters are connected at an appropriate voltage level in each network. Harmonic filters consist, depending on the requirements of each application, of one or more branches, each of which is tuned to harmonic frequencies appearing in the network in question.

4.2 Single-tuned filter

A filter tuned to one frequency consists of a capacitor bank and reactor connected in series, as shown in figure 18.

The capacitance of the capacitor bank is generally determined by the compensating power required for the fundamental frequency. The inductance of the filter reactor is chosen so that together with the capacitor it forms a a resonant circuit at the desired frequency.

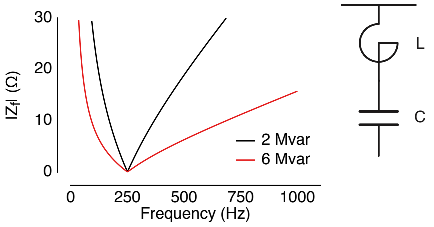

Figure 18: Single-tuned harmonic filter

4.3 Wideband filter

In a wideband filter a resistor is connected in parallel with the reactor, for example as shown in figure 19. The result of this configuration is that harmonics above the tuned frequency are also filtered.

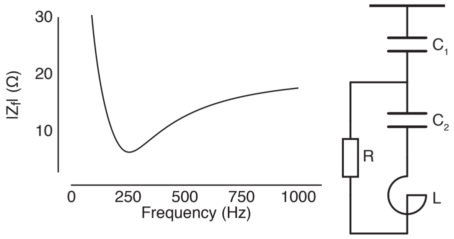

Figure 19: Wideband filter

The resistor reduces the filtering effect at the tuned frequency. The purpose of the capacitor C_2 is to reduce the fundamental frequency current flowing through the resistance and consequently to reduce the losses in the resistor.

4.4 Information required for filter design

Filters are always designed according to the requirements at the specific location where they will be used so that the relevant technical and economic factors can be taken into account in the best possible way.

For filter design, the following information is required from the client:

1. Desired reactive power at the fundamental frequency (maximum and minimum)
2. Service voltage and possible range of variation
3. Rated frequency
4. Insulation requirements if these are different from normal values at that service voltage

5. Required fault withstand capability
6. Frequency dependent network impedance for all possible operating conditions for which the filter is expected to provide the desired mitigation, or if not available then the actual short circuit current at the filter connection point and possible range of variation
7. Information of loads generating harmonics
8. Permissible harmonic content
9. Details of the installation environment (indoor/outdoor, pollution, temperature range, wind and seismic requirements, etc)

4.5 The need for harmonic filters

All networks have limits for the extent of harmonic distortion that can be present in the network. In almost all networks there are statutory limitations, for example legislation relating to the conduct of energy users that refer to technical standards to determine exactly what those limits should be.

Two broad categories of standards are used: those that aim to limit voltage distortion in the network by applying limits to the amount of harmonic current distortion caused by individual customers or loads (the IEEE Std 519 approach) and those that allocate permissible contribution to voltage distortion at specific nodes in the network based on network and load characteristics (the IEC 61000 approach). Neither approach is perfect or uniformly fair, and both rely on either making simplifying assumptions about the nature of the supply network (for example the IEEE approach does not expect any reactive power compensating capacitors to be in the supply network) or require detailed knowledge of the network (for example the IEC approach assumes that the frequency dependent nature of the supply network is known).

As networks become more exposed to harmonic producing loads and simultaneously are expected to last longer and transfer more power than before, there is widespread implementation of reactive power compensation in networks. These can be implemented as simple capacitor banks, possibly fitted with inrush current damping reactors, or as detuned or filter capacitor banks.

Any addition of capacitor banks to an existing, purely inductive and resistive network will result in a significant change in the network impedance. If a parallel capacitor alone is used in a network containing harmonics, then the capacitance together with the inductance of the feeding network forms a resonant circuit, with:

$$f_r = f_1 \sqrt{\frac{S_K}{Q_C}} \tag{4}$$

where

f_r = resonant frequency in Hz
f_1 = fundamental frequency in Hz, for example 50 Hz
S_K = short circuit power at the capacitor bank connection, in MVA
Q_C = capacitor bank compensating power, in Mvar

If the natural frequency calculated from equation 4 is near to some harmonic appearing in the network, then that harmonic will be amplified considerably. The biggest amplification factor may be in the order of 20.

4.6 Choice of filter

In designing a filter the aim is the simplest and least cost construction that will satisfy the requirements for reactive power compensation and filtering. In practise that may mean that the fifth and seventh harmonics may be filtered by single tuned filters, and the upper harmonics by a single wide-band filter.

Filter compensation power affects filter characteristics: the greater the compensation power the better the harmonic suppression. The different branches of a harmonic filter may be connected each to its own circuit breaker and use, for example, a reactive power regulator to control them according to the reactive power requirement, or can use a common circuit breaker. When each branch has its own breaker, connection of the different branches to the network should take place in the order of the harmonics, beginning with the lowest, and disconnection should take place in the reverse order. Switching order is important in order to avoid harmonic resonance.

In choosing and designing a filter a central factor is the distribution of compensating power between the different branches of the filter. This should be carried out so that:

1. The same capacitor units may be used in different branches
2. Capacitor banks are used at rated voltage (no excess voltages)
3. Parallel resonant frequencies occurring at frequencies between those of the absorption circuits do not coincide with harmonics that may appear in the network, for example even harmonics
4. Branch powers are suitable for (existing) switchgear
5. Filter inductors are reasonable to assemble
6. Filtering results are adequate.

4.7 Effects of filters

Filters are able to reduce from 60% – 90% of harmonics. Filtering results depend on the relation between the impedance of the supply network and the filter.

The solution is always a compromise since the filter removes those harmonic for which it has been designed but increases harmonics at intermediate frequencies.

An example of a filter application is shown in figure 20, where the harmonics produced by a nonlinear load are mitigated by a harmonic filter with three branches: single tuned filters for the fifth and seventh harmonics, and a wideband filter tuned to the eleventh harmonic.

In what follows, Z_n is the frequency dependent impedance of the network (dominated by the supply transformer, but with the additional impedance of the network in series with the supply transformer), and Z_f is the equivalent impedance of the three filter branches connected in parallel.

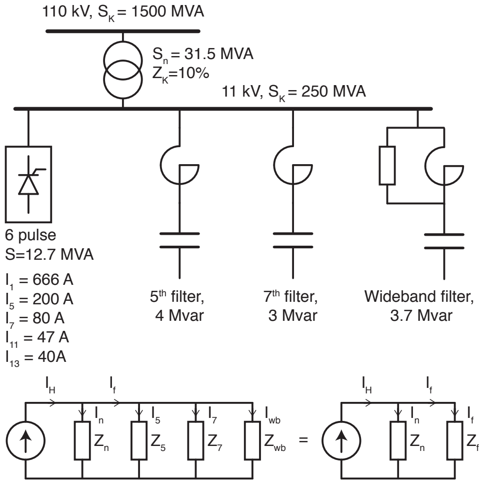

Figure 20: Example of a harmonic filter in industry

The frequency dependent impedance of the network and the filter alone are presented in figure 21.

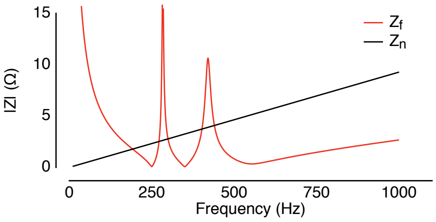

Figure 21: Filter and network impedance

The extent to which harmonics are absorbed by the filter or injected into the network is determined by the current divider expressions:

$$I_n = I_H \frac{Z_f}{Z_n + Z_f} \tag{5}$$

$$I_f = I_H \frac{Z_n}{Z_n + Z_f} \tag{6}$$

where

I_H = harmonic current produced by the load
I_n = current flowing into the network
I_f = current flowing into the filter
Z_n = network impedance
Z_f = filter impedance

When reviewing the impedance of the network with the filters connected, illustrated in figure 22, three clear resonance points can be observed. The lowest frequency resonance point is produced by the interaction of the total capacitance of the filter and the inductance of the network, and this frequency is always lower than the lowest tuned frequency of the filter. Two other resonance resonance points represent resonances between the separate branches of the filter.

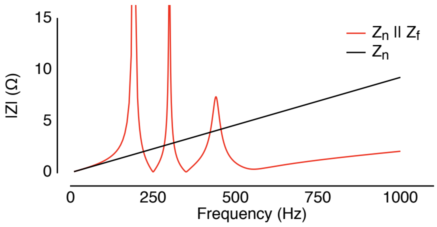

Figure 22: Network impedance with filters connected

Where the common impedance of the filter and network is less than the network impedance, harmonics are filtered according to the expressions in equation 5, and where the common impedance is greater than the network impedance, harmonics are amplified.

It is important to note that in most cases, Z_n will not be a simple inductance — the presence of one or more capacitor banks in the external network and changes in supply network topology may result in wide variations in impedances at fundamental and higher frequencies. One of the major challenges in filter design is to gain an accurate understanding of the nature of the network impedance. As this is largely out of the control of the filter designer, and may change at any time and over time, any filter design must take such variations into account and be robust enough to be effective under a variety of network conditions.

The art of harmonic filter design is to select the shape of the impedance Z_f to modify the network impedance Z_n in such a manner that the necessary reduction in harmonic current is achieved without causing amplification of other harmonics, taking into account the possible variations in network impedance, and to produce this solution at the lowest possible cost.

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