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# Innovative Applications of High Voltage Instrument Transformers for Monitoring Power System Transients and Harmonics

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**SUMMARY**

The increase in the number of large industrial consumers in the power systems has made it critical to provide high power quality. Also, the addition of distributed generation systems has introduced harmonics and transients into the power system. To be able to supply steady power to the users, the requirement for monitoring harmonics and transients in transmission and distribution grids has increased.

This paper presents the application of various instrument transformers to monitor or measure harmonics and fast transients in the transmission systems. While inductive voltage transformers (VT or PT) are often used to monitor harmonics, they are not an adequate solution. Enhanced/hybrid Capacitor Voltage transformers (CVT), while also known for their use in metering, protection, as well as Power Line Carrier (PLC) applications, they can be used to monitor harmonics within the frequency range of 50 Hz to 3000 Hz with an accuracy of ±5% amplitude. Furthermore, Resistive Capacitive Voltage Dividers (RCD), which are less commonly used for metering and/or protection applications in AC systems, are available with harmonics metering capability within the frequency range of 50 Hz to 3000 Hz with accuracy of ±0.2% and up to 10 kHz with accuracy of ±0.5% amplitude and reliable phase angle measurements.

High voltage transients in the transmission system are a major cause of failures to the high voltage equipment which would shorten the lifespan of the equipment even if there is no immediate damage. The accuracy of measurement for the available instrument transformers (i.e. current and/or voltage transformers) varies in higher frequencies. Therefore, they have limitations for harmonics or transient monitoring applications. Other equipment, such as enhanced CVT and RCD provide high accuracy within their specified range.

In this paper, the innovative use of Resistive Capacitive Voltage Dividers (RCD) designs for monitoring system transients is introduced. The proposed solution enables transient recorders to capture the transients of 1.2/50 μs lightning impulse waves or switching transients occurring in transmission systems with ±5% accuracy. The functionality of this transducer is shown over a frequency range of 50 Hz to 100 kHz with an accuracy of ±5% up to 3 kHz and an accuracy of ±12% up to 100 kHz.

In addition to introducing the new voltage transducer solution, the possibilities, and shortcomings of various high voltage instrument transformers in harmonics monitoring applications, and monitoring of fast transients are presented. The corresponding amplitude

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and phase accuracy in different frequency ranges are reported and compared using measurement results. The impact of nonlinearities and resonance behaviour of the inductive and capacitive instrument transformers, in addition to the influence of the load on the measurement results of the RCD units are explained.

The fidelity of the recorded transient response of an RCD is shown to be dependent on the load (i.e., length of the cable, and VA of the load). The recorded measurement results using an SEL400L with burden impedance of 1 MΩ/70 pF and maximum cable length of 30 m are shown in this paper.

**KEYWORDS**
Instrument transformer, high voltage, Capacitive voltage transformer, inductive voltage transformer, divider, transient transducer

## INTRODUCTION

The main application of high voltage (HV) instrument transformers (IT) in power systems is measurement, monitoring and protection. The HVITs are meant to provide transformed voltage or current with high accuracy where the relays or meters are connected on the secondary side. The accuracy of the response at the rated voltage, current and frequency is guaranteed by the manufacturers through the routine tests. However, it is important to know the accuracy of the response of any type of instrument transformer under special conditions in the system such as fault, switching and presence of harmonics.

The growing interest in power quality measurements necessitates the accurate measurement of harmonics (i.e., up to $50^{th}$ harmonic) [1]. Also, there has been failures of HV power transformers that were reported to be initiated by an interlayer resonance within the transformer's winding. The failure was initiated by travelling waves due to system faults, and switching instances [2,3]. The travelling waves could be low in voltage, but with high frequency content which would pass through the surge arresters and initiate resonance within the transformer's winding. A reported failure of a 500kV/345kV autotransformer in [2] was declared to be due to a sharp voltage transition which generated a travelling wave due to the mismatching impedance at different points in the system. The travelling wave could be initiated by system fault, impedance mismatching of cables during switching new lines into the system, or rapid charging of capacitance banks when switched into the system. Several failures of HV devices have been caused by disconnect switch operation. The disconnect switch operation consists of a number of restrikes in opening operation and a number of prestrikes for closing operation.

In any of the above-mentioned cases, the high frequency content of transition will cause most instrument transformers to go into self-resonances and therefore the reading at the secondary will not be a reliable replica of the HV side [4]. Therefore, special voltage transducers should be used for reliable measurement of power quality. Two aspects of transducers are of concern, one is the ability of the transducer to replicate the full scale of the HV signal without clipping the amplitude and the other is the accuracy of the measured frequency and phase [1]. In this paper, the amplitude and phase replication of HVITs at different frequencies are discussed. The fidelity of the response of these transformers for different applications can be interpreted from the reported graphs in this paper which have been collected by the authors based on availability of the data.

## Power quality measurement

Monitoring of power quality is important for refining the modelling of a system, better planning of new equipment and troubleshooting of failures. Considerations for the economic aspect of power quality is also important. It is important to consider the cost of measurement equipment, the labour associated with the installations, the communication systems, the data management system and the duration of monitoring the PQ. Permanent installations for monitoring PQ is beneficial in cases for identifying failing equipment before the failure, reduction of failure restoration time, contract compliance, and connection requirements for new equipment [1].

It is important to consider the rating, linearity, frequency and phase response, and the burden characteristics of a transducer to avoid incorrect measurement. The typical frequency range within which each type of HV instrument voltage transformer's (IVT) output response is a reliable replica of the HV side in that frequency range is shown in Figure 9 of [5] and described in detail in the following sections.

### 1. Inductive voltage transformer (IVT)

Inductive voltage transformers are one of the most common instrument transformers which consists of a wound transformer with a magnetic core. In these units, the magnetic core is prone to saturation. Also, the inductance and the inherent capacitance of these units resonate at the natural frequency of the unit depending on the voltage class and the design, single coil or cascaded. The typical frequency response of instrument transformers is shown in Figure 1 for a 420 kV IVT and Figure 2, showing the voltage class dependence of the resonance frequency. The IVT frequency response is flat for a few 100 Hz only, which means that these units are not adequate for power quality measurements at a wide range of frequencies. However, the frequency response depends also on the voltage rating of the IVT as shown in Figure 2.

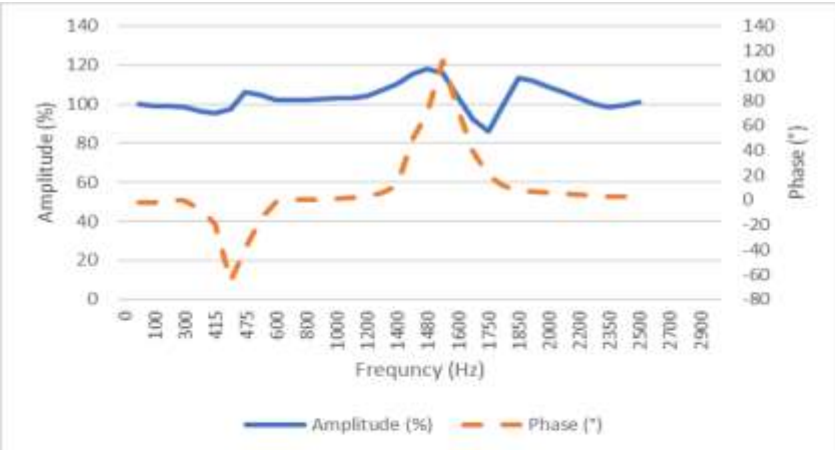


**Figure 1 Frequency response of a typical IVT for 420 kV system voltage**

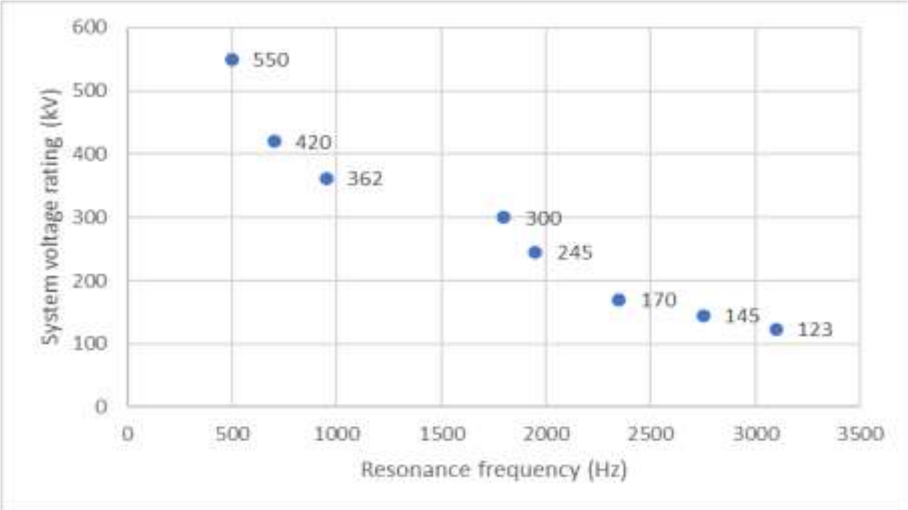


**Figure 2 First resonance frequency of typical IVT with their system voltage rating**

## 2. Capacitive voltage transformer (CVT)

Capacitive voltage transformers (CVT) are another common type of transducers used for measuring HV applications. In a CVT, the voltage is first stepped down by a capacitive divider and then a medium voltage inductive transformer further steps down the voltage to low voltage suitable for measurement equipment. The capacitance and inductance of a CVT are tuned to resonate at rated frequency. Therefore, the CVT units are nonlinear close to the operating point and any shift in the frequency or load could cause a significant drift in the voltage amplitude and phase. The linear part is limited to rated frequency ±10 Hz and therefore CVTs are not a reliable solution for harmonic measurements or any measurements other than at their rated frequency as shown in Figure 3.

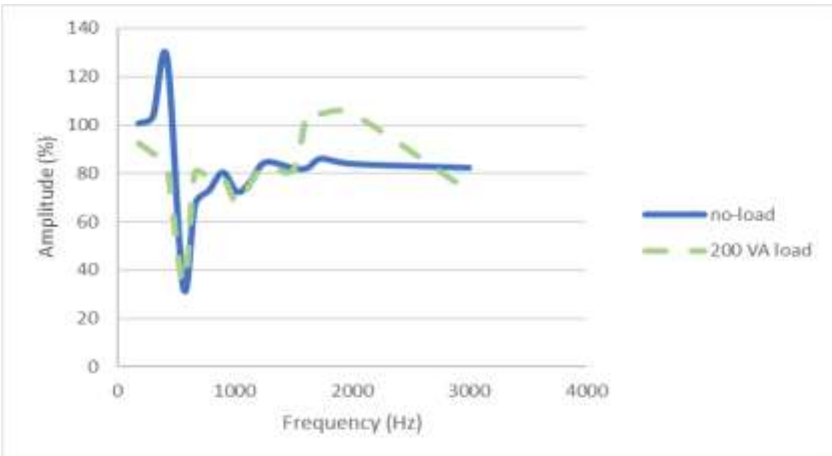


**Figure 3 Frequency response of a typical CVT at no load and 200VA load**

## 3. Hybrid instrument transformers

As was shown in the previous sections, the IVT and CVT designs are not meant for power quality measurements, therefore additional accessories are added to the capacitor section of the CVTs to create a wider frequency response in the amplitude. The two most common options are discussed here, Power Quality sensor and Harmonic Monitoring Device. These accessories provide a flat amplitude response, but their phase shift is a limitation for the PQ applications. Therefore, these units are suitable for monitoring purposes and with lower accuracy for metering applications. These units are inexpensive solutions for power quality measurements.

### A. Power quality (PQ) sensor

The power quality sensors consist of two low voltage current transformers (CT) that are placed on the CVT units and they measure the current of the C1 and C2 capacitors of CVT as shown in Figure 4. The voltage at the HV side is estimated by using the values of the previously measured current and the capacitance C1 and C2 of the CVT. Therefore, the output is very sensitive to changes in the capacitances due to temperature or other environmental conditions [6].

The quality sensors are declared to be used in the frequency range of 5Hz to 13kHz. Within the specified range, the ratio error is less than 2%, and the phase displacement is less than 1.5° up to 3 kHz and less than 3° at 5 kHz.

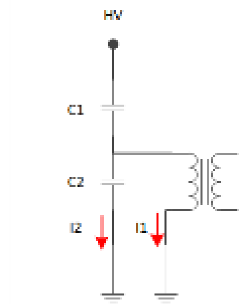


**Figure 4 Simplified circuit diagram of a CVT showing the currents I1 & I2measured by current transformers of the PQ sensor**

### B. Harmonic monitoring device (HMD)

The harmonic monitoring device consists of a low voltage divider that connects in series to the capacitors of CVT units and reduces the voltage to 80 V or 120 V. The schematic and the accuracy of the amplitude measurement up to the 50$^{th}$ harmonic is shown in Figure 5.

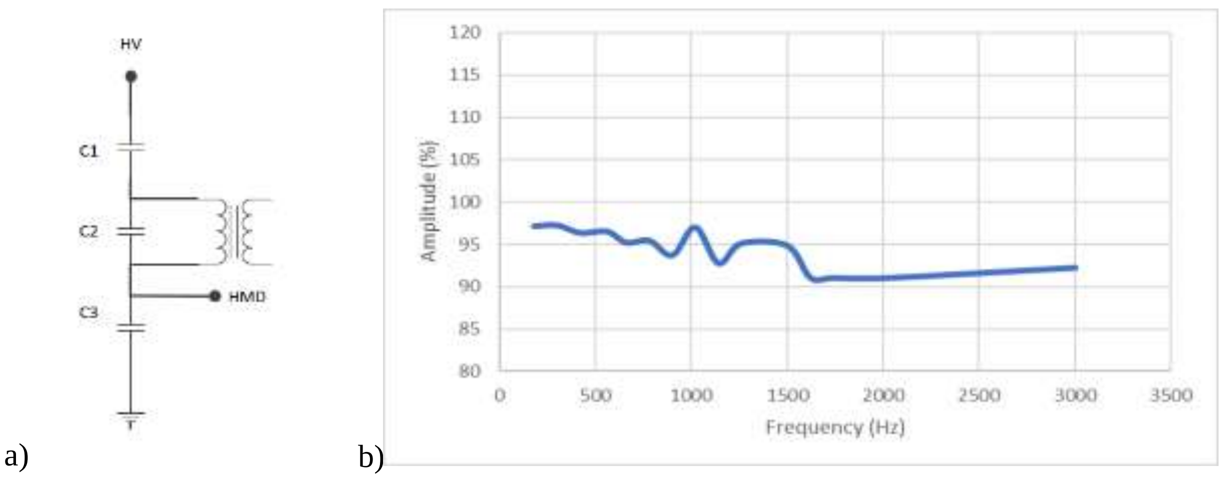


**Figure 5 Harmonic monitoring device a) schematic and b) accuracy of amplitude measurements**

### 4. Low-power instrument transformers

Dividers consisting of resistors and capacitors are another category of HVITs. The voltage is stepped down using capacitors and resistors with minor inherent loss. These units are standalone HVITs that are used in applications with high accuracy in PQ measurements at a wide frequency range (i.e., DC to a few kHz).

### A. Parallel resistive capacitive dividers (RC)

One type of divider consists of resistive and capacitive components which are configured in parallel in order to step down the voltage. The RC dividers provide a flat amplitude response for a wide range of frequencies. They are applicable for DC up to 3000 Hz with accuracy ±0.2% and up to 10 kHz with accuracy of ±0.5% amplitude and reliable phase angle measurements. The amplitude and phase response is shown in Figure 6.

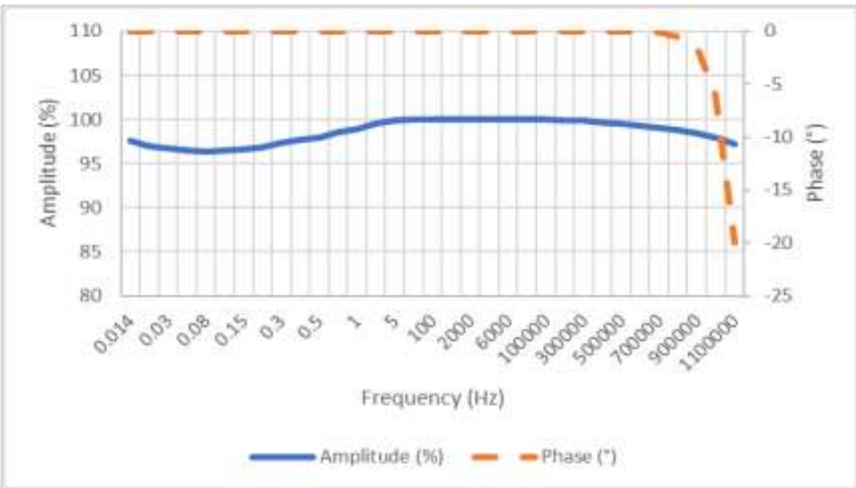


**Figure 6 Amplitude and phase response of a RC divider for 420 kV**

### B. Series capacitive resistive dividers (CR)

The series CR dividers are designed with capacitance and resistance elements in series and tuned to critical damping. Therefore, the frequency range of this type of dividers expands from DC to 100kHz with accuracy of ±5% up to 3 kHz and an accuracy of ±12% up to 100 kHz as shown in Figure 7.

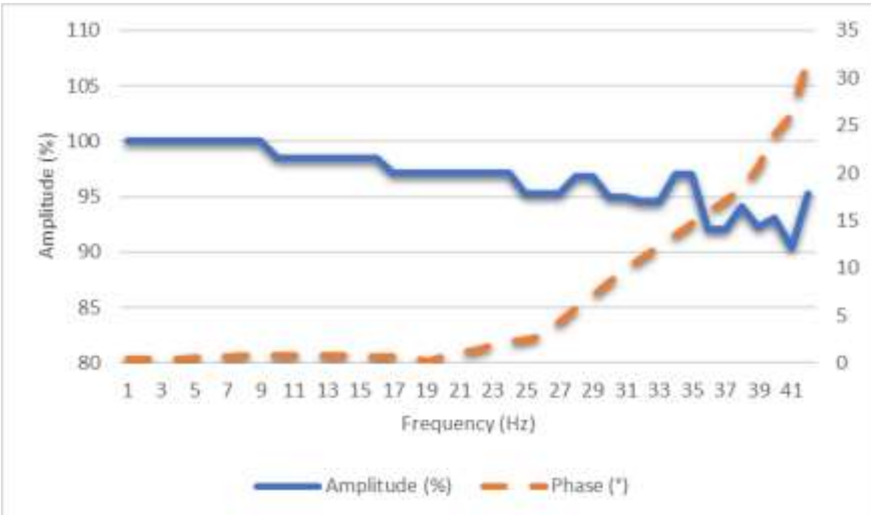


**Figure 7 Amplitude and phase response of a CR divider for 145 kV**

Trench fast transient transducers (TFTT) are one type of CR dividers that are meant for providing a reliable response of high voltage transients with a high frequency content, e.g., steep front impulses. The fidelity of the response of these dividers is shown in Figures 8 and 9 where the low voltage output of the divider is a replica of the impulse at high voltage side without any oscillations.

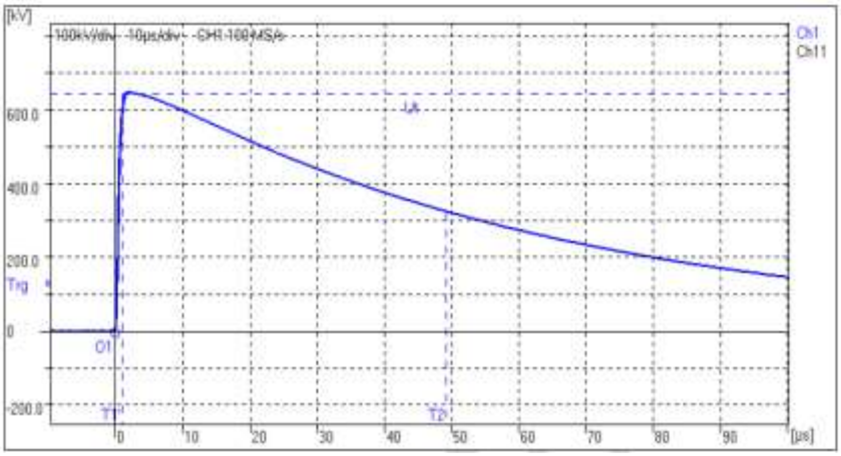


**Figure 8 HV input impulse with 650 kV peak amplitude**

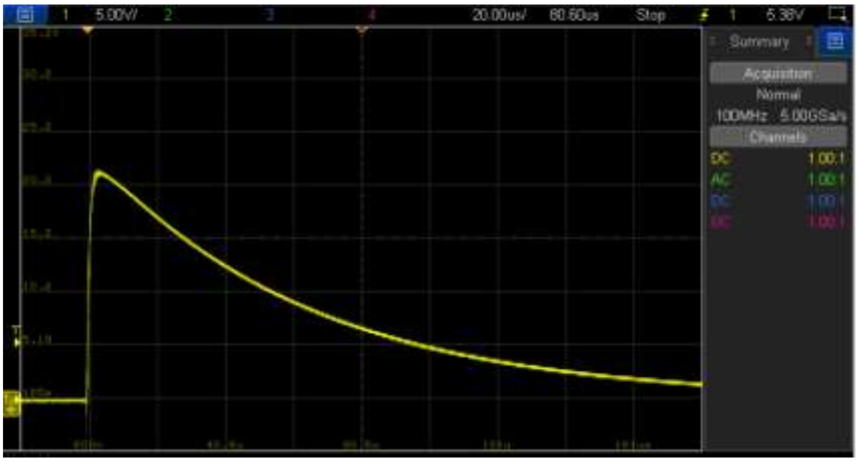


**Figure 9 Low voltage output of FTT with 210 V peak amplitude. X axis is 20 µseconds per division and Y axis is 5 volts per division**

## CONCLUSION

There is an increasing interest in accurate measurement of voltages at higher frequencies with low error in amplitude and phase angle. The accurate measurement of harmonics is tied to power quality and there are failures caused by transient voltages that are not detected by most instrument transformers. In this paper, the authors have shown the accuracy of high frequency measurements with different available options.

Among these solutions are IVT and CVT units which are the commonly used instrument transformers for measuring voltage at power frequencies. However, they are not suitable for accurate measurement of higher frequencies. There are hybrid solutions that are add-on options to CVT units which provide a reliable amplitude output to higher frequencies. These are simple, and less expensive solutions compared to the low power instrument transformers which are standalone units suitable for a wide range of frequencies. The discussed benefits and deficiencies of each solution is summarized in Table 1.

**Table 1 Summary of benefits and deficiencies of each type of HVITs in PQ and transient measurement**

| | IVT | CVT | PQ sensor | HMD | RC | CR |
|---|---|---|---|---|---|---|
| Accurate amplitude and phase measurement up to 50$^{th}$ harmonic | X* | X | ✓ | ✓ | ✓ | ✓ |
| Accurate impulse and switching response | X | X | X | X | ✓ | ✓✓ |
| temperature and environmental conditions do not change the accuracy of PQ measurement | ✓ | ✓ | X | X | ✓ | ✓ |
| Cost efficiency for PQ measurement | N/A | N/A | $$ | $ | $$$ | $$$ |
| Load changes do not influence the accuracy of PQ measurement | N/A | N/A | ✓ | X | ✓ | ✓ |
| Cable length at low voltage does not influence the accuracy of PQ measurement | N/A | N/A | ✓ | ✓ * | ✓ * | ✓ * |

✓ The design complies
✓✓ The design is meant for the application
✓ * The design complies within a defined range
X The design does not comply
X* The design might comply depending on the voltage class
N/A Not applicable
$ Inexpensive
$$ Expensive
$$$ Expensive as a standalone application

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