Composite High Voltage Source for the Instrument Voltage Transformers Frequency Response Evaluation up to 10 kHz

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***Abstract*—The measurement of high voltage, high frequency, harmonic distortion has gained the attention of numerous researchers recently. The increases in the number of harmonic emission sources due to the extensive use of power electronic devices has resulted in increased levels of harmonic voltages and currents in the power system. While measurement of harmonic voltages in LV networks is well established, MV distribution and HV transmission networks often require dedicated instrument voltage transformers (IVTs) in the measurement chain. The calibration and verification of the measurement accuracy of IVTs is generally performed under non-distorted sinusoidal input voltage conditions. The frequency dependent behaviour of IVTs is often unknown or not been properly verified. Hence, a HV calibration system, which allows calibration under distorted sinusoidal waveform conditions that represent actual power system voltage characteristics, is required. This paper presents the details of a composite voltage source that can generate a practical waveform with a HV fundamental component and superimposed voltage harmonics up to 10 kHz.**

Keywords—frequency response, HV transformers, high frequency harmonics, instrument transformers, power quality

I. Introduction

Compared to the conventional power system, the modern power system has been integrated with numerous non-linear devices. This includes large-scale and distributed renewable energy sources, power electronic control and conversion equipment, HV direct current transmission networks, flexible alternating current transmission networks, etc. The majority of these are power electronic semi-conductor-based switching devices that use high-frequency switching mechanisms. This results in increased emission of harmonic voltages and current in a broader frequency range in comparison to the conventional characteristic harmonics. These non-conventional harmonics include high-frequency harmonics above 2 kHz which are generated due to the use of pulse width modulation (PWM) switching-based converters.

Standards governing the instrumentation and procedures regarding harmonic measurement such as IEC 61000-4-7 provide informative guidelines on harmonic measurement in the frequency range from 2 kHz to 9 kHz [1]. However, it does not address the requirements for harmonic measurements in HV and MV networks. An instrument voltage transformer (IVT) is required to step down MV and HV voltages to compatible levels with measurement equipment. The majority of existing IVTs are magnetic or capacitive voltage transformers that are specifically designed for accurate voltage measurement at 50 Hz fundamental frequency and their voltage ratio errors and phase displacements at harmonic frequencies are generally unknown. Hence, their frequency response should be evaluated to determine the overall harmonic measurement accuracy performed in HV networks.

Conventionally, IVT harmonic measurement capability is completely characterized by its frequency response function (FRF) assuming a linear time-invariant behaviour [2-4]. In which, an LV single-tone frequency sweep can be used to characterize the IVT frequency response [5]. However, inductive transformer harmonic measurement accuracy can be impacted by magnetic core non-linearities such as hysteresis and saturation [6-8]. Under pure sinusoidal input signal conditions, LV FRF can be used to characterize inductive transformers with increased measurement uncertainty limits. Due to the increasing number of non-linear loads in modern distribution and transmission networks, the actual input voltage waveforms may deviate from pure sinusoidal conditions [9-13].

Several recent studies have shown that the harmonic measurement errors that occur due to weak non-linearities in inductive voltage transformers can be compensated by using different modelling and approximations techniques based on the application of distorted voltage signals to inductive transformers [6-7, 14-15]. In addition to that, IEC 61869-103 technical report suggests that, if the voltage transformer FRF is affected by the presence of fundamental voltage, a composite HV distorted waveform should be used in FRF characterization. The suggested harmonic magnitudes and the procedure for characterization are illustrated in Fig. 1.

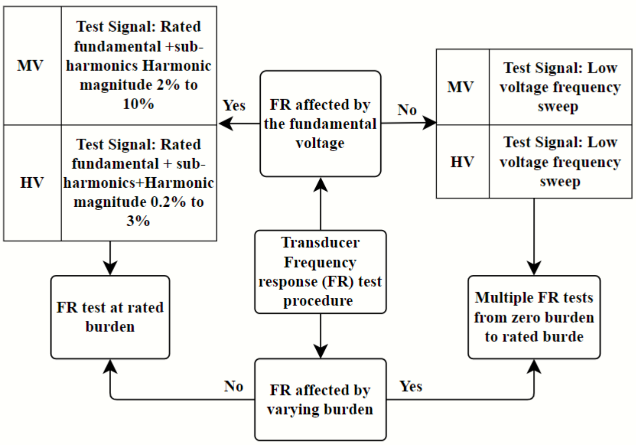

Fig. 1. Voltage transformer FRF test procedure suggested in IEC 61869-103

Accordingly, HV sources that can generate complex distorted waveform are essential to characterize inductive voltage transformer harmonic measurement performance and compensate for their non-linearity. Ref. [5] suggests several methods of generating HV test signals to evaluate IVT frequency response. An arbitrary waveform consisting of a fundamental component and superimposed harmonics amplified through a power amplifier and stepped up through a step-up transformer is used to generate a HV distorted signal. In cases where the power amplifier capacity is limited, two separate sources can be used to generate the fundamental component and the harmonic profiles and synchronised in phase by external means. However, in either case, the generation of high frequency harmonic components above 2 kHz will be difficult due to the limited bandwidth of the existing step-up transformers.

In order to overcome the frequency bandwidth limitations imposed by the step-up transformers several authors have suggested different modulation techniques to develop composite HV sources [2, 16-17]. Authors in [2] developed a system that use a modulation transformer to inject a 10% harmonic component up to 10 kHz to a fundamental component of $20/\sqrt{3}$ kV. Authors in [16] have proposed two types of HV sources that are based on inductive and capacitive parallel coupling between two step-up transformers to generate composite HV waveforms. The implementation of the inductive coupling-based system has shown the capability to inject 1% harmonics up to 1 kHz to a 230 kV fundamental HV component.

This paper presents a novel approach in generating a composite HV signal based on series connection of two voltage transformers with capacitive compensation that would enable the superposition of multiple harmonic components up to 10 kHz into a HV component up to a 50 kV magnitude. In comparison to other approaches, the proposed system architecture overcomes the effect of step-up transformer limited bandwidth to increase frequency range and the magnitudes of superimposed harmonics.

II. Experimental Setup

Two setups were developed to compare the proposed approach for generating HV composite waveforms for IVT calibration. The first setup shown in Fig. 2 (a) represents the conventional approach of generating HV composite waveforms using a signal generator, power amplifier and a step-up transformer. The proposed approach shown in Fig. 2 (b) consists of two independent sources and two step-up transformers to generate the HV fundamental component and the harmonic profile separately.

A. HV waveform generation

The composite signal for test setup is generated by using arbitrary waveform generators (AWG). In the conventional approach, a single AWG generates the composite signal that consists of a fundamental component and a superimposed harmonic profile that consists of 1% harmonics up to 10 kHz. The proposed approach uses two AWGs to generate the fundamental component and the 1% harmonic profile separately. A power amplifier with a 4000 VA capacity is used to step-up the AWG waveform in the conventional approach. The power amplifier has a small signal bandwidth of 40 kHz that enables the generation of harmonic components up to 10 kHz in addition to the fundamental component.

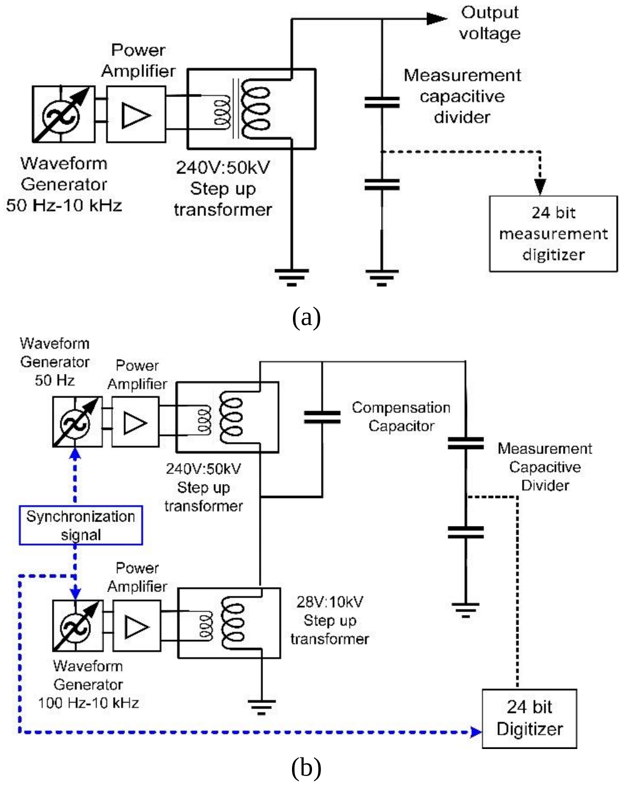

Fig. 2. (a) Conventional step-up transformer test setup (b) proposed two transformer-based test setup

The proposed approach uses a secondary power amplifier with a capacity of 1400 W and bandwidth of 15 Hz to 800 kHz to generate the harmonic spectrum. The fundamental component in this case is generated by the same 4000 VA power amplifier that was used in the conventional method. As the combined waveform is generated by two AWGs, a trigger signal is used to synchronize the harmonics phase angles to the fundamental signal in order to generate a stable waveform. A custom-built high frequency step-up transformer is used to generate the HV harmonics in the proposed method.

B. HV capacitive divider based measurement system

The measurement system consists of a HV capacitive divider with a nominal voltage ratio of 32000:1 and a two-channel measurement digitizer with 24-bit resolution.

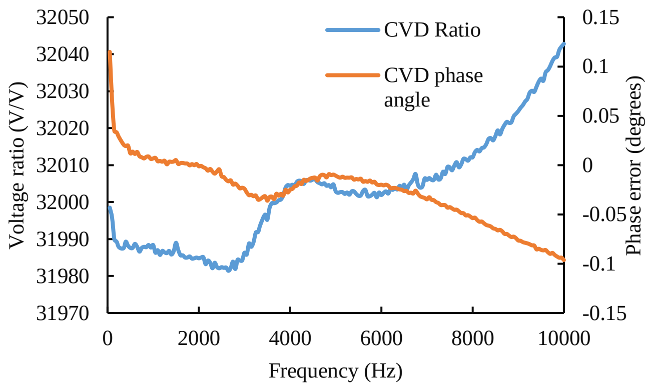

Fig. 3. Frequency response of measurement capacitive divider

The capacitive divider is based on a compressed gas HV capacitor and a multi-layer ceramic LV capacitor. The expanded uncertainties of voltage ratio and phase error are estimated to be ±0.21% and ±0.23 crad respectively from 50 Hz to 10 kHz. Fig. 3 shows the frequency response of the divider. The measurement divider plays the most important part in the proposed composite signal generator. Due to the frequency response function of the equipment chain that generates harmonics, an accurate measurement of harmonic voltages and fundamental component at the output is required to obtain the desired composite signal spectral magnitudes and phase angle alignments. This frequency response function will depend on the following factors.

- Impedance of the transformer under test
- Burden of the transformer under test
- Measurement divider impedance

In order to minimize the changes in harmonic frequency response function due to above factors, all those factors should be kept constant during the testing process. Therefore, for each calibration of a test transformer two steps are followed. In the first step, the harmonic magnitudes and phase angles in the AWG signal will be approximately 1% and phase aligned to the fundamental trigger signal. The high voltage output for this will be measured and used to calculate the FRF for the harmonic generation circuit. In the second step, the AWG input will be subjected to pre-filtering by using the calculated FRF. Pre-filtering FRF should be measured and modified each time the test transformer or its burden is changed.

In addition to the pre-filtering process, it should be noted that the use of composite signals will generate peak voltage amplitudes that are higher than that of the fundamental component amplitude. Therefore, when determining the harmonic amplitudes in the test waveform, a fundamental component magnitude should always be smaller than the rated peak voltage of the step-up transformer.

C. *Step-up transformer impedance measurement*

In order to compare the harmonic injection capability of the proposed approach, initial investigation of the step-up transformer HV and LV winding impedance measurement was carried out by using voltage and current measurements up to 10 kHz. Fig. 4 and Fig. 5 show the HV winding and LV winding impedance magnitudes and phase angles respectively.

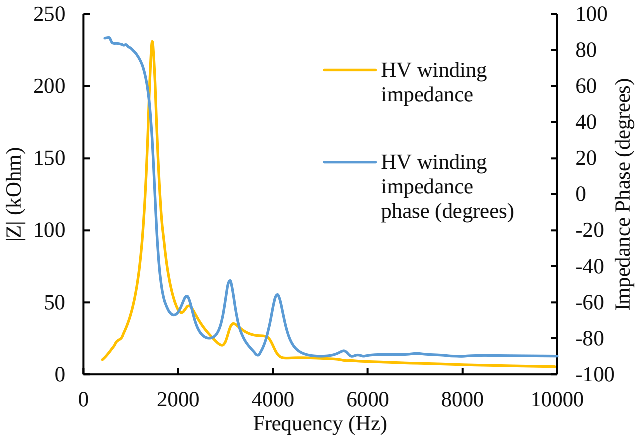

Fig. 4. Fundamental step-up transformer HV winding impedance

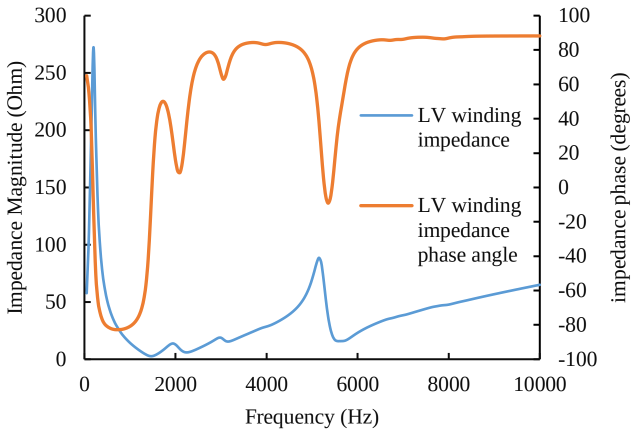

Fig. 5. Fundamental step-up transformer LV winding impedance

The HV winding impedance response shows a significant parallel resonance point at 1.45 kHz. Above this frequency impedance shifts from inductive behaviour to capacitive behaviour. Three more damped resonance points can be identified up to 4 kHz. Beyond this frequency the impedance remains capacitive up to 10 kHz.

According to the LV winding impedance response, a significant parallel resonance point is located at 200 Hz. Several damped resonance points are observed up to 5.35 kHz. However, beyond this frequency, the LV winding impedance shows an inductive behaviour up to 10 kHz. The main difference between the responses is the impedance behaviour after the final last resonance point. The LV winding shows an inductive behaviour while the HV winding impedance shows a capacitive behaviour.

D. *Step-up transformer frequency response measurement*

According to the impedance measurements shown in the previous section, it can be seen that the HV and LV winding shows different behaviours at high frequencies. The increasing inductive impedance seen from the LV winding side implies that the generation of high frequency harmonics feeding the transformer from LV side would be difficult. On the other hand, the HV winding shows a capacitive impedance behaviour at high frequencies, implying that the HV winding will provide lower impedance path for the harmonics generated by the high frequency transformer in the proposed approach. In order to further validate this, the step-up transformer frequency response was measured in both the conventional and the proposed new approach.

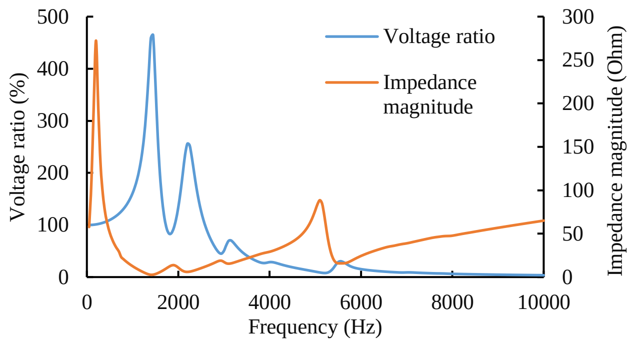

Fig. 6. Step-up transformer frequency response and impedance comparison using conventional approach

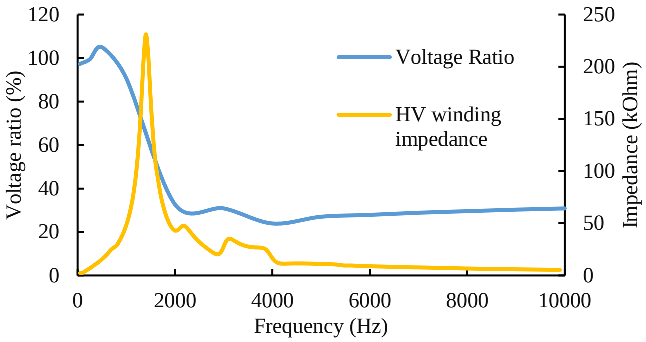

Fig. 7. Step-up transformer frequency response and impedance comparison using proposed HV modulation approach

A comparison between the voltage transformation ratio and impedance for each approach are shown in Fig. 6 and Fig. 7. Frequency response measurements shows that the inductive impedance behaviour in the conventional approach results in a reduction in voltage transformation ratio at high frequencies. On the other hand, the capacitive behaviour of the HV winding at high frequencies allows the generation of high frequency harmonics with a significant improvement in comparison to the conventional approach.

E. Capacitive compensation for high frequency harmonic components

In comparison to the conventional approach, the proposed HV modulation approach enables an approximate transmission of 30% of input harmonic voltages to the output for frequencies from 5 kHz to 10 kHz. The reduction of capacitive impedance at high frequencies can be identified as the main reason for this effect. In order to further increase the harmonic voltage transmission capability, a compensation capacitor is connected across the HV winding of the step-up transformer. The proposed approach was tested by using two high voltage capacitors with 100 pF and 2 nF capacitances respectively. Fig. 8 shows the comparison of the results with different capacitor values.

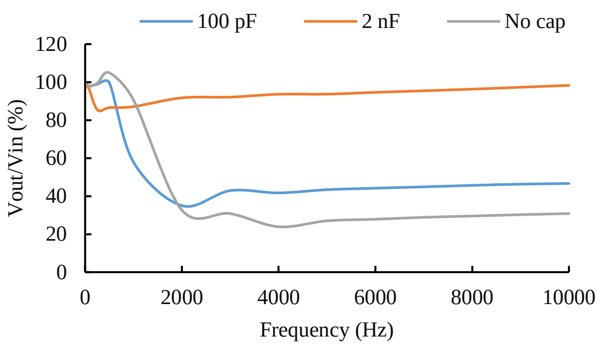

Fig. 8. Step-up transformer frequency response compensation under different capacitances

III. Harmonic Measurement Performance

A. Distortion indices for composite voltage source

A modified definition is suggested to be used for composite waveform total harmonic distortion calculation by removing the harmonic orders that are included arbitrarily.

$$THD_{composite} = \frac{\sqrt{\sum_{\substack{i=n \\ i\neq m}}^{N} V_i^2}}{V_1} \times 100 \qquad (1)$$

Where, V_i is the harmonic magnitude at harmonic order i, and m indicates the harmonic orders that are included in the waveform arbitrarily.

A composite signal consisting of a HV fundamental component and four harmonics components at 2.5 kHz, 5 kHz, 7.5 kHz, and 10 kHz was generated using the proposed approach. The calculated THD value considering all other residual harmonics up to 12.5 kHz is 0.32%. For comparison, the same waveform was generated by using the conventional approach which amounts to a THD value of 0.27%. Fig. 9 shows the output composite signal FFT spectrum that was used for the calculations. In order to avoid calculation errors, pre-filtering was not used in this test.

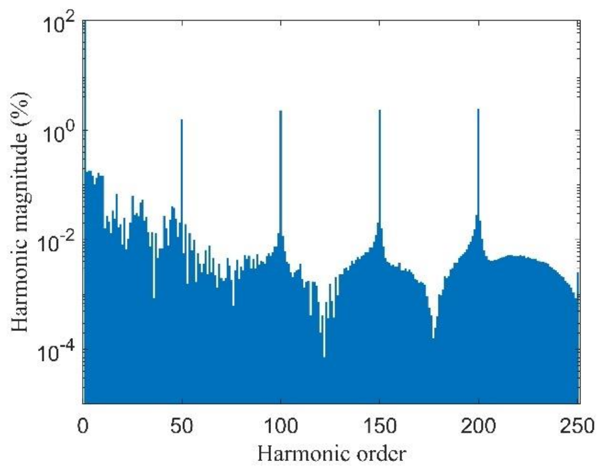

Fig. 9. Output composite signal spectrum used for total harmonic distortion calculation.

B. Stability of the composite harmonic amplitudes

The harmonic amplitudes in the composite HV output signal should be stable for the proposed system to be used for calibrating instrument transformers. Acceptable short-term stability is sufficient for the HV source to be used for the calibration depending on the fact that the measurement capacitive divider has sufficient long-term stability. Fig. 10 shows the percentage variation of harmonic amplitudes calculated over the measurements taken over 2 h in 5-min intervals.

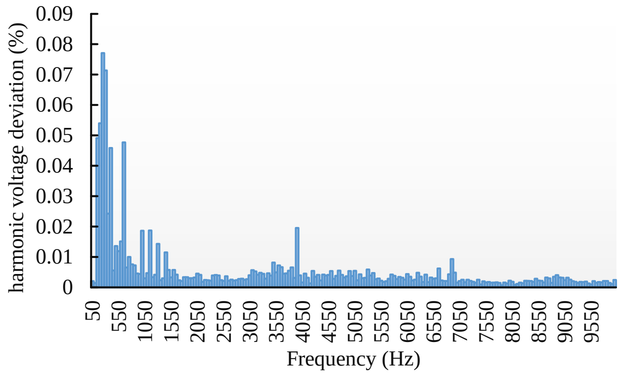

Fig. 10. Percentage variation of harmonic amplitudes over 2 hours in 5 minute intervals.

It can be seen that at lower harmonic orders, specially at odd harmonics, the deviation is significantly higher than the variations at higher harmonic orders. All the deviations are calculated in relative to the harmonic amplitude and they are below 0.1%. If the harmonic amplitudes deviations are calculated with respect to the fundamental amplitude, they are below 0.001%.

C. Effect of loading due to the connection of test transformer

When the proposed high voltage source and measurement system is used to evaluate the frequency response of a high voltage test transformer, the high voltage source performance could be affected due to the loading of the test transformer. In order to evaluate this effect, a test transformer frequency response evaluation was carried out by using a 40 kV rated fundamental component with superimposed harmonic components up to 10 kHz. 40 kV voltage was selected in order to avoid any possibility of step-up transformer saturation due to over-voltage. The harmonic voltage appearing across the test transformer in proportion to the harmonic voltage output generated by the high frequency transformer is shown in Fig. 11.

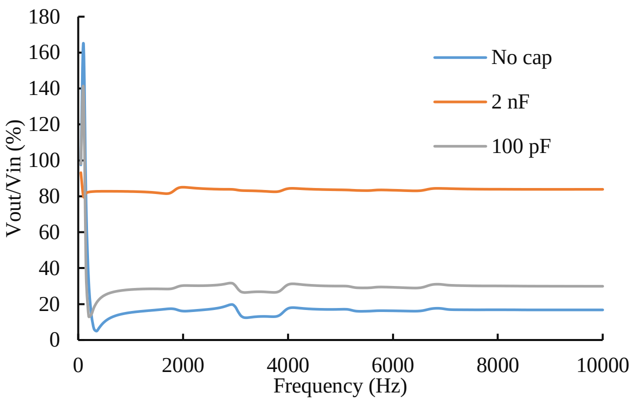

Fig. 11. Proportional harmonic voltage generated by the composite high voltage source when loaded with test transformer.

IV. Conclusion

A novel approach for generating a composite HV signal based on series connection of two voltage transformers with capacitive compensation that enables the superposition of multiple harmonic components up to 10 kHz into a HV component up to a 50 kV magnitude has been demonstrated. The performance of the system in regard to accuracy of magnitude and phase characterisation was presented. In comparison to other approaches, the proposed system architecture overcomes the effect of conventional step-up transformer limited bandwidth and increases the frequency range and the magnitudes of superimposed harmonics.

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