UNDERSTANDING THE HARMONIC PERFORMANCE OF VOLTAGE TRANSFORMERS FOR DISTRIBUTION SYSTEM POWER QUALITY MONITORING

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ABSTRACT

It is useful to understand the frequency response of voltage transformers used for power quality monitoring, so that power quality data is captured accurately and can be used for compliance purposes. This paper reports the results of frequency response testing conducted for Western Power Distribution at The University of Manchester of four 1-phase and 3-phase voltage transformers of types used in 11 kV and 33 kV distribution networks in Great Britain. The results show that the tested voltage transformers transfer harmonic voltages with attenuation that increases with frequency, and suggests that correction factors may be required to obtain accurate results at harmonic frequencies up to at least the 50th harmonic order.

INTRODUCTION

Over the coming years, increasing numbers of power electronic focussed low carbon technologies (LCTs), such as inverter-interfaced generation and Electric Vehicles (EVs) are expected to connect to distribution networks in Great Britain (GB) [1], which will have impacts on the network power quality [2]. Western Power Distribution (WPD) are undertaking the "Primary Networks Power Quality Analysis" (PNPQA) project [3] to better understand the current and future impact of LCTs on power quality within their "primary" distribution networks in GB. The project is funded via the Network Innovation Allowance operated by the GB regulator Ofgem.

The ability to accurately obtain voltage waveforms is critical when checking compliance against power quality standards; however, it may only be practical to use existing voltage transformers (VTs) to obtain this data. VTs step-down high line voltages (such as 33 kV) to voltage levels acceptable to measurement equipment (such as 110 V). One aspect of the PNPQA is to verify the performance of VTs used by WPD and other GB Distribution Network Operators (DNOs) for power quality monitoring. To this end, laboratory testing of the frequency response of four VTs has been completed at The University of Manchester, and this paper presents the testing method and results.

This paper is structured as follows: first, in the "Background" section, information is provided regarding previous work on VT frequency response testing. The "Test Setup" section includes details of the test circuit, test procedure, and calibration; and is followed by details of the VTs tested in the "Test Objects" section. The "Results" section provides the results of frequency response testing, followed by the final two sections which contain a discussion of the results and some conclusions.

BACKGROUND

The relevant standard for power quality monitoring, IEC 61000-4-30 [4], specifies accuracy requirements for measurement equipment but does not define requirements for the primary transducers that the measurement equipment is connected to, such as VTs. VTs are typically specified with accuracy requirements that only apply at the fundamental frequency.

In the absence of predefined requirements, there is uncertainty in the ability of VTs to accurately transfer harmonic voltages seen on the high voltage (HV, or primary) side to the low voltage (LV, or secondary) side. It is therefore of interest to understand the frequency response of VTs; however, few papers in the literature describe the results of testing this [5-11].

Previous work has tested single phase VTs with voltage ratings typical of GB distribution networks (≤ 132 kV) [5-10] as well as higher voltages up to 800 kV [9-11]. Most of the works test inductive VTs but some also test capacitive VTs [9-11]. These previous works all show that the VTs introduce error when transferring harmonic voltages, but the magnitude and sign of the error varies considerably, as does the phase shift introduced by the VTs. Typically, VTs with lower voltage ratings exhibit increasing attenuation of harmonic voltages as the harmonic frequency increases, whereas higher voltage VTs typically exhibit increasing amplification of harmonic voltages as the frequency increases. Furthermore, capacitive VTs typically introduce larger errors at lower frequencies compared with similarly-rated inductive VTs.

The previous work on frequency response testing of VTs has shown the response varies considerably depending on the type of VT. However, the works have not been specific to the types of VTs used in GB distribution networks and has focused on 1-phase VTs, whereas both 1-phase and 3-phase VTs can be found in GB distribution networks.

TEST SETUP

Test Circuit & Equipment

Photos of the test setup in the laboratory are provided in Figure 1 and the schematic in Figure 2 outlines the basic circuit for the 1- or 3-phase VT frequency response testing. A National Instruments USB-6229 data acquisition (DAQ) board and LabVIEW software are used to generate voltage waveforms to input in to the test object and to measure the resulting HV and LV voltages from the test object.

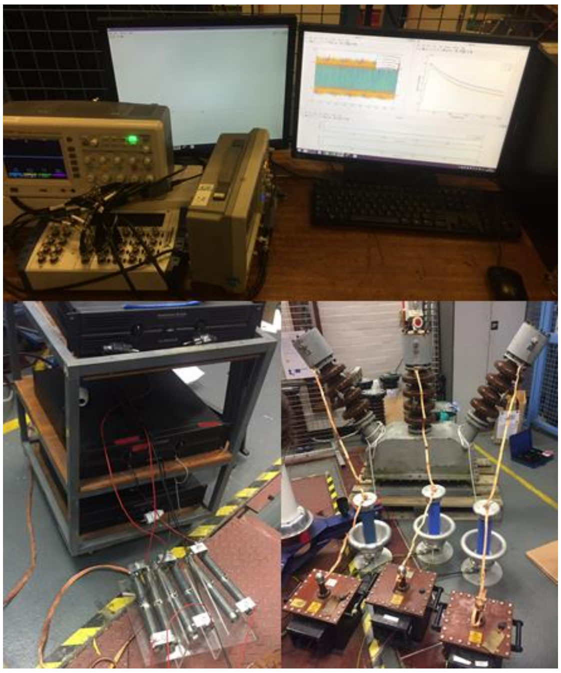

Figure 1 – Laboratory setup; top: LabVIEW DAQ and oscilloscopes; bottom left: audio amplifiers; bottom right: 30 kV test transformers, voltage dividers, and example test object (33 kV 3-phase VT)

Following generation of test waveforms in software, each DAQ output channel is used to drive the test object via an American Audio VLP2500 amplifier, an impedance matching resistor, and a 30 kV single phase HV test transformer. For 3-phase testing these components are duplicated 3 times. Each channel is used to inject harmonic level voltages into one of the phases of the test object.

The voltages on both the HV and LV side of the test object is stepped-down to measurement levels via voltage probes. For the HV side a North Star VD60 voltage divider (10,000:1) is used, for the LV side a 10:1 voltage probe is used. These are then connected to both an oscilloscope and the DAQ system. The oscilloscope provides a suitable input impedance for the measurement probes as well as providing instantaneous monitoring of the voltage signals.

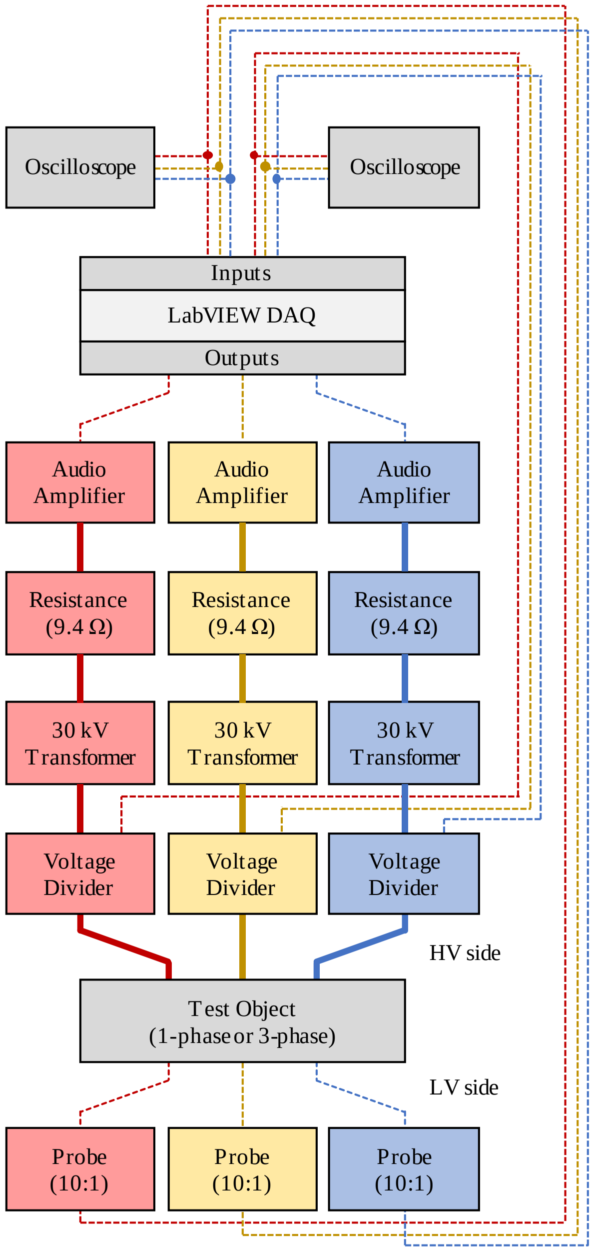

Figure 2 – Circuit schematic for VT frequency response testing

Test Procedure & Software

Using the test circuit and equipment described above, constant amplitude harmonic voltages of 1% of the nominal fundamental frequency voltage (0.01 pu) were achieved at frequencies from the 2nd to the 50th harmonic (2.5 kHz). The tests were automated to inject a single harmonic voltage at a time and measure the frequency response of the test object. The test set up supports simultaneous injecting a fundamental frequency waveform at nominal voltage, but for these tests this was omitted.

Voltage waveforms for each electrical phase at the input and output of the test object were measured by DAQ acquisition system. The Fast Fourier Transform (FFT) was then used to find the amplitude and phase of the input and output voltages at each test frequency. Once data for all the harmonic frequencies were collected, the frequency response of the test object could be determined by calculating the *normalised ratio* (NR) for each frequency (f) and electrical phase (p):

$$\mathrm{NR}_{f,p} = \frac{V_{\mathrm{out},f,p}}{V_{\mathrm{in},f,p}} \div \frac{V_{\mathrm{out,rated}}}{V_{\mathrm{in,rated}}}$$

Here, $V_{\mathrm{in},f,p}$ and $V_{\mathrm{out},f,p}$ are the amplitudes (calculated by FFT) of the harmonic voltages at the input and output; $V_{\mathrm{in,rated}}$ and $V_{\mathrm{out,rated}}$ are the rated input and output voltages of the test object at the fundamental frequency.

The phase shift ($\Delta\varphi$) introduced by the test object could also be calculated for each frequency and electrical phase:

$$\Delta\varphi = \varphi_{\mathrm{out},f,p} - \varphi_{\mathrm{in},f,p}$$

Where $\varphi_{\mathrm{in},f,p}$ and $\varphi_{\mathrm{out},f,p}$ are the calculated phase angles of the input and output voltage waveforms, respectively.

For testing 3-phase VTs, test signals with the appropriate phase differences were simultaneously generated and injected in to each phase.

Calibration

Sensitivity of the measurement system was verified using a hand-held voltage divider and oscilloscope system calibrated to UKAS standards. Tests were run to compare the measurements seen on the HV side and LV side and what was being recorded by the DAQ. A maximum deviation of 2.8 V was seen on the HV, and 0.05 V on the LV measurements.

TEST OBJECTS

Four test objects (the VTs) were tested as part of this work. The VTs were selected for testing as they were representative of the types of VT in use within WPD's distribution networks, covering different voltage levels, numbers of phases, ages and installation types. Table 1 lists the essential details of the VTs tested.

The first column ("Item Ref") in Table 1 contains a short name for referring to each VT which is used for the remainder of this paper. The second column ("Voltages") contains the primary and secondary voltages for each VT, given as phase-to-phase values. The third column ("Phases") states the number of phases per VT.

The fourth and final column ("Origin / Construction") in Table 1 states where each VT was obtained from, where each VT is designed to be installed, and the VT construction. Two of the test VTs were "used" assets sourced from within WPD. The "used" VTs were both over 10 years old and were previously connected in to WPD's distribution networks. The other two VT were "new" units from different manufacturers. Three of the test VTs were designed to be installed within switchgear whilst one was for use outdoors as a standalone piece of switchyard equipment. One VT was an oil-filled unit while the other three were made from cast resin.

Table 1 – Details of the VTs used as test objects

Item Ref	Voltages	Phases	Origin / Construction
11 kV 3-ph	11 kV / 110 V	3-ph	Used, switchgear-mounted, cast resin
33 kV 3-ph	33 kV / 110 V	3-ph	Used, outdoor, oil-filled
33 kV 1-ph #1	33 kV / 110 V	1-ph	New, switchgear-mounted, cast resin
33 kV 1-ph #2	33 kV / 110 V	1-ph	New, switchgear mounted, cast resin

RESULTS

The frequency responses of the four VTs were tested for each harmonic from the 2nd (100 Hz) to the 50th (2.5 kHz). The figures that follow present the frequency response of each VT in terms of the normalised ratio and phase shift, as described in the section "Test Procedure & Software".

Figure 3 shows the frequency response for each phase of the 11 kV 3-ph VT. At the 2nd harmonic order (100 Hz), the observed normalised ratio of all three phases is close to the expected nominal ratio (1.0); however, as the harmonic frequency increases the normalised ratio drops below 1.0 and continues to drop. For example, by the 10th harmonic (500 Hz) the normalised ratio drops to between 0.77 and 0.82 across the three phases. This is a result of attenuation of the harmonic voltage by the VT; in other words, the LV output voltage is lower than expected for the input HV voltage.

The increase in attenuation with frequency (seen by the decrease of the normalised ratio) is non-linear for each of the three phases, with the rate of increase reducing at frequencies around 1,000 Hz and above. Phase L3 has the least attenuation, with phase L1 following a similar trend but with lower normalised ratio values; however, phase L2 exhibits a different trend to the other phases, with less attenuation up to around the 20th harmonic (1,000 Hz), then the attenuation increases substantially compared with the other phases up to the 50th harmonic (2,500 Hz). This significant difference in response may be due to L2 being the middle phase of a 3-phase transformer, and therefore subject to a different flux distribution than the other

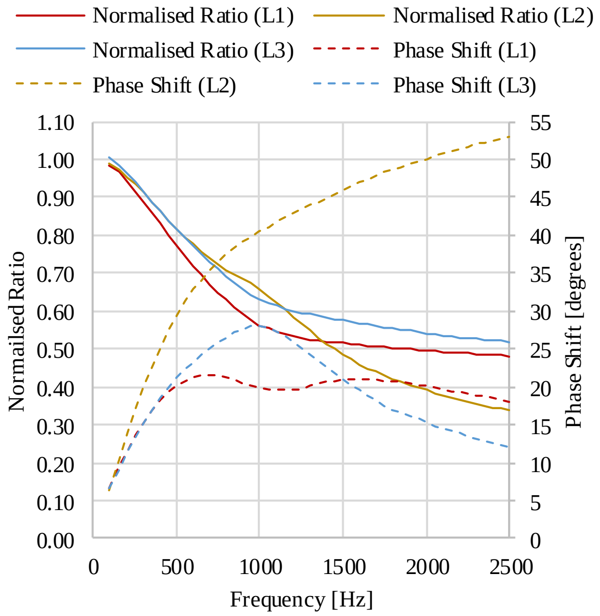

Figure 3 – Frequency response results for 11 kV 3-ph VT

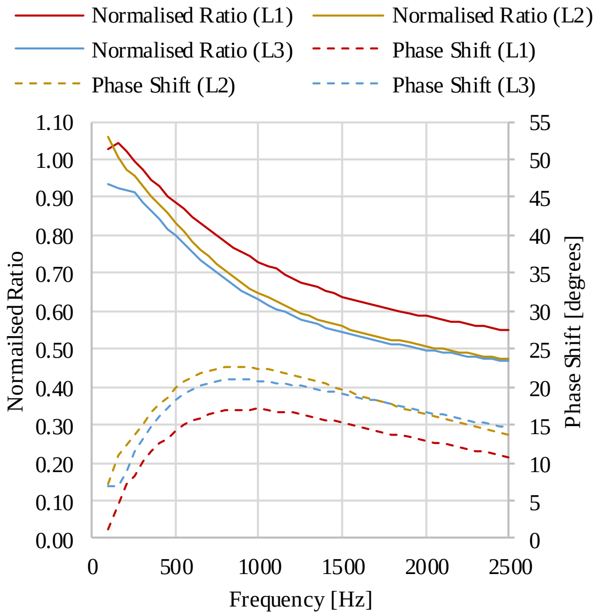

Figure 4 – Frequency response results for 33 kV 3-ph VT

phases. Additionally, it is possible that the VT was faulty, as its history was unclear, and it has at some point received damage (tracking on the insulation could be seen).

Figure 3 also shows the phase shifts observed for the 11 kV 3-ph VT. The responses of phase L1 and L3 are similar, with phase shift increasing with frequency, up to around 500 Hz. Past that frequency, the phase shifts of both phases reach different maxima and then have different responses. Phase L2 has much greater phase shift compared with the other two phases and this continues to increase with no maxima, which may be for reasons discussed above in relation to the normalised ratio.

Figure 4 shows the frequency response for the 33 kV 3-ph VT. Similar to the 11 kV 3-ph VT, the 33 kV 3-ph VT attenuates the harmonic voltages measured at the output, and the attenuation increases non-linearly with frequency. Phase shift also increases with frequency up to a maxima between 800 Hz and 1,000 Hz, then the shift reduces.

Another similarity to the 11 kV 3-ph VT is that one phase is observed to respond differently to the other two phases; however, rather this being the middle phase (L2) as was the case for the 11 kV VT, it is one of the outer phases (L1) that has a significantly different response to the other two phases for the 33 kV 3-ph VT. Furthermore, although the magnitudes differ, the shapes of the responses for all the phases are similar.

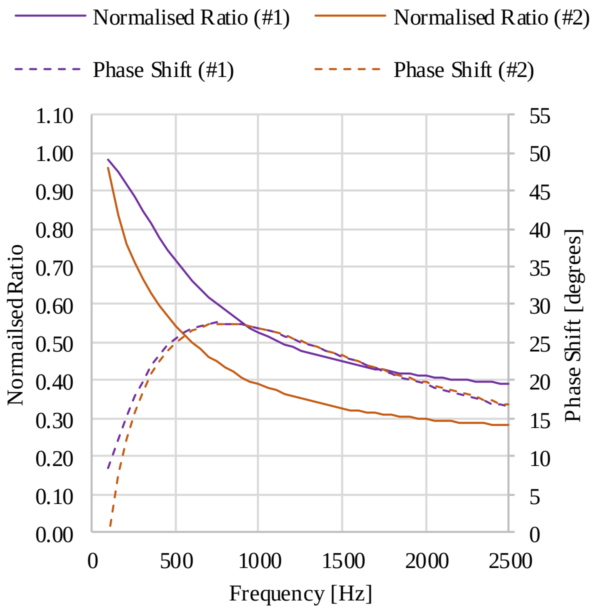

Figure 5 – Frequency response results for 33 kV 1-ph VTs

Figure 5 shows the frequency response for each of the two 33 kV 1-ph VTs (#1 and #2). Similar to the other VTs, attenuation of harmonic voltages is observed at the output, which increases non-linearly with frequency. Both 1-ph VTs have larger attenuation than the 3-ph VTs tested, and it can be seen that VT #1 has significantly greater attenuation (approximately 10%) than VT #2. The phase shift responses of the two VTs are almost identical and follow a similar trend to what was observed with the 33 kV 3-ph VT.

DISCUSSION

For the VTs and range of frequencies tested, attenuation of harmonic voltages has been observed – in other words, error is introduced – and this increases non-linearly with frequency. None of the tested VTs maintains an error of <5% at frequencies above the 10th harmonic (500 Hz), and at the 50th harmonic (2,500 Hz) attenuation (error) between 45% and 72% has been observed. Some work in literature have observed similar attenuation; for example, in [8] attenuation of >50% is seen at 2,500 Hz for a 35 kV VT. However, other works have seen much less attenuation for VTs of similar voltage ratings (e.g. [8-10]). These results suggest that using some VTs for power quality measurements may cause harmonic voltages to be underestimated, and that correction factors may be required to account for the discrepancies.

The inductive VTs tested for this paper include 3-phase and oil-filled units that have not previously appeared in the literature. However, only four VTs of different types were tested and there are many other types of VTs used within the distribution networks of WPD and other GB DNOs, and other work suggests there may be variations in frequency response between VTs of the same type [8], therefore it is difficult to generalise the results without further investigation.

Investigating the frequency response of existing VTs is hampered significantly by the availability of VTs for testing. Removing a VT from service purely for laboratory testing is impractical, so scrap or spare units could be obtained, if available. For example, the two "used" VTs tested for this paper only became available when they were being scrapped. Alternatively, in-situ testing of in-service VTs may be possible. Testing new VTs is much more straightforward, and characterisation of frequency response could be added to type or routine testing of VTs, although that would come at additional cost.

CONCLUSIONS

This paper presents the results of laboratory testing of the frequency response of four inductive VTs of types used in GB distribution networks. The results show that the VTs transfer harmonic voltages with attenuation that increases non-linearly with frequency, and suggests that correction factors may be required to obtain accurate results at harmonic frequencies up to at least the 50th harmonic order (2,500 Hz).

An extension of the present work would be to test the frequency response of the VTs up to higher frequencies, such as the 100th harmonic (5,000 Hz) and also including the fundamental frequency voltage. Further VTs used in GB distribution networks could be characterised, either through the laboratory testing method presented in this paper or through development of an in-situ testing method.

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