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HARMONICS

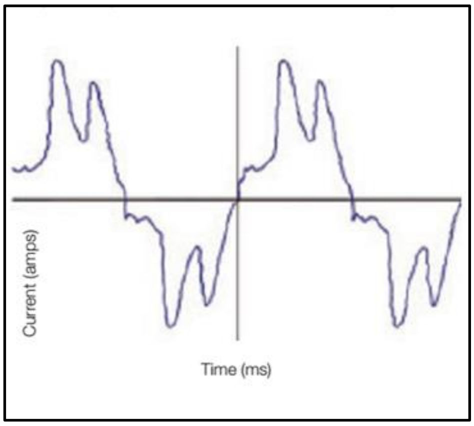
Harmonics are perhaps the most pronounced disturbances related to the supply waveform, operating at relatively low frequencies; their effects are generally noticed to a maximum of 2500 Hz.

Harmonics are generated by equipment termed “Non-Linear”, that is, they present a non-constant voltage/current ratio and will absorb a non-sinusoidal current when supplied by a sinusoidal voltage.

Typical examples of non-linear loads:

- Static Power Converters (SCR’s) such as variable speed drives, frequency converters, soft starts, battery chargers
- Arc furnaces and electric welding equipment.
- Certain U.P.S. systems.
- Single phase electronic equipment employing AC to DC power supplies.
- Electronic lighting control.
- Transformers and reactors having a nonlinear magnetising curve

Figure 4 - A typically distorted Current Oscillogram



What Are The Main Problems Associated With Harmonic Interference?

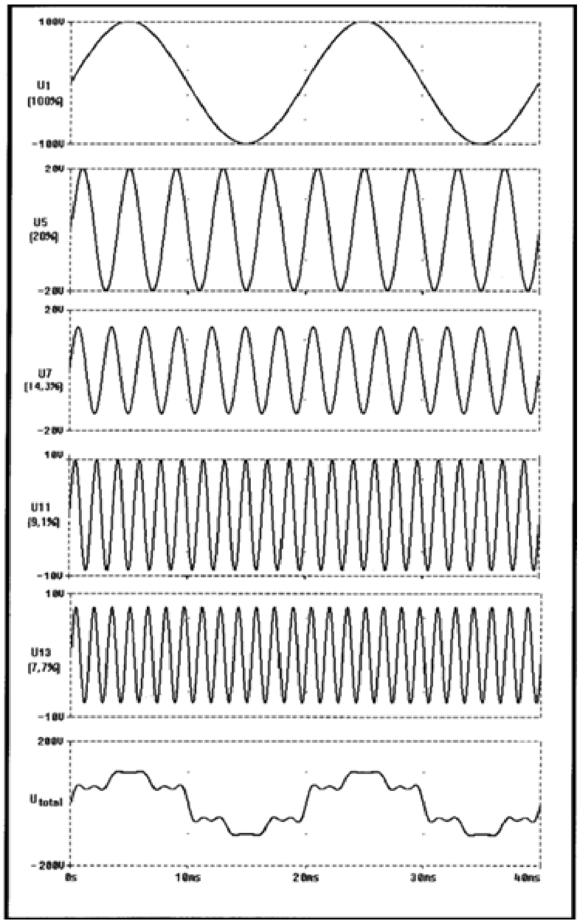
- Overheating of conductors
- Neutral overload
- Increased transformer losses
- De-rating of transformers
- Nuisance tripping of circuit breakers
- Overload and premature failure of PFC
- Neutral-earth potential
- Significant voltage distortion on weak networks
- Distortion reflected onto the common utility network
- Mal-operation of microprocessor-based equipment
- PC monitor “wobble”
- Lighting ballast premature failure
- Potential system resonance with PFC capacitors
- Causes linear devices to draw non-linear current
- Torque pulsation in motors
- Capacitor dielectric failure
- Insulation breakdown
- PC monitor and power supply failure
- Electronic Lighting failure

Harmonic Current Distortion

Both single and three phase non-linear loads can present a waveform that drastically departs from a sinusoid. Quantification of this complex signal can be derived by breaking it into its constituent components – known as “Harmonics”. A harmonic is a sinusoidal signal, the frequency of which is an integral multiple of the fundamental supply frequency (50 or 60Hz). The variation between the RMS value of the fundamental current and RMS value of the total (complex) waveform is termed “Total Harmonic Distortion” or THD and is measured as a percentage of the fundamental current.

As mentioned above a harmonic laden waveform can drastically depart from a perfect sinusoid. Fig 5 illustrates the composition of the resultant complex waveform from the fundamental and its constituent harmonics.

Figure 5 – Harmonic Waveform



Harmonic Voltage Distortion

Ohms law states that a current flowing across an impedance will generate a voltage drop; Non-linear load currents as illustrated above will create a volt drop at the frequency of the harmonic current causing it; this volt drop adds to the fundamental voltage causing it to be distorted. The variation between the RMS value of the fundamental voltage and RMS value of the total (complex) waveform is termed "Total Harmonic Distortion" or THD and is measured as a percentage of the fundamental voltage.

Voltage distortion causes negative effects on the entire distribution network and can have 2 origins:

1. Background distortion, this is present across the utility network supply due to the harmonic load placed upon it by the connected consumers' non-linear loads.

2. Local distortion, this is that present on the customers' own local distribution network due to its impedance and the harmonic loading placed upon it.

Local voltage distortion is generally much higher than the background voltage distortion on the utility supply since this has much lower impedance and the magnitude of the voltage distortion is directly proportional to the impedance of the system. Linear "Damping" loads present on the common supply will further reduce the level of voltage distortion.

System Resonance

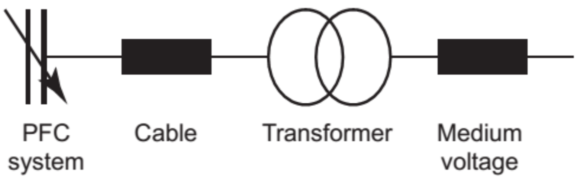
All electrical systems have a finite resonant condition; this is when the inductive reactance (X_L) and capacitive reactance (X_c) are equal, being in phase opposition, the two quantities cancel each other. If we consider system resistance (R) to be negligible when compared to either X_L or X_c then system impedance (Z) under resonant conditions will tend to zero. With little or no impedance to current flow, large circulating currents are generated.

If we consider that in an electrical power network the largest source of inductive reactance is the supply transformer with power factor correction capacitors being the largest source of capacitive reactance, forming a parallel circuit. So for given values of X_L and X_C the system will resonate at one particular frequency i.e. Resonant Frequency (f_0). If the resonant frequency is slightly below or equal to a harmonic frequency, then substantial magnification of current at that frequency will occur.

In practice a true resonant condition is rare due to the damping effect of series resistance and resistive loads, however, multiplication factors of 20 have been encountered. This illustrates that the presence of harmonic distortion is an important consideration when engineering a power factor correction scheme.

What Effect Does A PFC System Have On A Network With Harmonics?

A PFC system with no detuning forms a resonant circuit with reactive line impedances. The resonant frequency (f_0) is given by a simple rule of thumb:



$$f_r = 50Hz \cdot \sqrt{\frac{S_k}{Q_C}}$$

where

S_k = short-circuit power at the point where the correction system is connected
Q_c = correction system capacitor power rating

The short-circuit power (S_k) at the point where the PFC system is connected is:

- determined essentially by the transformer (S_n / Ƶ)
- reduced by some 10% by the impedance of the medium voltage system
- potentially greatly reduced by long lengths of cable between the transformer and the PFC system

Example:

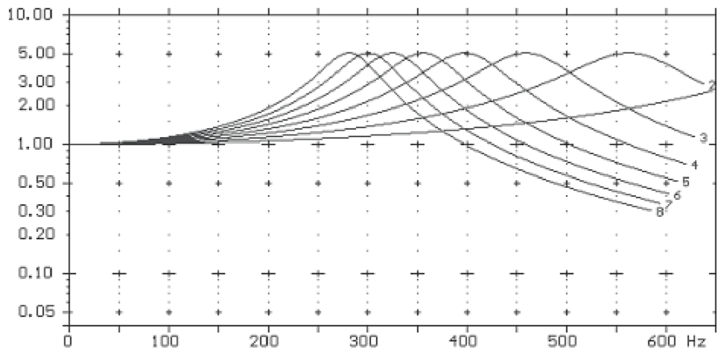
- Transformer 1000 kVA, Ƶ = 6%
- Short-circuit power of the medium voltage system 150 MVA, $S_k \approx$ 12.6 MVA
- PFC system 400 kVAr in 8 stages, not detuned

Capacitor power rating (QC)	Resonant frequency (fr)
100 kvar	562 Hz
250 kvar	355 Hz
400 kvar	281 Hz

When the capacitor stages of the correction system are switched in, the network resonant frequency (f_0) changes considerably and is repeatedly close to the frequency of a network harmonic.

If the natural resonance of this oscillatory circuit is near to a network harmonic that is present, it is to be expected that resonance will increase the harmonic voltages. Under certain conditions, these may be multiplied by an amount approaching the network Q-factor (in industrial systems about 5-10).

Figure 6 - Amplification factor for harmonic voltages in PFC system without detuning in the low voltage network



When Can Dangerous Network Resonances Occur?

From Fig. 6 it can be seen that it is possible to assess whether resonance problems can occur with harmonics. Simple rules can be applied from this this:

1.) If the resonant frequency is:

- **10%** below/above a network harmonic, the latter will be amplified in a network with a high Q-factor (e.g. in the evenings and at night) **by a factor of up to 4**.
- **20%** above a network harmonic, the latter will be amplified in a network with a high Q-factor **by up to 2.5.**
- **30%** above a network harmonic, the latter will be amplified only slightly, **by a factor of up to about 1.7.**

2.) In a network with no harmonic generator of its own, but with pronounced harmonics present in the medium voltage system, the following can occur:

- at a resonant frequency below 400 Hz - resonance peaks of the 7th harmonic
- **at a resonant frequency below 300 Hz - dangerous resonance peaks of the 5th harmonic (250 Hz)**

What Effect Does The Network Configuration Have On The Problem Of Harmonics?

The network short-circuit power determines the resonant frequency and, where harmonic generators are present in that network, the amplitude of the harmonics in the network voltage.

- If the networks short-circuit power at the point where the PFC system is connected is too low, this causes problems.
- If the short-circuit power is changed radically due to altered switching conditions, this causes problems.

Example:

In many large commercial facilities continuity of power supply is achieved by connecting the low voltage distribution points via a ring circuit. This network has a high short-circuit power even with large PFC systems and heavy rectifier loads with hardly any harmonics problems arising since the resonant frequency is high and the harmonic currents are dissipated with low voltage drops into the medium voltage system. If a break is made in the ring circuit, for example for maintenance work, the short-circuit power can decrease considerably under certain conditions, so that the resonant frequency can fall below 300 Hz!

Voltage and Current Loads On PFC Systems Without Detuning

When resonance occurs, the network r.m.s. voltage only increases slightly, but the r.m.s. value of the capacitor current increases considerably. In the case of resonance with the fifth harmonic, this can reach a level of, say, 15% in which case:

- The network r.m.s. voltage increases by 1%
- The crest working line voltage increases by 10-15% (depending on phase angle)
- **The r.m.s. value of the capacitor current increases by 25%!**

In the case of resonance with the 11th harmonic, this can reach a level of, say, 10% in which case:

- The network r.m.s. voltage increases by 0.5%
- The peak value of the mains voltage increases by 6-10%
- **The r.m.s. value of the capacitor current increases by 50%!**

Measures To Counteract Expected Resonances

If harmonics with high voltage levels, such as:

4%	of the	3rd harmonic	(150 Hz)
5%	of the	5th harmonic	(250 Hz)
4%	of the	7th harmonic	(350 Hz)
3%	of the	11th harmonic	(550 Hz)
2.1%	of the	13th harmonic	(650 Hz)

Due to resonance induced amplification are anticipated when planning a PFC system, serious disruptions can occur in the low voltage distribution system:

- Problems with IT systems and CNC machines
- Damage to rectifiers and/or converters
- Uncontrolled tripping of a variable capacitor bank and circuit breakers
- Shutdown of PFC systems without detuning
- Voltage peaks in the distribution system
- Increased eddy current losses in transformers and induction motors

If the level of individual harmonics with no PFC system amounts to more than 1.5% (7th and higher harmonics) or 2% (5th harmonic) and the resonant frequency of the network can be close to these harmonics, then it must be assumed that these permissible limits will be exceeded by resonance-induced amplification.

In situations of this type, only detuned PFC systems should be used in order not to jeopardize the reliability of the low voltage distribution system.

Detuned Power factor Correction

Detuning reduces the resonant frequency to a value below 250 Hz. All harmonics above the resonant frequency of the detuned system are attenuated.

A detuned capacitor consists of a capacitor in series with a filter reactor. Its series resonant frequency is adjusted by appropriate design of the filter reactor so that it is below the frequency of the 5^{th} harmonic (250 Hz). This combination therefore has an inductive characteristic for all frequencies above the series resonant frequency. Resonance between the capacitors and the reactive network impedances is no longer possible. A detuned system suppresses some of the harmonic currents. To prevent overloads due to the 5th harmonic still present in the network, it is present-day practice to adjust the resonant frequency of the detuned circuit to 189 Hz or less.

The detuned circuit is characterized either by the capacitor-choke resonant frequency (f_r) or by the relative voltage drop (p) at the choke. These two parameters are related by the following formula:

$$f_r = 50Hz \cdot \sqrt{\frac{1}{p}}$$

Example:

p = 0.07 (7%)
f_r = 189 Hz

Harmonic Standards.

The last 20 years have seen a steady increase in the levels and associated problems due to harmonic pollution, in an attempt to subdue this increase, standards have been adopted world-wide to limit the level of harmonic distortion on the public supply network. In the USA IEEE 519 is the applicable standard, in Europe the EN61000-3-2/3/4/5 series is sited; whereas in the UK ENA Engineering Recommendation EREC G5/5 is adopted.

Engineering Recommendation G5/5

Engineering Recommendation G5/5 sets planning levels for harmonic distortion to be used in the process for the connection of non-linear equipment to the electrical network. The planning levels are adopted with respect to harmonic voltage compatibility levels set by International Standards.

G5/5 sets limits for the voltage distortion at the point of common coupling (PCC); this being the point being the point where the consumer connects a network where another consumer is (or could be) connected. Although G5/5 is not a standard, Network Operating Companies (NOC's) have adopted it as regulatory and are increasingly enforcing these limits; the intention being to prevent the levels of harmonic distortion on the common supply exceeding the maximum permitted levels given in European Standards IEC 6100-2-2, IEC 61000-2-12 & BS EN 60150, beyond which mal-operation or damage can be caused to connected electrical plant.

Figure 7 - G5/5 Extract: TABLE 1 - Planning Levels for Total Harmonic Voltage Distortion (THvD) at supply system PCC nominal Operating Voltage.

Nominal voltage (*V*) **kV**	***THD*$_V$** **% *h* = 1**
$V \leq 0.4$	5
$0.4 < V \leq 25$	4.5
$25 < V \leq 66$	3.7
$66 < V \leq 230$	3
$V > 230$	3

% h = 1 means 'as a percentage of the voltage at the fundamental frequency'.

Figure 7 - G5/5 Extract: TABLE 2 - Planning Levels for Harmonic Voltages in 400V Systems & below

Odd harmonics (non-multiple of 3)		Odd harmonics (multiple of 3)		Even harmonics	
Harmonic order (*h*)	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**
5	4.0	3	4.0	2	1.6
7	4.0	9	1.2	4	1.0
11	3.0	15	0.5	6	0.5
13	2.5	≥ 21	0.2	8	0.4
17	1.6	—	—	10	0.4
19	1.5	—	—	≥ 12	0.2
23	1.2	—	—	—	—
≥ 25	25/*h*	—	—	—	—

* Total Harmonic Voltage Distortion Planning Level = 5%

Figure 8 - – G5/5 Extract: TABLE 3 - Planning Levels for Harmonic Voltages above 0.4kV & ≤ 25kV

Odd harmonics (non-multiple of 3)		Odd harmonics (multiple of 3)		Even harmonics	
Harmonic order (*h*)	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**
5	3.0	3	3.0	2	1.5
7	3.0	9	1.2	4	1.0
11	2.0	15	0.4	6	0.5
13	2.0	≥ 21	0.2	8	0.4
17	1.6	—	—	10	0.4
19	1.5	—	—	≥ 12	0.2
23	1.2	—	—	—	—
≥ 25	25/*h*	—	—	—	—

* Total Harmonic Voltage Distortion Planning Level = 4.5%