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Behavior of voltage transformers under distorted waveforms

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Abstract. In this work, we present testing results of voltage transformers (VT) errors, under distorted waveforms. Different types of VTs used in high voltage power networks were analysed. This includes inductive as well as capacitive VTs. The main tests were done at nominal voltages, but a comparison with another low-voltage testing method was included.

1. Introduction

The continuous proliferation of non-linear loads in power networks leads to increase the harmonic content of the voltage. To mitigate this problem, filters and other devices are used. Anyway, measurements of voltage harmonic distortion are necessary to demonstrate that they are under regulated limits. In high-voltage networks, the voltage measurement is done through voltage transformers (VT) with primary voltages in the range of 6 kV up to 500 kV, or even more. There are different types of VTs. Inductive type (IVT) is based on the same principle than power transformers. They have a magnetic core and primary and secondary windings. Other type called capacitive voltage transformer (CVT) has a high-voltage capacitive voltage divider followed by a conventional medium-voltage transformer. The behavior under distorted waveform is very different for one type or the other. International most used standards only propose to test these transformers at power frequency [1, 2]. In this case, the errors at higher frequencies are not known. Additional requirements for harmonic response would be find in other standard [3], but most VT in service were not manufactured to fulfil this standard. Table II of that standard shows the limit ranges for harmonic measurement. They go from 1% and 1° for 1st and 2nd harmonic, and 5% and 5° for harmonics from 3th to 50th. For this work, a high-voltage source with programmable harmonic content was used, as well as a measuring bridge that gives the error in ratio and phase for each harmonic order. They are described in [4].

2. Tested units

Units of both types, IVT and CVT, were tested. Their behaviours are very different, as will be shown in the following paragraphs.

2.1. Inductive type

A low frequency model for IVTs is shown in figure 1.



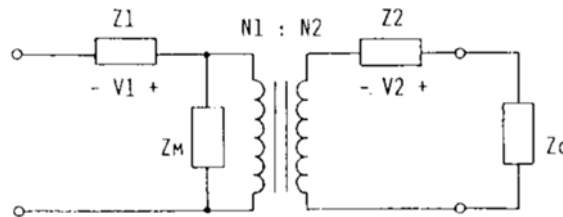


Figure 1. Model for inductive voltage transformers.

Z_1 and Z_2 are the primary and the secondary winding impedances. Z_M is the magnetizing branch, modelled by a resistor in parallel with a capacitor and a non-linear inductor. The behaviour of the inductor is taken into account modifying its value in function of the applied voltage. At low frequencies, errors in IVTs are due to voltage drops in the series impedance Z_1 and Z_2 . We performed two different tests: low-voltage tests up to 20 kHz, and nominal-voltage tests up to 3 kHz.

2.1.1 Low voltage tests

Tests were done with a FRA equipment [5], with voltages around 10 V. The ratio between the output and input voltages was computed, expressed in dB. Figures 2 and 3 show the behaviour of the frequency response of different IVT used in high voltage power networks. Their nominal voltages go from 6 kV up to 150 kV. All curves show a similar behaviour up to 2 kHz, corresponding to the 40th harmonic. They remain approximately constant up to 2 kHz, with variations lower than 2 dB. At higher frequencies, the 6-kV IVT reduces the ratio voltage, but the 60-kV and 150-kV ones, increase it. This is due to resonances between series inductance and parallel capacitances. The ratio variation at 2 kHz reaches values up to 25% for the 150-kV IVT. The others have lower variations.

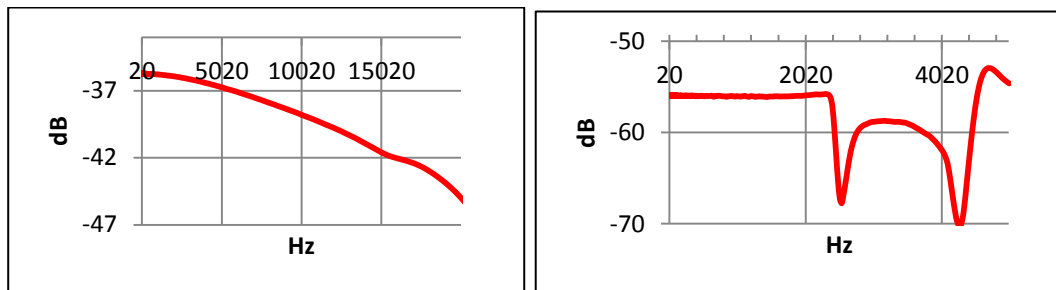


Figure 2. Frequency response of 6 kV and 60 kV IVTs.

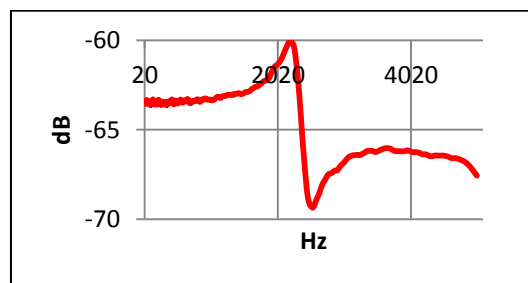


Figure 3. Frequency response of a 150 kV IVT.

2.1.2 Nominal voltage tests

These tests were done at 53 Hz of fundamental frequency, to prevent noise influence from the power network. The voltage at fundamental frequency was set between 80% and 100% of the nominal value of the VTs. A first test was done adding single tones to the fundamental frequency, from 3th (159 Hz)

component to 49th (2597 Hz) one. The amplitude of the harmonic components was set around 10% of the fundamental one. In this condition, transformer errors were measured for fundamental and for each harmonic. A second test was done applying the fundamental component and all harmonics together. Again, the transformer errors were measured at fundamental and at each harmonic component. Only results on units of 6 kV and 60 kV are shown, but they are similar for other IVT. Figures 4 and 5 show the ratio error and phase shift with single tones and with high distortion (all harmonic components at the same time). No significant difference between both tests was detected, which corresponds to linear behavior of the tested IVTs.

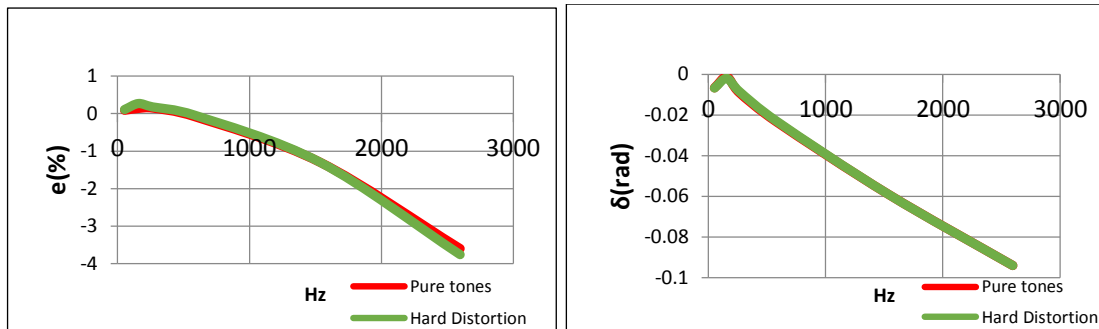


Figure 4. Ratio error and phase shift of a 6 kV IVT at 80% of nominal voltage.

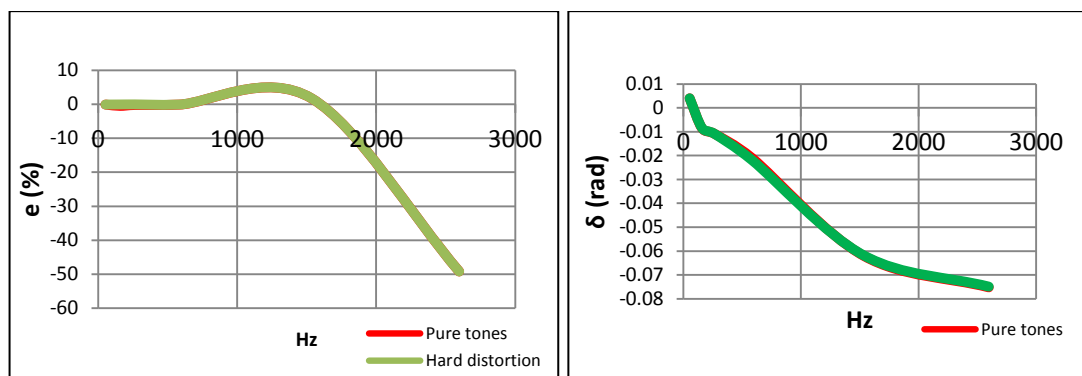


Figure 5. Ratio error and phase shift of a 60 kV IVT at 100% of nominal voltage.

Ratio errors at 2 kHz reaches -2.2% for the 6-kV IVT and -18% for the 60-kV unit. Although they are much larger than the accuracy class of these transformers (0.5), they can be compensated applying a correction table.

The shapes of these curves are close to those got from low-voltage tests, but the differences between both tests do not allow the use of low-voltage tests for error correction. Low-voltage test is good for having a quick view of the frequency response, but if corrective factors are intended to use, tests at nominal-voltage must be done.

2.2. Capacitive type

The simplest model for this type of VT is shown in figure 6.

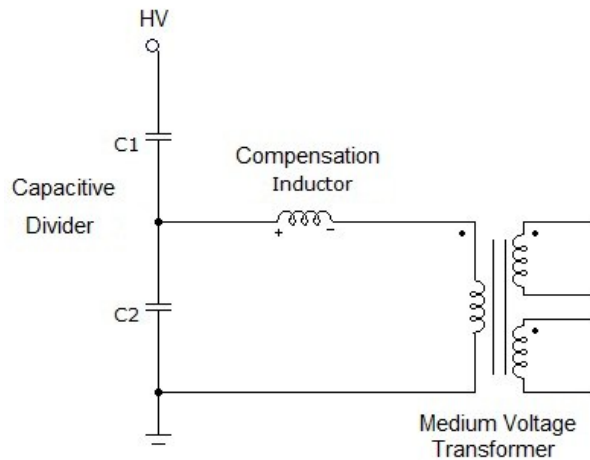


Figure 6. Simplified model of a capacitive voltage transformer

$C1$ and $C2$ form a capacitive divider that is followed by a compensation inductor and a conventional medium-voltage transformer. The inductor is designed to resonate with the capacitors at power frequency to null the capacitance impedance. But, at other frequencies, the series impedance increases, so that, the errors. For the test, it was used the equivalent circuit, shown in [2]. In this configuration, the low terminal of $C2$ is disconnected from ground, and connected to the upper terminal of $C1$. In this way, both capacitors are in parallel, in a Thevenin configuration. The advantage of this testing method is that the value of the applied voltage must be the rated voltage of the medium voltage transformer, around 10 kV, much lower than the nominal voltage of the CVT under test. Many tests were done on different units from 60 kV up to 500 kV. As an example, figure 7 shows the ratio error and phase shift of a 150-kV CVT, 200 VA, class 0.5, at two different voltages: 80% and 120% of the nominal one. The applied voltage had harmonic contents that include many orders from the 3th up to the 49th. The amplitude of each one was around 10%.

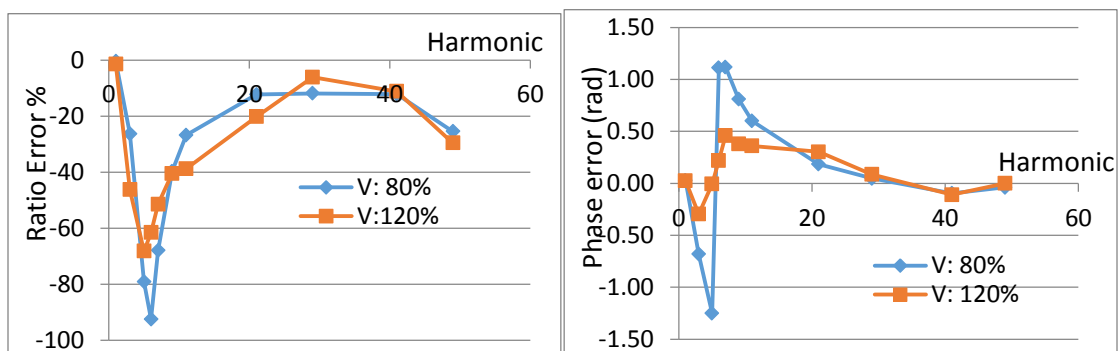


Figure 7. Ratio error and phase shift of a 150-kV VCT.

The results show that this transformer has very large errors at any harmonic frequency. Even, these errors depend on the voltage. Other tests were done varying the burden, and again, a behaviour that depends on the burden was detected. This means that in practice it is not possible to use correction factors for compensating those errors. This kind of VT is not suitable for harmonic measurement unless compensating devices were added. There are proposals [6] for that, but they need of special internal connections and add external devices. Unfortunately, most of the installed CVTs do not have the possibility to be compensated using that technique, because internal points, where currents must be measured, are not accessible.

It is undergoing a project for compensating conventional CVTs, avoiding to change them for other types that allow harmonic measurement.

3. Conclusions

Results of tests on VTs under distorted waveform were presented. Low-voltage tests method (FRA) is useful to get a quick view of the frequency response, but tests at nominal-voltage must be performed to know precisely the value of the errors. Many IVT can be compensated using corrective factors for each harmonic, but this cannot be done for CVT. Their errors are so large that other compensation techniques are necessary.

4. References

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Acknowledgments

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