



Power Factor Correction and Harmonics

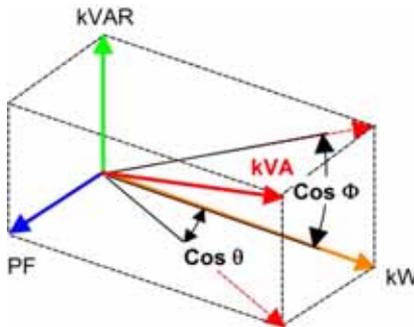
(Passive Inductance Solutions)

Types of Power Factor

There are two types of power factor:

- the **Displacement Power Factor** which is caused by inductance in an electrical load causing the consumed current to lag behind the supply voltage and
- the **Harmonic Power Factor** which results from non-linear switching of the supply voltage as in the case of rectifiers or power semiconductors.

Therefore the true power factor is a combination of both of these.



The apparent power kVA delivered to an electrical load is always much higher than the power used (kW). Hence electrical equipment has to be rated for the kVA and this also means that the current is much higher than that given on the rating plate of the load and so the supply cables, protective devices and transformers have to be oversized accordingly.

Harmonic Distortion Definitions

The harmonic distortion created by a load is obtained by measuring the current at each harmonic frequency (multiples of the mains supply frequency which is normally 50Hz or 60Hz for the public supply network). Then for each harmonic the ratio of the harmonic current to total current is calculated.

$$\frac{I_n}{I_t}$$

Total Harmonic Distortion (THD) is the ratio of the rms value of the harmonics (in this context harmonic currents I_n of the order n) to the rms value of the fundamental.

$$THD = \sqrt{\sum_{n=2}^{40} \left(\frac{I_n}{I_t}\right)^2}$$

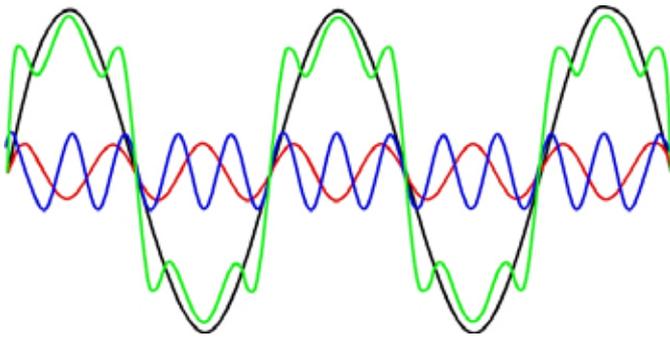
Partial Weighted Harmonic Distortion (PWHD) is the ratio of the rms value of a selected group of higher order harmonics (here beginning from the fourteenth harmonic order, to the rms value of the fundamental).

$$PWHD = \sqrt{\sum_{n=14}^{40} n \left(\frac{I_n}{I_t}\right)^2}$$

Note: The partial weighted harmonic distortion is employed in order to ensure that the effects of the higher order harmonic currents on the results are reduced sufficiently and individual limits need not be specified.

Voltage Distortion (THDU) is caused mainly by the high level of Current Distortion (THDI) and the level of THDU is very much dependent on the source impedance. Higher source impedance means a higher THDU.

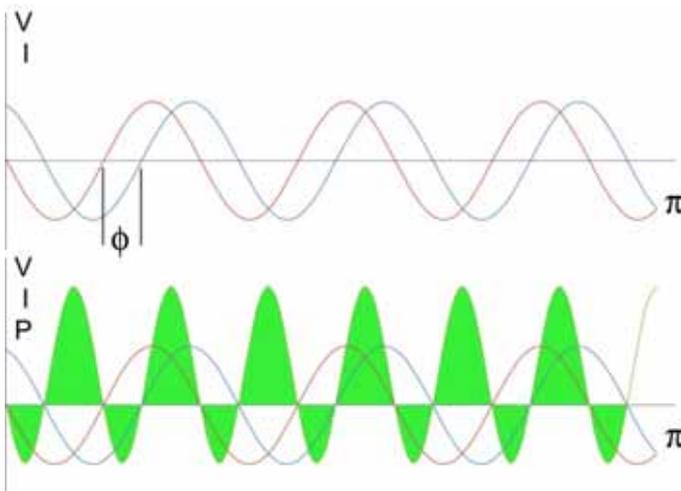
Problems associated with harmonics



1) Mains voltage distortion

The fundamental current waveform is in black and the third and fifth harmonics are in red and blue respectively.

The resulting distorted current waveform is shown in green. This can be any shape depending upon the frequencies and magnitudes of the most dominant harmonics.



2) Losses of electrical energy

With any inductive load the reactive component has the effect of impeding current flow and so the net effect is that the current waveform lags the voltage waveform. Consequently because $P = V \times I$ sometimes one of these values is negative, which means that the power is being returned back to the mains. Hence more power is required in addition to useful power. The returned power generates losses in the circuits and components and so part of the power is wasted. There is a power factor relating to each harmonic.

3) Increase in the apparent power and over-sizing of sources

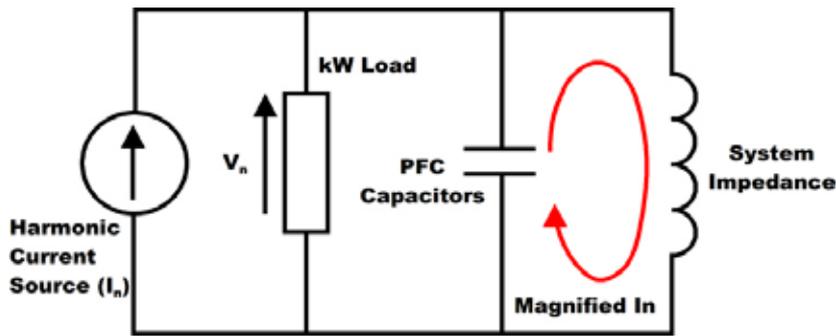
The apparent power increases as explained in (2) and so does the supplied current. For this reason when harmonics are present conductors and components have to be rated for much higher currents than they need to be, with a corresponding increase in the cost of installation. Failure to up-rate cables could cause current overload and subsequent heating or even fire in extreme cases.

4) Damage to capacitors

The mains network is generally considered to be inductive and its impedance increases with frequency. Conversely the impedance of capacitors reduces with frequency and so harmonic currents which are at higher frequencies are more likely to flow in capacitors that are connected in circuit. The increased currents cause higher voltages across the dielectric of the capacitor which can lead to stress and premature failure.

5) Harmonic resonance

Because capacitors work in the opposite manner to inductors, i.e. they encourage current flow rather than oppose it, they are often used as a solution for power factor correction. The current waveform of a charging and discharging capacitor leads that of the supply voltage waveform. Therefore by connecting the correct amount of capacitance into a circuit that has bad power factor due to inductive reactance, it is possible to alter the power factor so that $\cos \Phi$ is approximately 0.95 (it becomes progressively more expensive as a power factor of 1 is approached and so often this cannot be justified – also Power Utility Companies do not like to have capacitive reactance connected to their power network for various reasons).

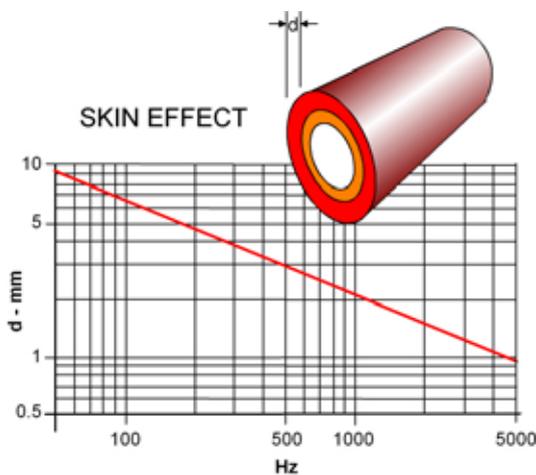


Harmonic resonance is generally caused by parallel resonance between the Power Factor Correction capacitors connected to a load and the transformer supplying that load. When a number of harmonic current sources are injecting currents into the supply and the frequency of one of the harmonics coincides with the

resonant frequency of the supply transformer and Power Factor Correction capacitor combination, the system resonates and a large circulating harmonic current is excited between these components. The result of this is that a large current flows in the supply transformer, resulting in a large harmonic voltage distortion possibly causing equipment malfunction, loss of transformer output due to increased heating, interference with communication systems, premature failure of motors and power factor capacitors.

6) Transformer and neutral conductor overload due to excessive zero-phase currents

Most single-phase loads such as PCs and similar equipment utilising a Switch-mode Power Supply and connected between a phase and neutral demand a 3rd, 9th and 15th order of harmonic currents, termed as TripleN which have a return path through the neutral conductor. However, these TripleN harmonics do not cancel each other out, but instead add to each other. This is why most IT suites and buildings require a double-rated neutral.



7) Conductor losses (skin effect)

The resistance of a conductor increases as frequency increases due to a phenomenon known as the “skin effect”. This causes the current to concentrate around the outer surfaces of a conductor so that its cross-section no longer has uniform current density. The “skin depth” is the depth below the surface of a conductor by which the current density has reduced to 1/e of its value at the surface (approximately 1/3).

In the case of copper, for example, at 150Hz (3rdharmonic) the “skin depth” is 9mm whereas at 1050Hz (21stharmonic) it is only 2mm. Hence conductors become less efficient and generate heat.

8) Negative rotation sequences in motors

The outside stationary stator in an induction motor has coils which are supplied by AC current to produce a rotating magnetic field which is followed by the rotor. Some harmonics, particularly the 5th, 11th and 17th create a negative sequence which opposes the rotating field. This can generate high losses within the motor and possibly overheating leading to premature failure.

9) Overheating of transformers

Transformer windings suffer increased I^2R self-heating (often called “copper losses”) due to the presence of harmonic currents plus their increased resistance at higher frequencies due to the “skin effect”. Also, the harmonic currents in neutral conductors in transformers suffer from harmonic build-up (especially TripleNs), which can reach 2.1 times the phase currents.

An effect similar to the “skin effect” in conductors increases the eddy current losses in the silicon-iron cores of mains transformers as frequency increases, causing an increase in the eddy current losses for a given power transfer than would be expected from the true rms current values.

Special “K rated” transformers are used where harmonic currents are known to exist.

10) Nuisance tripping

Waveforms distorted by harmonics can cause fuses, circuit breakers and other over-current protection devices to trip to protect from overheating, despite the fact that they are correctly calculated for the rated load but assuming a pure sine-wave supply. Therefore, oversized protection devices have to be fitted, which are more expensive but more importantly they may not prevent damage to the equipment which is supposed to be protected or a possible fire hazard.

11) Zero-crossing noise

There are a number of control and timing systems that rely on the zero-crossing point of the mains sine-wave for timing, e.g. phase-angle controllers, automatic voltage regulators and three-phase rectifiers for DC motors. Some combinations of harmonics can cause several zero-crossing points to occur and can disrupt the operation of electrical equipment that require timing related to the fundamental frequency.

12) Failure of stand-by generating sets

Harmonics can cause unforeseen problems when switching over from mains to stand-by power such as in the case of a hospital for instance.

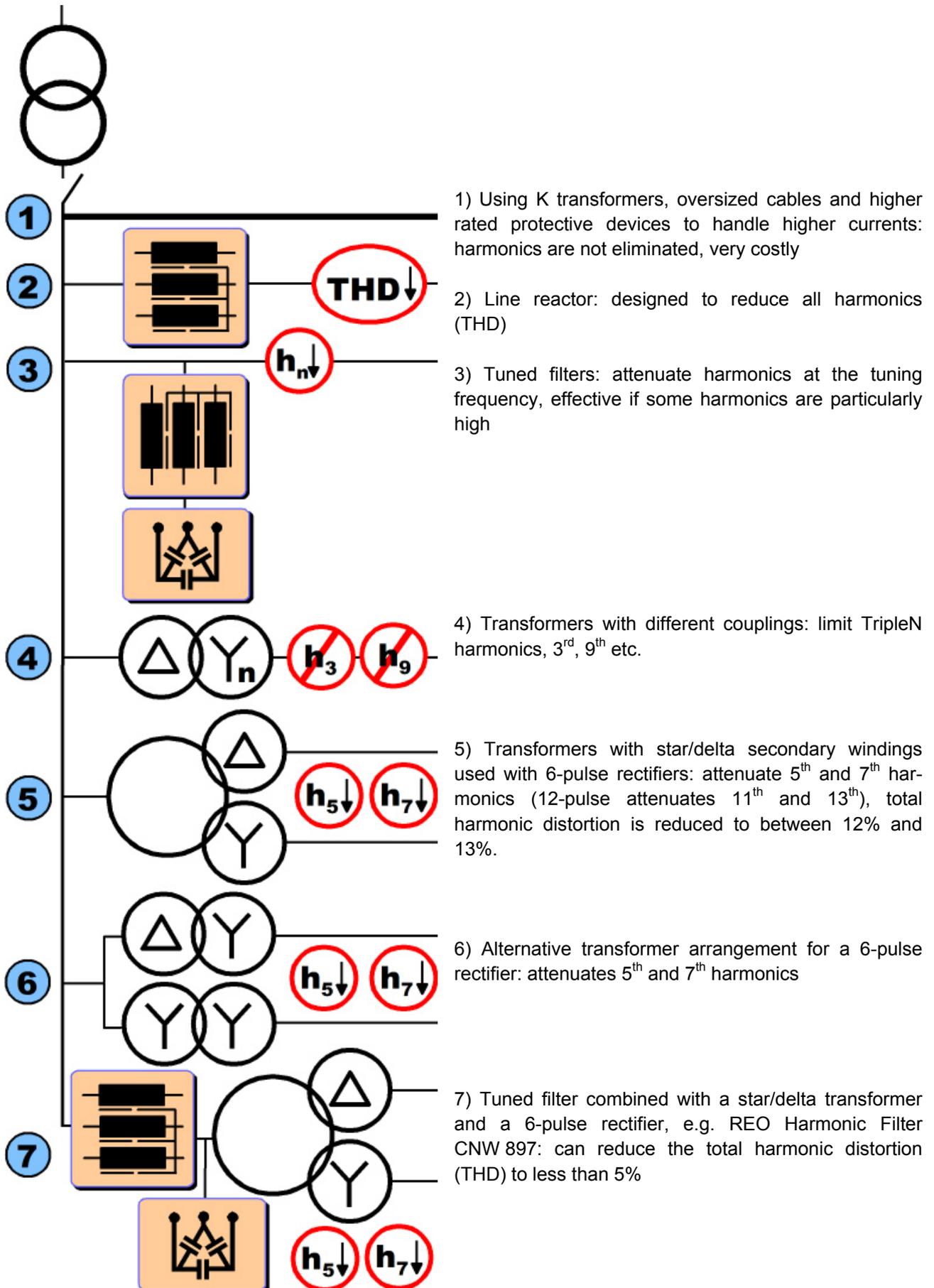
Causes of harmonics

Any non-linear load, which includes switching, on the mains distribution network will generate harmonics and the waveform associated with a load can be analysed and broken down to give a harmonic spectrum. The following are just a few examples of electrical equipment that produces harmonics:

- Uninterruptible power supplies
- Motors, fans and pumps
- Servers (especially blade-servers which have a leading power factor)
- Personal computers, video monitors, printers and photocopiers
- Fluorescent lights, low energy bulbs and low voltage lighting using electronic transformers
- Lifts and escalators
- Variable speed drives and switched-mode power supplies
- Rectifiers, power converters and thyristor power controllers
- Chillers, compressors, freezers and microwave cookers
- Air-conditioning, heating and ventilating equipment

Passive Solutions

There are a number of solutions available for limiting and attenuating harmonics. The following techniques employ passive components which are selected to attenuate particular harmonics rather than the whole range, which generally is a more economical approach.



Limits for Emission

In the European community there are now two standards for limits that are called up by the EMC Directive 2004/108/EC. These are

- **EN 61000-3-4** which is for equipment with an input current of up to 16A per phase and
- **EN 61000-3-12** which is for equipment with an input current of greater than 16A per phase up to 75A per phase (introduced on 1st February 2008).

In these standards there are prescribed limits for emissions which apply to 230/400V, 50Hz systems. The following two tables have been extracted from EN 61000-3-12.

Table 2 – Current emission limits for equipment other than balanced three-phase equipment

Minimal $R_{s_{ce}}$	Admissible individual harmonic current I_n/I_1 ^a %						Admissible harmonic current distortion factors %	
	I_3	I_5	I_7	I_9	I_{11}	I_{13}	<i>THD</i>	<i>PWHD</i>
33	21,6	10,7	7,2	3,8	3,1	2	23	23
66	24	13	8	5	4	3	26	26
120	27	15	10	6	5	4	30	30
250	35	20	13	9	8	6	40	40
≥ 350	41	24	15	12	10	8	47	47

The relative values of even harmonics up to order 12 shall not exceed $16/n$ %. Even harmonics above order 12 are taken into account in *THD* and *PWHD* in the same way as odd order harmonics.

NOTE Linear interpolation between successive $R_{s_{ce}}$ values is permitted. See also Annex B.

^a I_1 = reference fundamental current; I_n = harmonic current component.

Table 3 – Current emission limits for balanced three-phase equipment

Minimal $R_{s_{ce}}$	Admissible individual harmonic current I_n/I_1 ^a %				Admissible harmonic current distortion factors %	
	I_5	I_7	I_{11}	I_{13}	<i>THD</i>	<i>PWHD</i>
33	10,7	7,2	3,1	2	13	22
66	14	9	5	3	16	25
120	19	12	7	4	22	28
250	31	20	12	7	37	38
≥350	40	25	15	10	48	46

The relative values of even harmonics up to order 12 shall not exceed $16/n$ %. Even harmonics above order 12 are taken into account in *THD* and *PWHD* in the same way as odd order harmonics.

NOTE Linear interpolation between successive $R_{s_{ce}}$ values is permitted. See also Annex B.

^a I_1 = reference fundamental current; I_n = harmonic current component.

In the USA the relevant standard is IEEE519 – more concerned with the point of common coupling (PCC)-point in the public network which is closest to the consumer concerned and to which other consumers are or may be connected.

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