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Voltage and Current Harmonics – Case Study

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C7.1 SELECTION AND RATING OF TRANSFORMERS FOR A SIX-PULSE CONVERTER [10]

When the harmonic spectrum is known, or at least can be measured with a certain reliability or predicted, the additional losses can be easily calculated.

The process of calculation should be made through the following steps:

1. Determination of all the components of additional losses due to the presence of harmonics.
2. Determination of the harmonic spectrum, either by measurement or by estimation, taking into account all harmonic generating equipment, in particular electronic converters.
3. Calculation of the contribution of each harmonic component and determination of total additional losses.

In practice, it is important to use the real harmonic current magnitudes rather than theoretical values.

Table C7.1 shows the calculated additional losses, for harmonic currents up to order 25, for two transformers at normal environmental temperature, assuming the current harmonic spectrum illustrated in Figure C7.1.

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Table C7.1 Additional losses calculated in the presence of non-sinusoidal currents

Loss type	First transformer (21.5°C)	Second transformer (22.8°C)
Rated power (kVA)	1250	1600
Additional with sinusoidal current (W)	520	1721
Additional with non-sinusoidal current (W)	871	4351

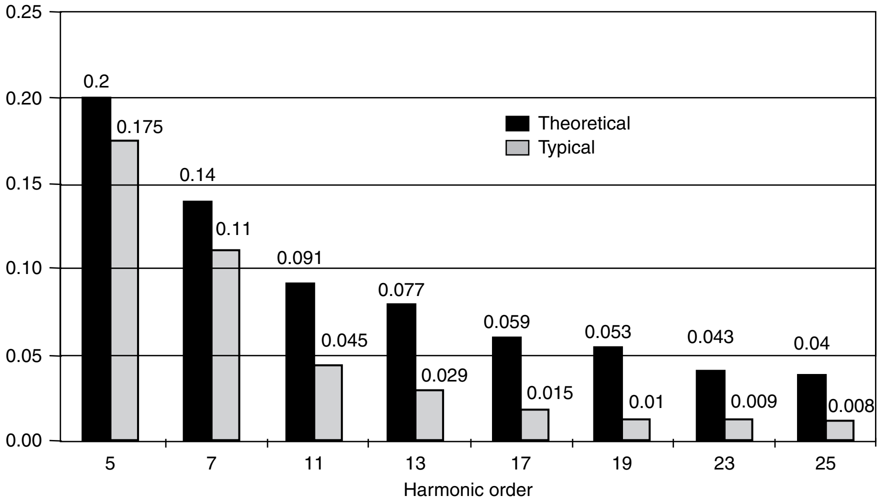


Figure C7.1 Theoretical and actual values of current harmonics for a six-pulse converter (in pu)

The results demonstrate that the transformer characteristics play an important role in determining the losses with harmonic loads.

The transformers in this example were measured at slightly different temperatures (21.5°C for the first and 22.8°C for the second); this will not change the reliability of results.

C7.1.1 Calculation of the *K* Factor

Table C7.2 shows the calculation of the *K* factor for the harmonic spectrum of Figure C7.1 on a per unit basis.

The first step is the calculation of the r.m.s. value of total current *I*, 1.0410 in this case, after which the squares of the proportionate values of each harmonic current can be calculated, leading to the value of *K*. For such a load, a transformer with a *K* rating of 9 would be appropriate for a six-pulse converter.

Table C7.2 Reduction factors for current harmonics

Harmonic order	I_h/I_1	$(I_h/I_1)^2$	I_h/I	$(I_h/I)^2$	$(I_h/I)^2 \times h^2$
1	1.000	1.0000	0.9606	0.9227	0.9227
5	0.200	0.0400	0.1921	0.0369	0.9227
7	0.140	0.0196	0.1345	0.0181	0.8862
11	0.091	0.0083	0.0874	0.0076	0.9246
13	0.077	0.0059	0.0740	0.0055	0.9246
17	0.058	0.0034	0.0557	0.0031	0.8971
19	0.056	0.0031	0.0538	0.0029	1.0446
23	0.043	0.0018	0.0413	0.0017	0.9025
25	0.040	0.0016	0.0384	0.0015	0.9227
	Sum =	1.0838			8.3476
	Total (r.m.s.) =	1.0410			
				K factor =	8.3476

C7.1.2 Calculation of the Factor *K*

The first step in establishing factor K (Table C7.2) is to discover the value of e, the ratio of eddy current loss to total load loss at fundamental frequency. The transformer manufacturer should be able to provide this, otherwise it is likely to lie in the range of 0.05 to 0.1. The exponent q depends critically on the construction of the transformer and should also be

Table C7.3 Reduction factors for current harmonics

Harmonic order	I_h/I_1	$(I_h/I_1)^2$	h	$(I_h/I)^2 \times h^2$
	1.000	1.0000	1.0000	1.0000
	0.200	0.0400	15.4258	0.6170
	0.140	0.0196	27.3317	0.5357
	0.091	0.0083	58.9342	0.4880
	0.077	0.0059	78.2895	0.4642
	0.058	0.0034	123.5274	0.4155
	0.056	0.0031	149.2386	0.4680
	0.043	0.0018	206.5082	0.3818
	0.040	0.0016	237.9567	0.3807
	Sum =	1.0838	$[a]=$	4.7511
	Total (r.m.s.) =	1.0410	$[a] \times (I_1/I)^2 =$	4.3839
			$e/(e+1) =$	0.091
	$(I_1/I)^2 =$	0.9227		
			$K^2 =$	1.3985
			$K =$	1.18

available from the manufacturer. It is likely to lie in the range 1.5 to 1.7. As before, the calculations are based on the theoretical values from Figure C7.1. In practice, the transformer would need to be derated to 84.75 % (1/1.18) of nominal power rating when supplying a six-pulse converter.

C7.2 DERATING CABLES

As described in Section 7.6.2, the current amplitude in the neutral due to the third harmonic could exceed in amplitude the phase current at the fundamental frequency. In this case the neutral current should be considered with regard to the sizing of the circuit cables. This example is related to an office building where four different harmonics spectra have been used to evaluate the cable size to be installed.

The system is a three-phase circuit with a 32 A rated load to be installed using a four-core EPR insulated cable laid directly onto the wall.

C7.2.1 Scenarios

These are as follows:

1. *Absence of harmonics*. For this current it is common practice to use a copper conductor cable with a 4 mm^2 cross-section with a capacity of 35 A [5] .
2. A value of 22 % of the third-order harmonic (Figure C7.2). For this spectrum the neutral current will be $I_N = 32 \cdot 0.22 \cdot 3 = 21.1\,\text{A}$, $I_N < I_F$, so the value is selected on the basis of the line current. Applying a 0.86 reduction factor (Table 7.12), the equivalent load current is $32/0.86 = 37.2$ A. For this value the cable section has a 6 mm^2 cross-section with a capacity of 44 A [5].

   For a value of 42 % of the third-order harmonic (Figure C7.3), $I_N = 32 \cdot 0.42 \cdot 3 = 40.3\,\text{A}$, $I_N > I_F$, so the value is selected on the basis of the neutral current. Applying a 0.86 reduction factor, the equivalent load current is $40.3/0.86 = 46.9$ A. For this value the cable section has a 10 mm^2 cross-section with a capacity of 60 A [5].

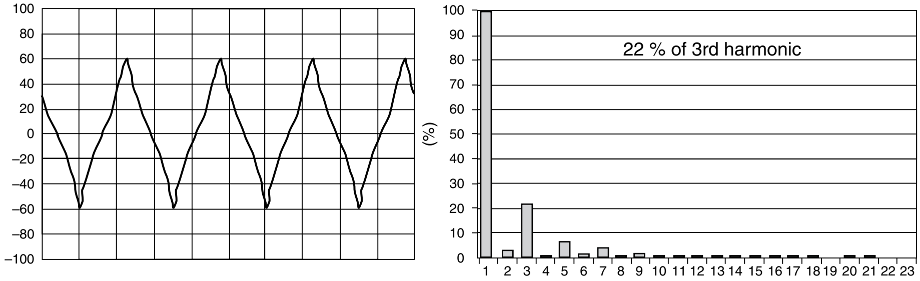


Figure C7.2 Current waveform and its spectrum

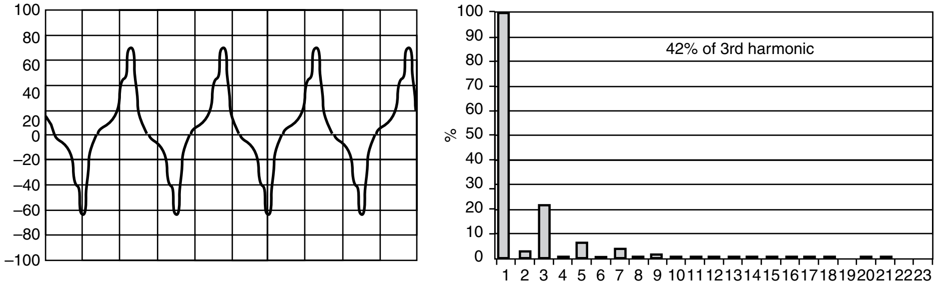


Figure C7.3 Current waveform and its spectrum

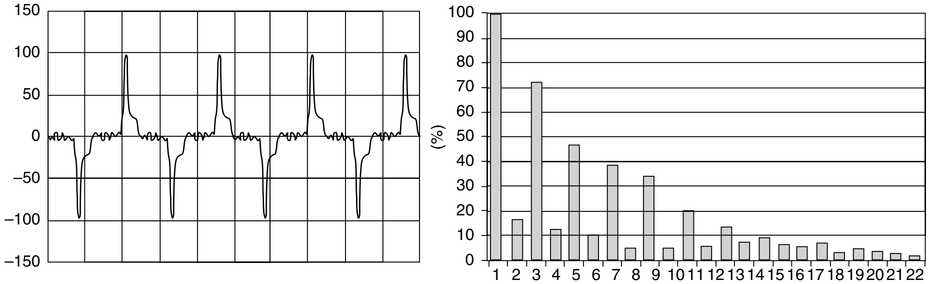


Figure C7.4 Current waveform and its spectrum

3. Third-order, harmonic-rich environment, as in Figure C7.4. The neutral current will be $I_N = 32 \cdot 1.31 \cdot 3 = 125.76\,\mathrm{A}$, $I_N > I_F$, so the value is selected on the basis of the neutral current. Applying a reduction factor equal to 1, the equivalent load current is $125.76/1 = 125.67$ A. For this value the cable section has a 35 mm^2 cross-section with a capacity of 128 A [5].

C7.3 HARMONIC SOURCE LOCATION

In the event of significant distortion of the supply network voltage at the PCC between the electricity supplier and customer, the source of disturbance should be located. This becomes of particular significance when formulating contracts for electric power supply or charging for worsening the quality of supply. In many cases also a quantitative determination of the supplier and customer(s) contribution to the total voltage distortion at the PCC is required.

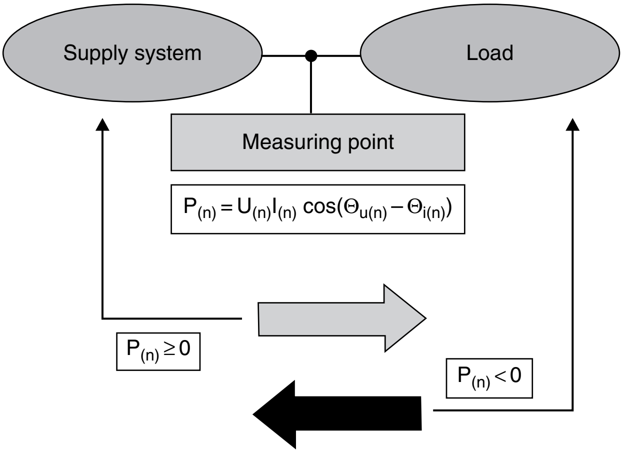


Figure C7.5 The principle of locating the *n*th harmonic source on the basis of its active power measurement

The most common practical method for locating harmonic sources is based on determining the direction of active power flow for given harmonics, though many authors indicate its limitations and propose others methods (investigation of the direction of reactive power flow and the 'critical impedance', interharmonic injection, determining voltage and current relative values, etc. [34],[35]). In most cases these methods, apart from their technical complexity, require precise information on values of equivalent parameters of the analyzed system, which are difficult to access, or can only be obtained as a result of costly measurements.

According to the *direction of active power flow* method, the dominant source of a given harmonic (of order *n*) can be located by determining the direction of this harmonic active power flow at various points of the system (Figure C7.5). A non-zero value of $P_{(n)} = U_{(n)} I_{(n)} \cos\left(\Theta_{u(n)} - \Theta_{i(n)}\right)$ is the effect of the interaction of voltage and current with the same frequency. A linear load supplied with distorted voltage draws active power for each harmonic: $P_{(n)} \geq 0$. If non-linear elements exist at the customer side, the active power for some harmonics can be supplied to the network: $P_{(n)} < 0$. The sign of $P_{(n)}$ can be determined by means of measuring the phase angles of the voltage and current of the same order: $\Theta_{u(n)}$ and $\Theta_{i(n)}$.

The principle of this method is explained in the example of a single-phase circuit, shown in Table C7.4 (the supply voltage source is U_S, L_S), where the non-linear load is the thyristor power controller (TYR1, TYR2, resistance R_{ONL}, inductance L_{ONL}), which is the source of harmonic currents of order $n = 2k \pm 1 = 3, 5, 7, 9, 11, 13, 15$, (for $k = 1, 2, 3, \ldots$). There cases, distinguished by location of the voltage distortion source, are discussed for the power controller located: (i) upstream of the PCC, (ii) downstream of the PCC, and (iii) harmonic sources at both sides of the PCC.

Table C7.4 Example simulations illustrating the method for harmonic source location based on the active power measurement

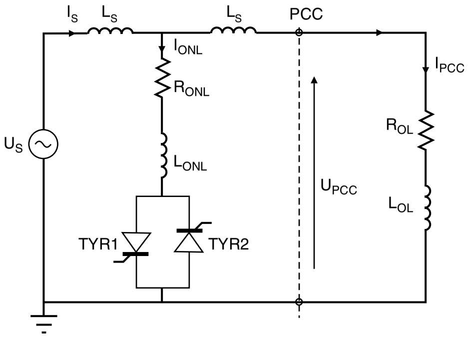
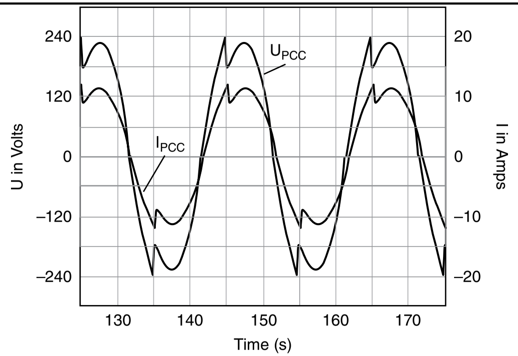
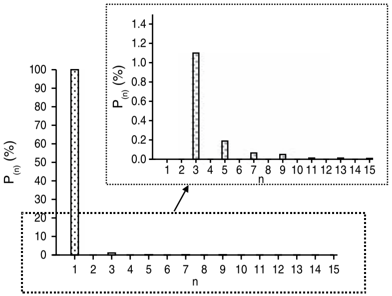
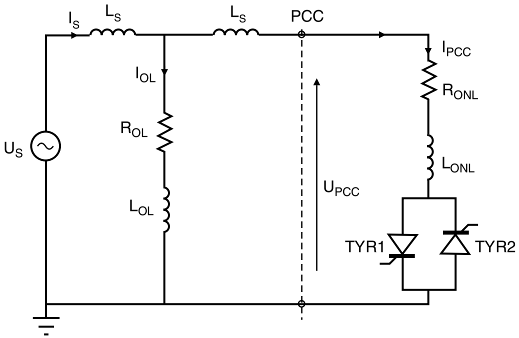
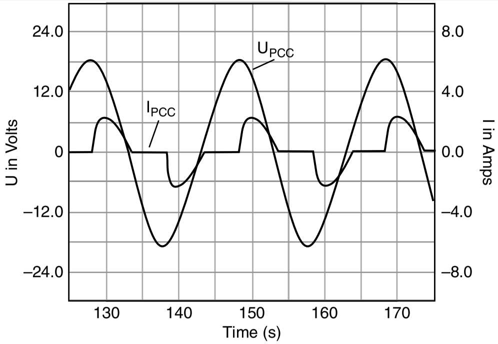
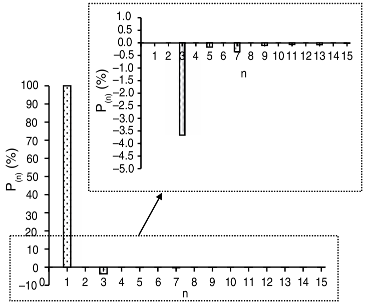
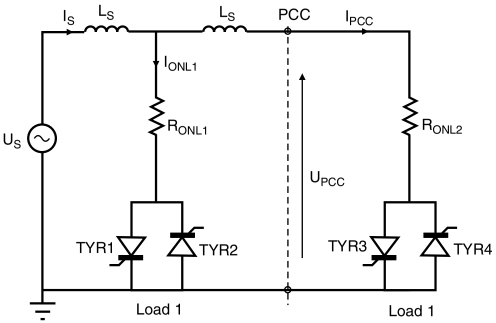
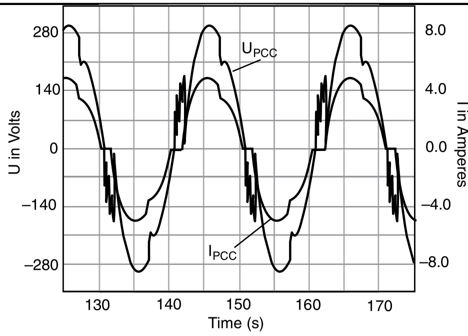
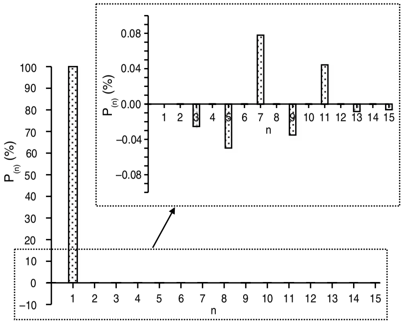
Model of the electric power network with harmonic source	Waveforms of voltage U_{PCC} and current I_{PCC}	Active powers of individual harmonics
Harmonic source at the supplier's side Active powers of individual harmonics have a positive sign. The supplier is responsible for the voltage waveform distortion.		
		
Harmonic source at customer's side Active powers of given harmonics have a negative sign. The customer is responsible for the voltage waveform distortion.		
		

Table C7.4 (Continued)

<table>
<tr><th>Model of the electric power network with harmonic source</th><th>Waveforms of voltage U_{PCC} and current I_{PCC}</th><th>Active powers of individual harmonics</th></tr>
<tr><td colspan="3">Harmonic source at both the customer’s and supplier’s side
Depending on the control angle α of thyristor switches, one of the parties, either the supplier or the customer, will be the dominant contributor to voltage distortion.</td></tr>
<tr><td> </td><td> </td><td> </td></tr>
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