Estimating Total Harmonic Voltage Distortion

■ Introduction

Often it is a requirement, that a quick estimate of the Total Harmonic Voltage Distortion (THVD) be made. This document presents a simple method of estimating the voltage distortion caused by a non-linear load such as a VLT® Drive. The method takes all the ac-side reactances (X) into account and the effect of inserting an ac-side reactor can thus also be evaluated.

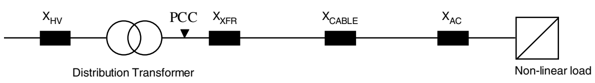

Figure 1: Reactances in the system

Since the main reason for calculating THVD is to find out if the level is so high, that other user on the same transformer are disturbed, then the calculation should be done in the Point of Common Coupling (PCC) directly on the transformer secondary. Making the calculation on the transformer primary only makes sense, if the investigation is to determine if loads on other transformers are disturbed. Making the calculation directly at the drives does not tell about the level, which other users in the network will see.
It is important to keep in mind, that the method described in this application note is only intended to be a rough estimate. If it is necessary to conform to a specific level, then a more sophisticated simulation must be made, to increase the accuracy of the result.

■ Definitions

The Total Harmonic Voltage Distortion is dependent on the individual voltage drops (V_h) at all harmonic frequencies (h) is defined as:

$$THVD = \sqrt{\sum_{h=2}^{h=40} \left(\frac{V_h}{V_1} \right)^2}$$

Equation 1: Base definition of THVD

THVD depends upon each harmonic voltage drop, ie. the product of current and reactance at each harmonic frequency. The voltage distortion therefore depends upon the harmonic spectrum and not upon the total harmonic current distortion (THCD) alone. For example one ampere 5th harmonic (I_5) causes a reactive voltage drop five times larger than one ampere fundamental current (I_1). Thus, the voltage distortion can be recalculated as

$$THVD = \sqrt{\sum_{h=2}^{\infty} \left(\frac{h \cdot X_1 \cdot I_h}{V_1} \right)^2} \times 100\% = \frac{X_1}{V_1} \sqrt{\sum_{h=2}^{\infty} (h \cdot I_h)^2} \times 100\% = \frac{1}{I_{sc}} \sqrt{\sum_{h=2}^{\infty} (h \cdot I_h)^2} \times 100\%$$

Equation 2: THVD based on Current distortion

For a given non-linear load it is convenient to define a Harmonic Constant (H_c) as

$$H_c = \sqrt{\sum_{h=2}^{\infty} \left(h \frac{I_h}{I_1} \right)^2} \times 100\%$$

Equation 3: Definition of Harmonic Constant

Using this definition, THVD can be estimated based on active power drive load (P_{VLT}) and Short Circuit Power (S_{SC}) at PCC as

$$THVD = H_c \frac{P_{VLT}}{S_{SC}} [\%]$$

Equation 4: THVD based on Harmonic Constant

The lower the harmonic constant, the lower the current and thus the voltage distortion. Adding ac-side reactance is damping the harmonic currents and thus limits H_c for the non-linear load. From the graph below we get a simple approximation for H_c as a function of the total amount of ac-side reactance (calculated in VLT® drive % = 100*VLT® drive p.u.). The competitor drive is a standard PWM drive with no dc reactors or ac reactors built-in.

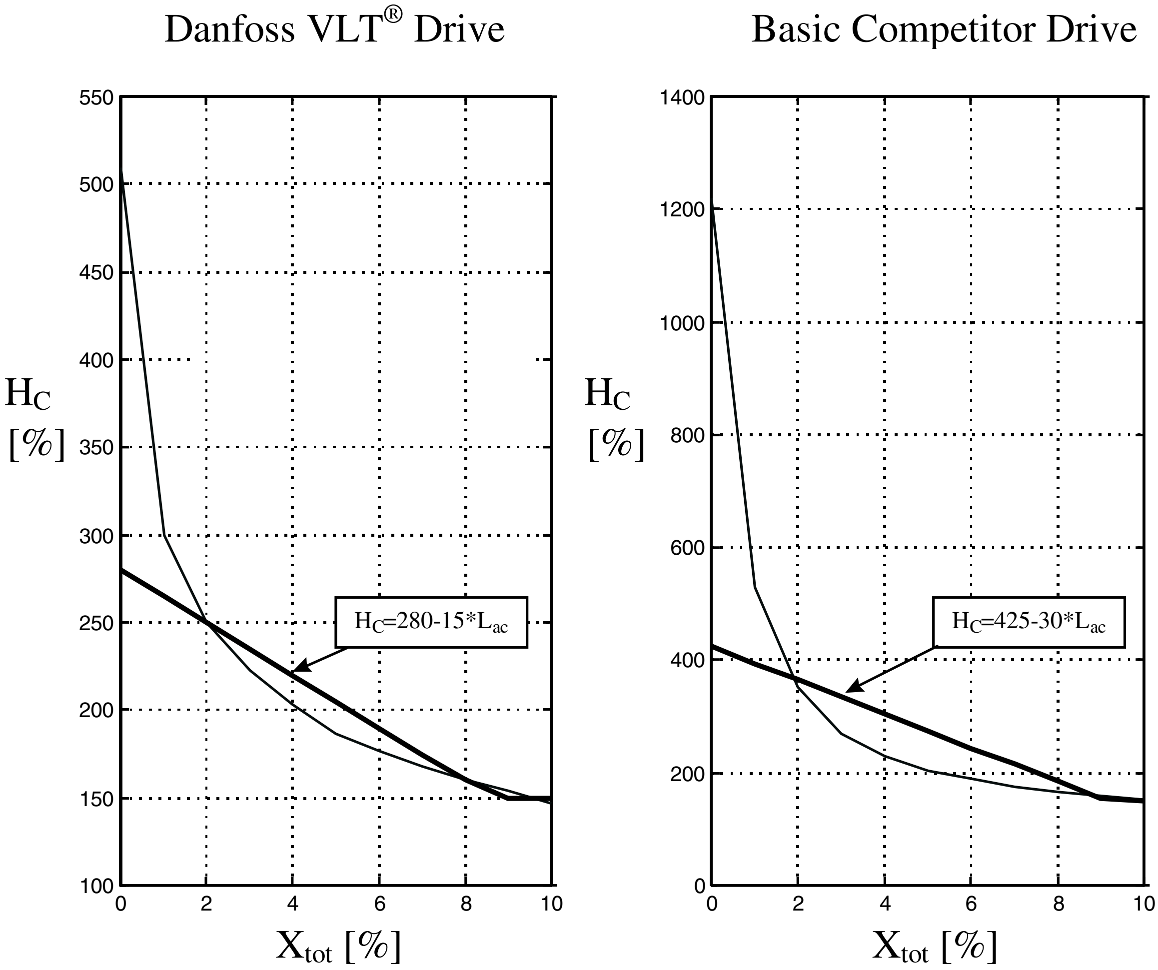

Figure 2: Estimating the Harmonic Constant

The equations shown next to the thick curves can be used as a simple estimate of H_C based on the total ac impedance, as per figure 1. In order to avoid problems due to the fundamental voltage drop caused by the use of ac reactors, the total ac reactance of the drive (X_{tot}) should not exceed 10%.

This means that increasing X_{tot} by one percent approximately reduces H_c by 15% on a VLT® Drive. Knowing H_c, we can calculate the voltage distortion anywhere in the system by using equation 4 and inserting the short-circuit power at the point of interest.
The base impedance of the VLT® drive per-unit system is calculated as $Z_{B,VLT} = \frac{V_{nom}^2}{P_{VLT}}$ using the nominal line-line rms voltage and the total three-phase power. If the reactances of the system (X'_{HV},X_{XFR} and X_{CABLE}) are expressed on another per-unit basis than the VLT® drive per-unit, they have to be transformed into the VLT-per-unit system. This is done by multiplying the per-unit impedances by multiplying the per-unit impedances by the ratio $\frac{Z_{B,OTHER}}{Z_{B,VLT}}$. The calculation procedure is easiest illustrated by an example.

Example Calculation

How would adding a 4% reactor in front of the drive influence the voltage distortion at the transformer secondary side in the system shown below ?

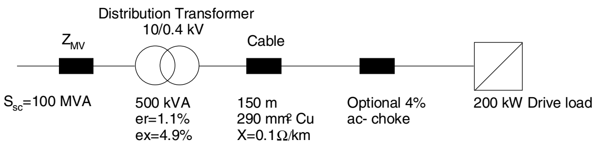

Figure 3: Example System

Step 1 Calculate all impedances in the Drive per-unit system

The base impedance for the drive is $Z_{B,VLT}$ = V_{nom}^2/P_{VLT} = $400^2/200*10^3$ .... = 0.8 Ω

The cable impedance is $R_C + jX_C$ where

$R_C = \rho * l / A$ = 0.0175 Wmm^2/m * 150m / 90mm^2 ....= 9mΩ

$X_C = X * l$ = 0.1Ω/km * 0.15 km.................... = 15mΩ

which in the drive per-unit system corresponds to

$R'_C + jX'_C = R_C + jX_C / Z_{B,VLT}$ = 1.12 + j1.87 %

The transformer impedances are expressed on a transformer-per unit base where

$Z_{B,XFR} = V_{nom}^2/S_{XFR}$ = $400^2/500*10^3$.................= 0.32 Ω

Thus, the transformer impedances expressed in the drive per-unit system becomes

$Z'_{XFR} = e_r' + je_x' = (e_r + je_x) * Z_{B,XFR} / Z_{B,VLT}$

= (1.1% + j 4.9%) * 0.32/0.8 ....= 0.44 + j 1.96 %

In this example the medium voltage side impedance Z_{MV} is expressed by the short-circuit capacity on the 10 kV side. Thus $Z_{MV} = V_{MV}^2/S_{sc}$

= (10 kV)^2 / 100 MVA...................................... = 1Ω.

We have to move this impedance to the secondary side of the transformer. This is done by multiplying by the square of the voltage transfer ratio. This means that

$Z_{MV}' = Z_{MV}*(400V/10kV)^2$........................... = 1.6 mΩ.

This medium voltage impedance is assumed purely as reactance. In the drive per-unit system, the medium voltage reactance is thus represented as

X_{MV}' .... = j 0.2%.

This is seen to be a very small value and is usually omitted unless the high voltage side is very weak or the voltage distortion on the high voltage side is needed.

Step 2 Estimate H_C

The total reactance on the ac-side of the drive equals

$X_{tot} = X_{HV} + X_{XFR} + X_C$

= 0.2% + 1.96% + 1.87% .... = 4.03%

Thus H_C is approximated by

$H_C \approx 280 - 15 \times X_{tot}$

= 280- 15*4.03 .... ≈ 220 %

An additional 4% reactor reduces H_C to approximately

$H_{C4\%} \approx 280 - 15 \times X_{tot}$ = 280 - 15*(4.03 + 4) ≈ 160 %

Step 3 Calculate voltage THD at point of interest

At the transformer secondary side we have the short-circuit power

$$S_{sc,XFR} = \frac{S_{nom,XFR}}{e_X} = \frac{500.000}{0,049} = 10.20 \text{ MVA}$$

Without adding the 4% reactor, the voltage distortion becomes

$$THVD_{XFR} = H_c \frac{P_{VLT}}{S_{SC}} = 220 \cdot \frac{200e3}{10.20e6} = 4.31\%$$

Adding a 4% reactor in front of the drive we get

$$THVD_{XFR} = H_c \frac{P_{VLT}}{S_{SC}} = 160 \cdot \frac{200e3}{10.20e6} = 3.14\%$$

The harmonic constant of the current is unchanged through the transformer. If we want to calculate the voltage distortion at the primary side of the transformer we get

$$THVD_{MV} = H_c \frac{P_{VLT}}{S_{SC}} = 220 \cdot \frac{200e3}{100e6} = 0.44\%$$

and including the 4% reactor

$$THVD_{MV} = H_c \frac{P_{VLT}}{S_{SC}} = 160 \cdot \frac{200e3}{100e6} = 0.32\%$$