NEW METHODOLOGY FOR ON-SITE MEASUREMENT OF VOLTAGE TRANSFORMER MAGNITUDE AND PHASE RATIO AS A FUNCTION OF FREQUENCY

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ABSTRACT

Inductive Voltage Transformers are commonplace in low and medium voltage power distribution networks and are important for network monitoring and protection. Their performance at frequencies above 50Hz, defined as maintaining transformer ratio and input/output phase relationship, is often completely unknown. It is also a challenge to remove VTs from existing installation points to test thoroughly for VT ratio and phase frequency response using the standard swept-sine variable frequency testing. To meet this challenge, the Power Networks Demonstration Centre (PNDC) has developed a technique which relies on a harmonic analysis of the relationship between the transformer input and output. In laboratory testing it has a speed and safety advantage over conventional techniques, while in the future it may allow comparison with known levels of harmonics distortion on the distribution network to calculate the performance at higher frequencies of VTs in-situ.

INTRODUCTION

The performance of existing Inductive Voltage Transformers on power distribution networks is not well known at frequencies higher than the mains frequency [1]. In the near future, levels of distributed energy resources, electric vehicles and local storage are expected to increase. As a result, it is expected that harmonic emissions at distribution level could rise to levels which may damage or shorten the life of a wide range of network assets. Therefore, understanding how the performance of voltage monitoring sensors varies with frequency will be important as these network changes take place. The G5/4-1 [2] engineering recommendations are used by UK utility companies to determine acceptable voltage and current harmonic limits at medium to low voltages, however, inductive VTs are known to be unable to meet their design specification accuracy above mains frequency [3]. Understanding the variance in VT measurement is therefore a vital component in network planning and compliance studies.

Measuring the VT performance is possible in the laboratory by injecting the transformer primary with a variable frequency waveform and measuring the resulting secondary waveform. A comparison of the primary voltage to the secondary voltage gives the transformer ratio, and the phase difference between the waveforms gives the phase response as a function of frequency.

The established method for performing a frequency response analysis of a sensor is to sweep a sinusoidal waveform in small frequency increments from a low frequency to a target high frequency, and for each frequency step, perform a Fast Fourier Transform (FFT) analysis on the input and output waveforms to deduce the transfer function [1]. This is a slow method, which requires significant post-processing of the test data to derive the real sensor response.

One of the VTs tested at PNDC was also tested at the Istituto Nazionale Ricerca di Metrologica (INRIM), where a variation of the above method was employed, using a two-tone frequency sweep, the first tone is the fundamental at 50 Hz, and the second tone is varied in frequency and magnitude. The test methodology at INRIM used a non-portable 6 kV source with a controllable waveform generator, and the testing was carried out as part of the EMRP –funded EURAMET project on Smart Grids II [4].

PNDC have developed a variation on this method, using a programmable oscilloscope and deriving ratio and phase information from the Fourier analysis and comparison of the input and output waveforms. A fundamental part of the new method described here was to create a distorted waveform for the waveform generator in the programmable oscilloscope, which contains harmonics superimposed on a fundamental frequency, all with known amplitude and phase. The main findings of this paper are the comparison of INRIM data on one of the VTs tested at PNDC, with a swept-sine analysis and with the PNDC method for an accuracy comparison. On this basis, two more VTs were tested comparing the swept-sine technique and the new PNDC technique to show the variation in frequency response with VT specification and construction.

METHOD

Hardware

The programmable oscilloscope (PicoScope 4824 80 MHz 8-channel 12-bit resolution with inbuilt signal generator) is interfaced via USB to a laptop, which can run the Pico software or use MATLAB in conjunction with Pico's Software Development Kit [5] to control the oscilloscope and analyse the results. A high-speed HV amplifier was procured to raise the VT primary voltage to 1 kV for high impedance loads (TREK 2210), and in order to match the

PicoScope output signal to the 10V required for the HV amplifier, another instrumentation amplifier was used, which had suitable performance and programmable gain, with a maximum output of 10V. This hardware was configured as shown in Figure 1, and the output from the instrumentation amplifier was routed directly back to the oscilloscope input and compared with the VT secondary measurement.

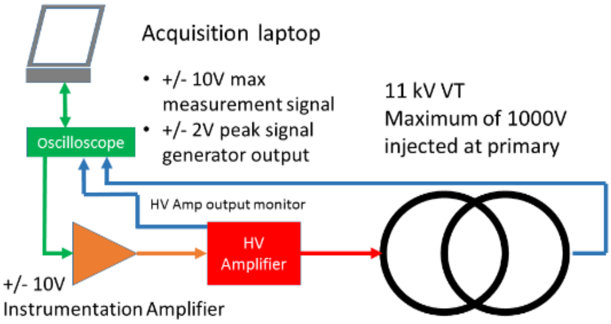

Figure 1: Measurement setup at PNDC

Voltage Transformers tested

PNDC had access to three 11 kV Inductive Voltage Transformers for testing, shown in Figure 2. These VTs had different specifications and dimensions, and a difference in the output measurements was expected due to the variance in construction [6].

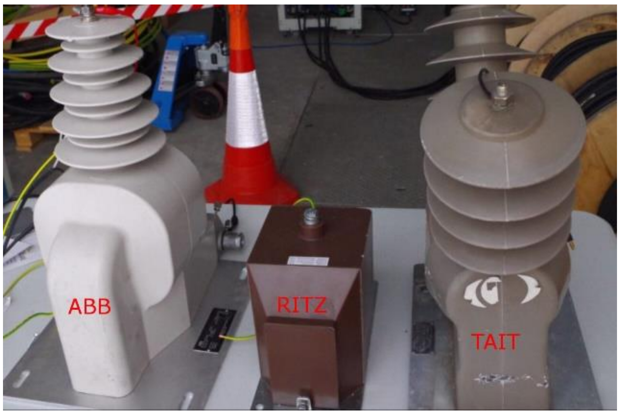

Figure 2: 11 kV voltage transformers used in testing at PNDC

The VTs were sourced from PNDC members and manufactured by ABB, RITZ, and TAIT. Some relevant parameters are shown in Table 1, and for all testing described in this paper, the VTs were connected in **open circuit** configuration.

New Method

The test method used a set of distorted waveforms which consisted of a fundamental sinusoid with harmonics superimposed by a custom MATLAB function. The PicoScope was controlled by a MATLAB GUI (Graphical User Interface), developed by PNDC. The concept of harmonic injection to measure VT response was described previously in [7], and the PNDC method extends the range of measurement to 30 kHz and extracts the phase response simultaneously. The process followed the flow outlined in Figure 3 to generate and then analyse a set of distorted waveforms, where the VT primary signal was compared with the direct measurement on the VT secondary. From an FFT analysis of the waveforms, it is possible to calculate the VT ratio and phase frequency response

Table 1: 11kV VT nameplate parameters

Property	ABB 11 kV VOG-24 VT	RITZ 11 kV VES 12-02 VT	TAIT 11 kV UREM VT
Measurement Class	0.2	0.2	5
Ratio	100:1	100:1	100:1
Typical Burden (VA)	25	0 – 7.5	100
Max Thermal Burden (VA)	500	175	350

The order of processes in the method which are controlled by the GUI are as follows:
First the harmonic waveform generation function creates a distorted wave consisting of a fundamental with a sequence of harmonics added, then the parameters for the on-board signal generator on the PicoScope are set. Next, the signal generator is started, and the data acquisition on two input channels is configured and started. The data from the amplifier monitor output is captured on one input at the same time as the VT secondary is captured on another input of the PicoScope, then the FFT of each measurement channel is calculated. The magnitude and phase of the harmonics, relative to the fundamental, can then be extracted directly, and the relative change between the input and output yields the frequency dependence of the VT in terms of ratio and phase response.
Figure 4 shows an example swept sine input, demonstrating how the PicoScope could be controlled to perform the conventional test. Figure 5 shows an example of the distorted waveform generated in the MATLAB GUI, which contains a fundamental at 50 Hz, with 50 harmonics added with the same magnitude and random phase with respect to the fundamental. To extend the range and usefulness of the measurement, this process was performed iteratively by the GUI, where the fundamental was first set at 50 Hz, and the number of harmonics fixed at 120, which gave a frequency range of 6 kHz at a resolution between the measurement points of 50 Hz. The fundamental frequency was then increased automatically to 100 Hz, extending the range to 12 kHz at a resolution of 100 Hz. To capture any resonant behaviour at higher frequencies, the fundamental was again increased to

250Hz, with a maximum frequency range of 30 kHz, with a resolution of 250 Hz between measurement points.

This sequence of measurements was performed automatically by the MATLAB GUI and could be completed with a graphical presentation of the VT frequency response in ratio and phase within 30 seconds on a typical laptop using a dual-core processor running at 3 GHz.

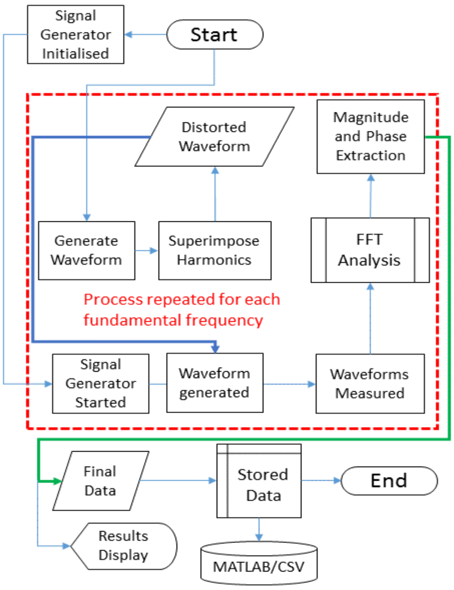

Figure 3: Flowchart of the software process handled by the PNDC MATLAB GUI.

For a swept-sine measurement, a typical example containing 1000 frequency points, ranging from 50-20000 Hz, and a sample time at each frequency of 0.2 seconds, requires a minimum of 200 seconds to acquire the data, and more time to organise the data, process it and collate the results.

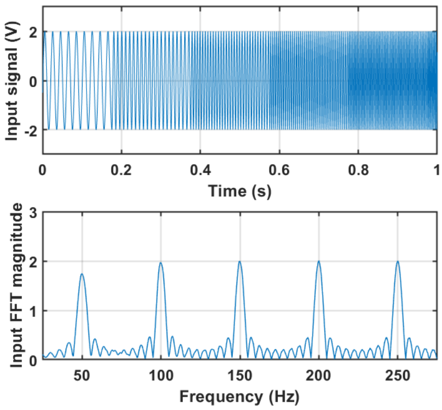

Figure 4: Top: an example of a swept sine input signal. In this example the sine wave frequency is increased by 50Hz for every increment of 0.2 seconds. Bottom: the magnitudes of these frequencies can be derived from a Discrete Fourier Transform analysis of the time-domain signal, as shown.

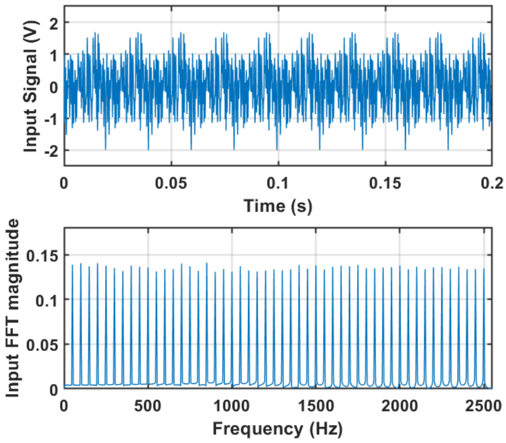

Figure 5: Top: an example of the harmonic distorted wave, generated by summing 50 harmonics of fixed amplitude to a fundamental 50 Hz sine wave. Bottom: the magnitudes of the frequency components are extracted in one analysis process using the FFT transform.

To extract the magnitude A and phase $\emptyset$ of the input and output waveforms at a given frequency f from the FFT output, the following formulae were used (shown for the VT output):

$$A_{vt_{out}}(f) = 2 * abs\left(FFT_{out}(f)\right)$$

$$\emptyset_{vt_{out}}(f) = atan2\left(\frac{im(FFT_{out}(f))}{re(FFT_{out}(f))}\right)$$

TEST RESULTS

To verify the new method, the experimental set-up was first used to perform the standard swept-sine measurement on the RITZ transformer, which had been previously tested at INRIM to measure the VT frequency response in terms of ratio and phase angle results. The same measurement was performed using the new technique, and the overall comparison of INRIM results, PNDC implementation of the swept-sine method and the new PNDC GUI shown in Figure 6.

The PNDC testing was continued on the other VTs available, and the comparisons are shown in Figures 8-10. Figure 7 shows the iterations performed by the MATLAB GUI when the fundamental frequency for the signal generator is increased from 50 Hz to 100 Hz and then to 250 Hz.

All of the INRIM results shown in this paper were measured at 6 kV input voltage, the PNDC swept-sine results were obtained at 1000V peak-to-peak, and the distorted waveform used by the PNDC GUI had a peak-to-peak amplitude of 700V.

Comparison with INRIM results

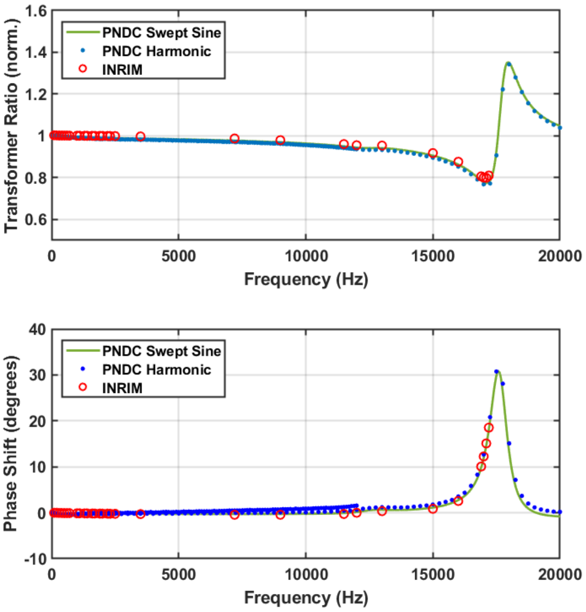

Figure 6: Top figure shows the RITZ transformer ratio measurement, comparing measurements from INRIM (red) with a swept-sine measurement at PNDC (green), and the harmonic superposition method (blue). Bottom figure shows the same group of measurements reporting the phase difference observed between VT primary and secondary.

The RITZ transformer used for this comparison shows good agreement for all the measurement methods, up to the maximum frequency range of the INRIM results at the 17 kHz resonance.

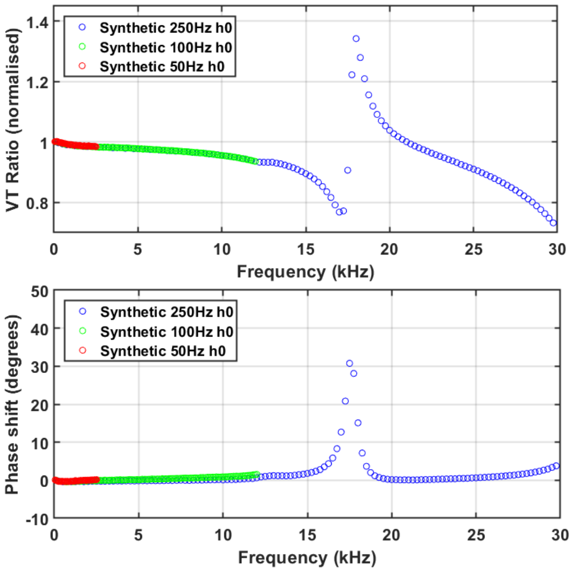

Figure 7: Top plot shows range covered by each distorted harmonic waveform, and the VT ratio response calculated by comparing the input and output signal FFT results. Bottom plot shows the phase angle response of the VT derived similarly.

Comparison for ABB VT

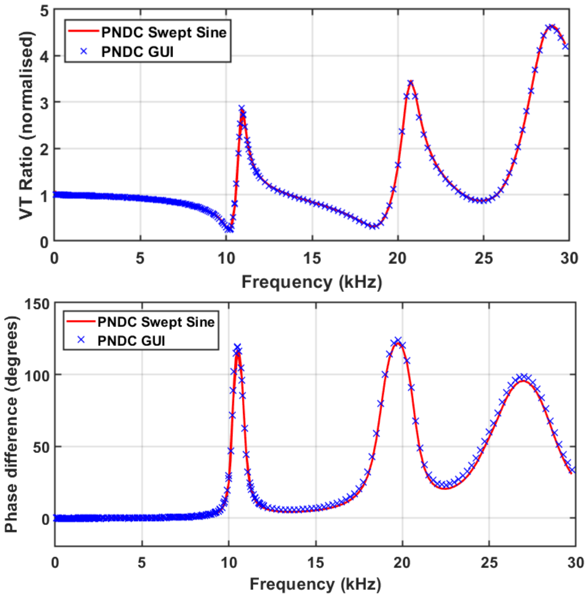

Figure 8: Top plot shows the ratio measured from the ABB VT, comparing the swept sine measurement in red with the harmonic superposition method in blue. Bottom plot shows the phase response for the ABB VT.

The ABB VT shows a series of strong resonances in the measured secondary voltage at 10, 20 and 30 kHz, which are also seen in the phase response with shifts of greater than 90° associated with the resonant peaks.

Comparison for RITZ VT

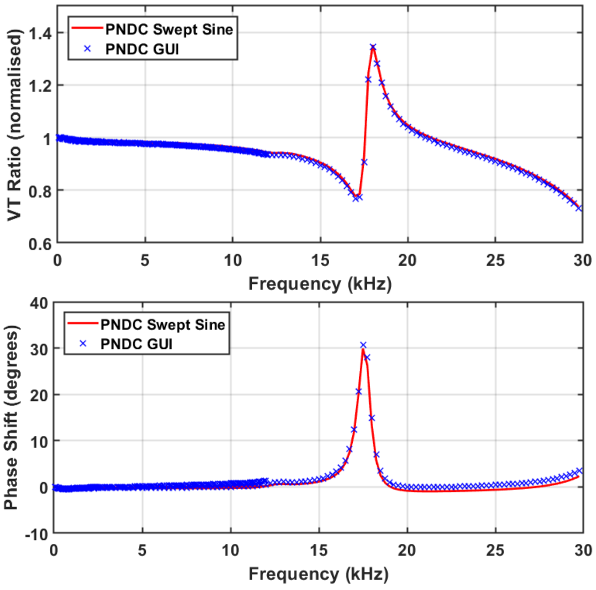

Figure 9: Top plot shows the ratio measured from the Ritz VT, swept sine measurement in red, harmonic superposition method in blue. Bottom plot shows the phase response for the Ritz VT.

The RITZ VT shows a small resonance in the secondary output at 17 kHz, and maintains good performance up to 10 kHz. The phase response is flat up to the same resonant peak, where a small phase shift of +30° was observed.

Comparison for TAIT VT

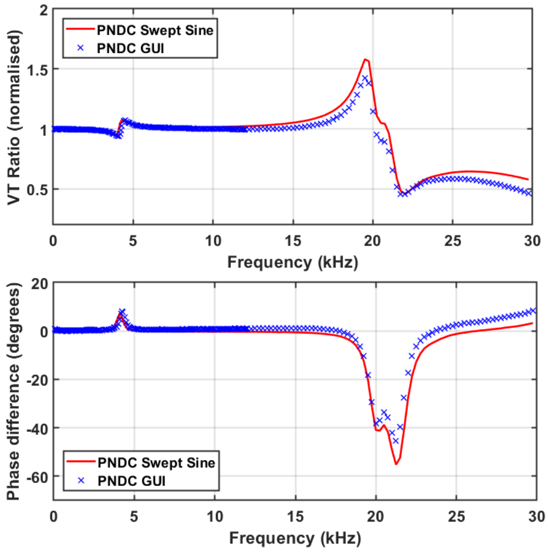

Figure 10: Top plot shows the ratio measured from the Tait VT, swept sine measurement in red, harmonic superposition method in blue. Bottom plot shows the phase response for the Tait VT.

The TAIT VT shows a small resonance in the secondary output at 4 kHz, then a large resonance at 19 kHz. The phase response shows a small shift of + 10° at the 4 kHz peak, and then a much larger shift of -50° at 19 kHz.

Measurement Errors

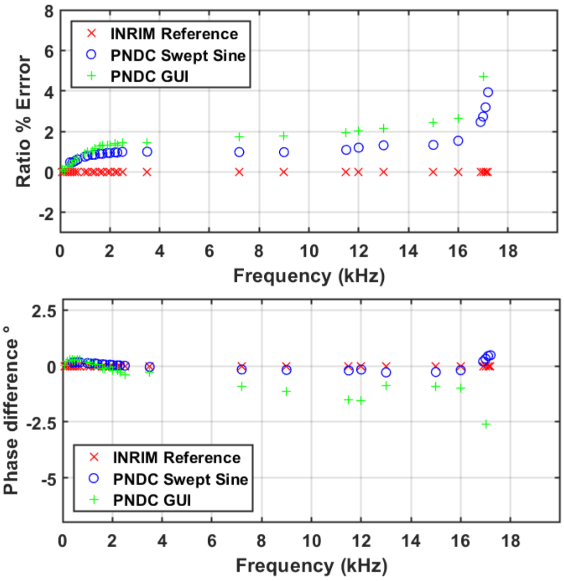

Figure 11: Top plot shows the relative error in measured VT ratio, relative to the results from INRIM on the RITZ 11kV VT. Bottom plot shows phase shift error relative to INRIM.

Figure 11 shows the relative error in ratio, compared to the INRIM measurements made at 11kV input, for the PNDC measurements. The increase in ratio and phase error close to the resonant peak is due to the peak shifting frequency slightly as the input voltage level is changed, and is likely connected with changes in the HV amplifier performance.

CONCLUSION

The method described here shows comparable accuracy to those developed at INRIM as accurate methods for measuring VT frequency response. Since the technique uses FFT analysis to extract harmonic components, it is fast and can be compared with other power quality measurements. It was also observed experimentally that good results in agreement with the standard swept–sine technique could be achieved at 10 V input range, which allows a measurement to be performed using low-voltage portable equipment. For future work, this analysis technique could be applied to the task of inferring VT frequency response by utilising the FFT measurement results on the VT secondary and comparing with power quality measurements from other points in the distribution network to help address the gap in knowledge regarding the behaviour of existing VTs on the distribution network.

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