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Wideband Voltage Sensors For The Modern Substation

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SUMMARY

The addition of power electronics to the power system has resulted in a significant increase in harmonic injection. Many power electronic systems operate at switching frequencies in the kilohertz range. However, most modern voltage sensing technologies do not have good frequency response above 600 hertz. This paper describes technologies that enable wide-band sensing of voltage within the power system. Better visibility of the higher frequencies enables utilities to better understand the impacts of harmonic flows on their system. More importantly, this enables utilities to understand their compliance with nationally recognized harmonic standards like IEEE 519 and IEC 61000-4-3.

KEYWORDS

RCVD, RC-dividers, wideband voltage sensors, harmonics, frequency response, power quality

1. Introduction

Power electronics abound in the modern grid. On the consumer side, everything from the light bulb in the house to the variable frequency drives on industrial motors has a power electronic component. On the utility side, the reliance on distributed energy resources has changed the way power is generated from well behaved generation to highly reactive power electronics. These changes have resulted in the introduction of higher frequency components to the power system. Figure 1, below, shows the harmonic emissions from three modern wind turbines [14].

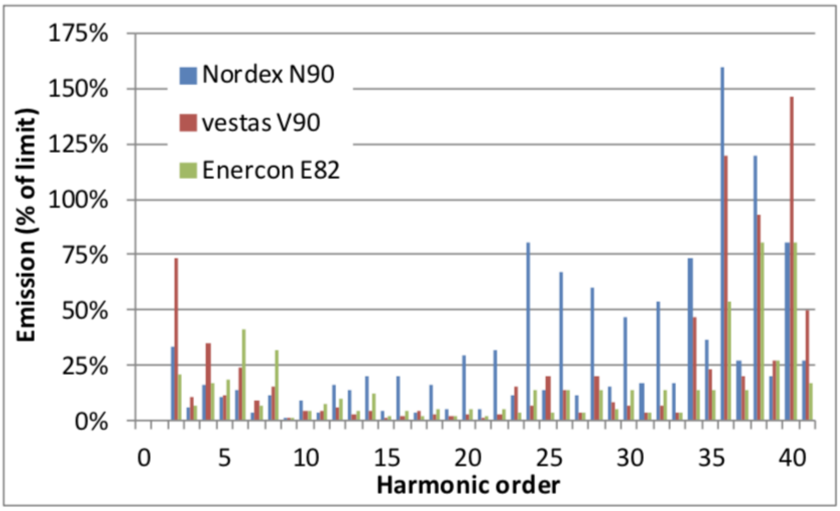


Figure 1 – Harmonic Emission Limits according to IEEE 519 limits

In addition to the changes in load and generation, there are changes to the way the devices on the grid communicate with one another. Power line carrier sets have been used for decades. Historically, these have been at frequencies well beyond the harmonics produced by the grid (> 9 kHz). However, HVDC and FACTS based systems use active converters with switching frequencies that can occur at similar frequencies. Communication services which provide revenue information, and, in some cases, critical protection functions may be negatively impacted.

Table 1 [14], below shows various equipment types and the typical power quality disturbances associated with each type of equipment. The table contains a variety of phenomenon, but what is important to note is the number of devices that are related to Supraharmonics (harmonics in the 2-150kHz band). Certainly, existing equipment in the utility networks like electric arc furnaces and other high-ramp-rate loads also have harmonic injections that should not be ignored.

Table 1 – Equipment and Disturbance Types

Equipment	Voltage dips	Voltage swells	Harmonics	Interharmonics	Subharmonics	Supraharmonics	Slow voltage variations	Fast voltage variations	Transients	Voltage unbalance	Frequency variations	DC components
PV inverters	X											
Production units	X										X	
Active converters	X	X	X	X	X	X	X	X	X	X	X	X
LED lamps				X				X				
Power line communication						X			X			
Transformers						X			X			
Rotating machines						X			X			
Cable insulation						X						
Instrument transformers						X						
Three-phase converters										X		

The characteristics of electrical energy in distribution networks are defined according to EN 50160. Transmission networks are subject to similar requirements. The main parameters are voltage amplitude, waveform, frequency and balance of the phase voltages. Because of the increasing use of alternative sources in energy production and the type of feed-in technology, the power quality is substantially affected by various causes. Figure 2 illustrates the frequency components to be found in an electric power supply system. The blue line represents the rated network frequency component; the orange line specifies sub-harmonics, flicker, dips and swells; the green lines define the harmonics which are divided into three frequency ranges. The first (50 Hz to 2.5 kHz) is according to IEC 61000-4-30 Ed.2.0. The second (2.5 kHz to 150 kHz) is according to IEC 61000-4-30 ed.3.0, valid only for low-voltage networks. The third (50 Hz to 10 kHz) is a proposal of IEC-TC38 WG47 as a result of the work; the red lines are typical transient impulses. The DC component which may occur as an offset is also shown. [10]

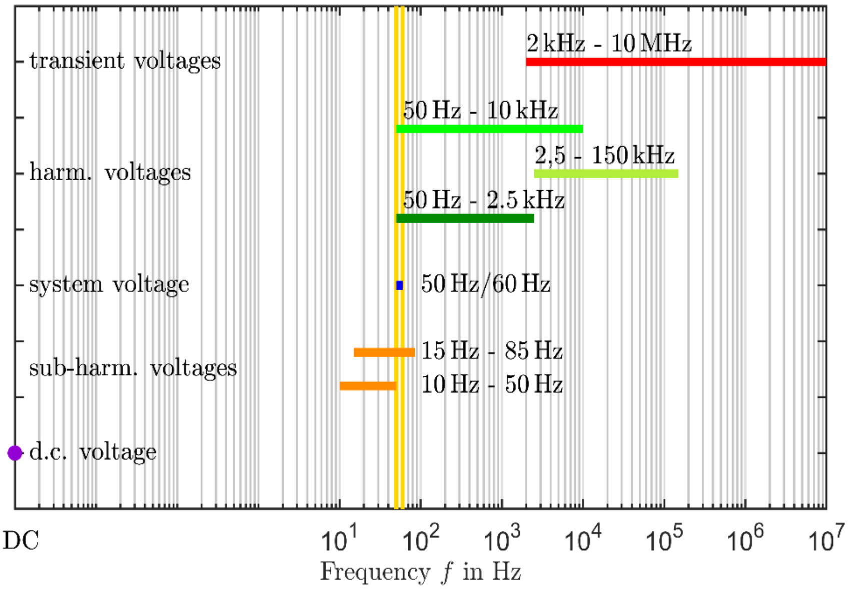


Figure 2 Frequency content in a AC network [8]

2. Impacts to the high voltage equipment in a network

There are serious consequences to lack of visibility of higher frequency components of the power system. These include:

- -increasing of power losses within the network
- -increasing electric stresses within the HV insulation system (permanently as well as transient)
- -thermal stresses within the connected equipment due to harmonic currents
- -increasing sound noise emission (transformers, coils, capacitors, etc.)
- -incorrect control of equipment.
- -faulty activation of protection equipment (old protection system)

Ultimately, all the mentioned points above inducing a forced aging of the high voltage equipment, which results in reduced lifespan. The ultimate consequences are additional cost as well as a non-stable power network.

3. Types of instrument transformers for voltage measurement

World-wide, almost 99 % of voltage measurements in HV and EHV networks are realized using conventional instrument transformers. For voltage measurement in EHV networks, two different measuring systems are in operation. One variant is the conventional inductive voltage transformer (VT), the other one is the capacitive voltage transformer (CCVT). In the case of power quality parameter measurement functions, it is firstly recommended that the behaviour of the conventional instrument transformer is known. A technical report from the IEC TC38 committee was published in 2012. This report IEC/TR 61869-103 gives advice on the usage of all known measuring technologies. It includes very important information concerning the influence of the system voltage level on the frequency response behaviour of conventional measuring transformers. [9]

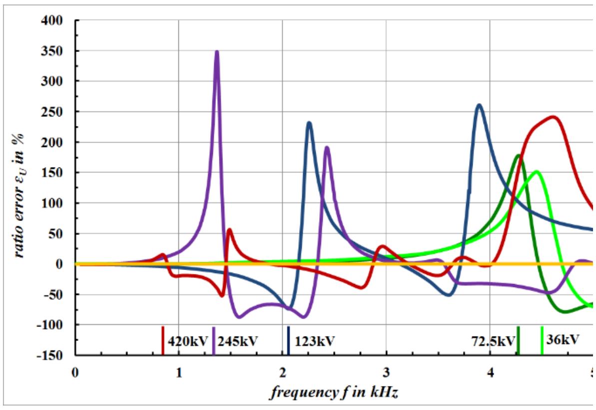


Figure 3: Frequency response of ε_U(f) for 36kV-VT(light green), 72.5kV-VT(dark green), 123kV-VT(blue), 245kV-VT(purple),420kV-CTVT(red) and 420kV-RC-divider (yellow), as measured at PFIFFNER

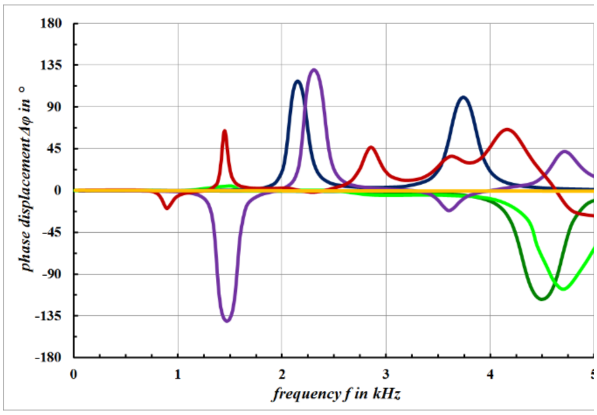


Figure 4: Frequency response of $\Delta\varphi$(f) for 36kV-VT(light green), 72.5kV-VT(dark green), 123kV-VT(blue), 245kV-VT(purple),420kV-CTVT(red) and 420kV-RC-divider (yellow); as measured at PFIFFNER

All conventional instrument transformers have resonance frequencies with very high accuracy errors in the frequency range up to 5 kHz, see figure 3 and 4. In comparison, the 420 kV RC-divider shows a linear frequency response (see yellow curve). By increasing the system voltage level, the first resonance peak moves to a lower frequency. For several test objects, figure 3 shows the first resonance peak depending on the system voltage V_m. It confirms the behaviour of results published in the IEC/TR 61869-103 report.[7]

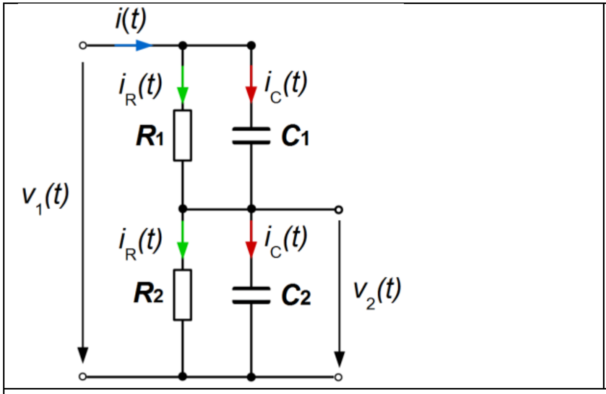
The accuracy of capacitive voltage transformers (CCVT) is affected by frequency variations. A compensation coil, connected between the capacitive divider and the intermediate voltage transformer, is in resonance with the C-divider at system frequency. Frequency variations have a very large influence on the ratio error as well as on the phase displacement. A common CCVT cannot be used for power quality measurements. In case of small adaptions on the secondary capacitance part, a limited frequency band can be measured with a reduced accuracy, but better than using an IVT. [10]

As a result, it is not possible to measure this very wide frequency range, from DC up to several MHz, with conventional instrument transformers with reasonable accuracy [5,6,7]. As an alternative, a non-conventional instrument transformer, e.g. resistive-capacitive voltage divider (RC- divider), can be used for power quality measurement. In this paper we demonstrate that a very high accuracy is achievable with this type of technology.

4. Theoretical aspects of RC-dividers

The RC-divider technology is well known for more than 80 years. Typically, such devices are used for voltage measurements and impulse voltage measurements in test laboratories. In the middle of the 1950s, the first RC-dividers were used for HVDC transmission measurements in a Swedish substation. With the reduction of the power consumption of meters and protection devices by changing from conventional technology to electronic technology, RC-dividers can be used now as a standard voltage measuring unit in modern substations.

An RC-divider consists of a capacitive divider and a resistive divider, which are electrically connected in parallel. The very simplified equivalent circuit diagram is shown in figure 5. Any expected stray capacitances and parasitic inductances are not considered.



V_1: Primary voltage
V_2: Secondary voltage
C_1: Primary capacitance
R_1: Primary resistance
C_2: Secondary capacitance
R_2: Secondary resistance
i_C: Capacitive current
i_R: Resistive current

Figure 5: Simplified equivalent circuit diagram of a RC-divider [5]

As shown in figure 5, the system current consists of a resistive part and a capacitive part. Depending on the selection of the resistances R_1 and R_2 (R-divider), the capacitances C_1 and C_2 (C-divider), and under consideration of frequency and amplitude of the voltage, one of the two divider ratios is more dominant. The transformation ratio $\underline{r}(\omega)$ is defined in equation 1. It shows the ratio between the primary and secondary voltages.

Formula 2 represents the complex transfer function $\underline{k}(\mathrm{j}\omega)$ and describes the mathematical representation of the relation between the input and output voltage of a time-invariant system within zero initial conditions and zero-point equilibrium.

$$r(\omega) = \left|\frac{\underline{V}_1(\mathrm{j}\omega)}{\underline{V}_2(\mathrm{j}\omega)}\right| = \left|\frac{\underline{Z}_{\mathrm{total}}}{\underline{Z}_2}\right| \quad (1)$$

$$\underline{k}(\mathrm{j}\omega) = \frac{\underline{V}_2(\omega)}{\underline{V}_1(\omega)} = \frac{\underline{Z}_2}{\underline{Z}_{\mathrm{total}}} \quad (2)$$

The impedances are defined as:

$$\underline{Z}_1 = \frac{R_1}{1 + \mathrm{j}\omega C_1 R_1} \qquad \underline{Z}_2 = \frac{R_2}{1 + \mathrm{j}\omega C_2 R_2} \qquad \underline{Z}_{\mathrm{total}} = \frac{R_1}{1 + \mathrm{j}\omega C_1 R_1} + \frac{R_2}{1 + \mathrm{j}\omega C_2 R_2}$$

With respect to equation 2, the complex transfer function $\underline{k}(\mathrm{j}\omega)$ of the secondary voltage $\underline{V}_2$ divided by the primary voltage $\underline{V}_1$ is:

$$\underline{k}_{\mathrm{C}}(\mathrm{j}\omega) = \frac{C_1}{C_1 + C_2 \cdot \frac{(1 + 1/(\mathrm{j}\omega C_2 R_2))}{(1 + 1/(\mathrm{j}\omega C_1 R_1))}} \quad (3) \qquad \underline{k}_{\mathrm{R}}(\mathrm{j}\omega) = \frac{R_2}{R_2 + R_1 \cdot \frac{(1 + \mathrm{j}\omega C_2 R_2)}{(1 + \mathrm{j}\omega C_1 R_1)}} \quad (4)$$

Equations 3 and 4 represent the mathematical results for the simplified equivalent circuit diagram of figure 4 and can be mutually transformed. For the following detailed discussions and a better understanding, the more suitable version of the equations will be used. Both equations indicate that the transfer function characteristic is frequency dependent. Depending on the angular frequency ω=2πf, the following conclusions can be made:

$$f \to \infty \qquad\qquad f \to 0$$

$$\frac{Z_2}{Z_{\mathrm{total}}} = \frac{C_1}{C_1 + C_2} \quad (5) \qquad \frac{Z_2}{Z_{\mathrm{total}}} = \frac{R_2}{R_2 + R_1} \quad (6)$$

For high frequencies ($f \to \infty$), the capacitive divider is the dominant part of the transfer function and is comparable with a pure capacitive divider. This condition represents the first of both worst-case scenarios. From the theoretical point of view, an RC-divider is able to measure voltage signals up to an unlimited frequency. Later discussions will show that there are physical limits.

For very low frequencies down to DC ($f \to 0$), the resistive divider dominates the transfer function. This condition is equivalent to a purely resistive divider and will be defined as the second of both worst-case scenarios. Such RC-dividers can also be used for DC voltage measurements.[5,12,13]

Another very important condition can be derived from equation 3 or 4. The compensation condition demands that the resistive divider ratio k_{R} has to correspond to the capacitive divider ratio k_{C}. The time constant τ is defined as an RC term. For a frequency-independent divider ratio of V_1/V_2, up to very high frequency values, the time constant τ_1 of the primary part has to be identical to the time constant τ_2 of the secondary part.

$$\tau_1 = \tau_2 \;\rightarrow\; R_1 \cdot C_1 = R_2 \cdot C_2 \qquad (8)$$

Three main system states can be distinguished.

1 $\tau_1 > \tau_2$, undercompensated
2 $\tau_1 = \tau_2$, compensated
3 $\tau_1 < \tau_2$, overcompensated

In the case of system state 2, the secondary voltage follows the primary voltage with a constant frequency-independent time delay. The rise-time T_{a} depends on the following formula.[13]

$$T_{\mathrm{a}} = 2.2 \cdot \tau_1 = 2.2 \cdot \tau_2 \qquad (9)$$

The main divider ratio itself is constant at all times during this state.

The components of the primary part used, as well as those of the secondary part of an RC-divider are subjected to different physical impacts. The capacitance and resistance are affected mainly by temperature or amplitude of voltage variations. The temperature dependency for a capacitor and a resistor can be calculated by following formulas:

$$C(T) = C_{\vartheta}[1 + \alpha_{\mathrm{C}}(T - \delta)] \quad (10) \qquad R(T) = R_{\vartheta}[1 + \alpha_{\mathrm{R}}(T - \delta)] \quad (11)$$

The material-dependent temperature coefficients are defined as α_{C} and α_{R}. The unit used is ppm/K. The parameter T represents the current temperature and δ defines the reference temperature. Using formula 10 in formula 5, the ratio $k_{\mathrm{C}}(T)$ is shown in equation 12 for the extreme point $f \to \infty$. The same discussions concerning formulas 11 and 6 show the result for the ratio $k_{\mathrm{R}}(T)$ in equation 13 for the extreme point $f \to 0$.

$$k_{\mathrm{C}}(T) = \frac{1}{1 + \frac{\mathrm{C}_{2\vartheta}[1 + \alpha_{\mathrm{C2}}(T - \vartheta)]}{C_{1\vartheta}[1 + \alpha_{\mathrm{C1}}(T - \vartheta)]}} \quad (12) \qquad k_{\mathrm{R}}(T) = \frac{1}{1 + \frac{R_{1\vartheta}[1 + \alpha_{\mathrm{R1}}(T - \vartheta)]}{R_{2\vartheta}[1 + \alpha_{\mathrm{R2}}(T - \vartheta)]}} \quad (13)$$

The single components themselves can vary depending on their own temperature coefficients. When the temperature coefficients of the capacitor material α_{C1} and α_{C2} as well as the temperature coefficients of the resistor material α_{R1} and α_{R2} are identical and under the same ambient conditions, the divider ratio will not be affected by changes in temperature.
For voltage variation dependencies, the same theoretical discussions and conclusions can be made. Voltage coefficients are defined in ppm/V.[9,10]

5. Frequency response behaviour of RC-dividers

In the high voltage network, the nominal system voltage is defined as a sinusoidal voltage signal with a rated frequency of f_R. In addition to this fundamental voltage, signals with a bandwidth close to DC and up to high frequency could also be contained in the system voltage. As a second important phenomenon, transient voltage signals occur as a result of impacts like natural lightning strikes, switching operations, or system fault conditions.

When RC-dividers designed for metering, measuring, protection functions, or for diagnostics and monitoring purposes up to higher frequency ranges, the complex transfer function $\underline{k}(j\omega)$ has to be discussed for the non-ideal case. This is the case when the time constant τ_1 of the primary part is not identical to the time constant τ_2 of the secondary part. Typically, it is not possible to adjust the primary components as well as the secondary components in an ideal way.

$$\tau_1 \neq \tau_2 \;\rightarrow\; R_1 \cdot C_1 \neq R_2 \cdot C_2 \qquad (14)$$

With respect to the information in formula 14, a frequency-dependent divider ratio of V_1/V_2 can be found. As an example, formulas 16 and 17 have to be used for the final calculation of the voltage error ε_U and the phase displacement $\Delta\varphi$.

$$r(\omega) = \frac{1}{\left|\underline{k}_{\mathrm{R}}(j\omega)\right|} = \frac{R_2 + R_1}{R_1} \sqrt{\frac{1 + \left(\frac{R_1 R_2}{R_1 + R_2}\right)^2 \omega^2 (C_1 + C_2)^2}{1 + (R_1 \omega C_1)^2}} \qquad (15)$$

The formula for the calculation of voltage error ε_U is defined in IEC61869-3, sub-clause 3.4.3 as:

$$\varepsilon_{\mathrm{U}} = \frac{r(\omega) \cdot V_2 - V_1}{V_1} \cdot 100\ [\%] \qquad (16)$$

The definition of the phase displacement $\Delta\varphi$ can be found in IEC 61869-1, sub-clause 3.4.4. It is defined that, in the case of positive phase displacement, the secondary voltage leads the primary voltage. The phase displacement calculation is defined as:

$$\Delta\varphi = \arctan(R_1 \omega C_1) - \arctan\left(\frac{R_1 R_2}{R_1 + R_2} \omega (C_1 + C_2)\right) \qquad (17)$$

The introduction of equation 15 in equations 16 and 17, shows a frequency-dependent behaviour of both the voltage error as well as the phase displacement. On the other hand, with these equations, it is possible to perform pre-calculations for an active modification to the characteristics.

With respect to the discussions above, a measurement of the frequency-response behaviour of several RC-dividers for a system voltage level of 420 kV was performed. For each frequency, the primary voltage V_1 divided by the nominal ratio r and the secondary voltage V_2 were measured simultaneously.[6]

Based on international standards on the display of accuracy for instrument transformers, the frequency-dependent voltage error and phase displacement are shown in figure 5.

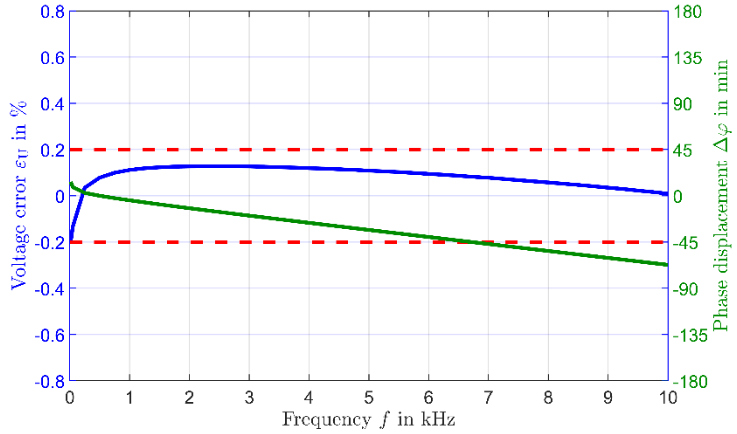


Figure 6: Frequency response of voltage accuracy $\varepsilon_U(f)$(blue) and phase displacement $\Delta\varphi(f)$(green) of an AIS RC-divider type ROF 420. [10]

Figure 6 illustrates the frequency response of an RC-divider for AIS application of a system voltage level of 420 kV with the voltage accuracy ε_U (*blue*) depending on frequency *f*. The red dotted lines shows the limits with ± 0.2 %. The phase displacement $\Delta\varphi$ depending on frequency f is shown as a *green* colored curve. The main impact to the phase displacement causes by using analogue transmission cables with its length (270 m). The typical signal delay of this type of cable is 5.02 ns/m.

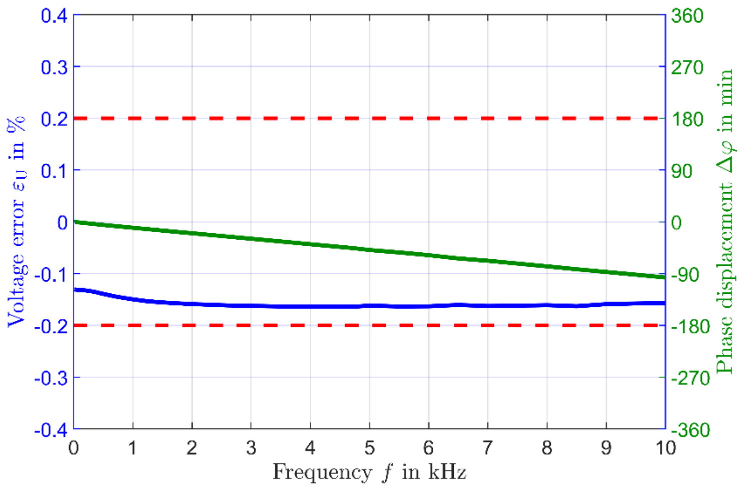


Figure 7: Frequency response of voltage accuracy $\varepsilon_U(f)$(blue) and phase displacement $\Delta\varphi(f)$(green) of an GIS RC-divider type RGK 500DC.

Figure 7 illustrates the similar results as in figure 6, but of an RC-divider for GIS application of a system voltage level of 500 kVDC. The *red* dotted lines helps to identify the expected limits of ± 0.2 %. The phase displacement (*green* curve) has a similar run as in figure 6 because of the same length of transmission cable.

The voltage error characteristic ε_U (blue curve) in both figures shows that the RC-dividers have no resonance frequency in the measured frequency range. The accuracy obtained is within ± 0.2 % over the whole range. The phase displacement over the frequency range is displayed in green. The phase displacement error for both types of dividers is low enough for the identification of the direction of the spurious signal sources. Several series of measurements confirmed the findings stated.

Another important aspect is the linearity of the divider ratio depending on voltage variation. As described above, the primary voltage can vary due to different system conditions and failures. For example, a low primary voltage can occur in the case of voltage dips and swells or interruptions.

Overvoltage phenomena may occur in cases of failure within the network, switching operations or lightning impulses. Therefore, the relevant standard for instrument transformer defines accuracy classes for measuring and protection functions.

The behaviour of three identical RC-dividers for a system voltage level of 420 kV with respect to its linearity is illustrated in figure 8. The measurement was performed according to international measuring rules for instrument transformers. The measurement performed also included the transmission cable and the rated burden connected to the secondary terminals. Figure 8 shows the voltage error against voltage variation with *blue* colored curves and different line styles. The accuracy class limits are indicated as dashed red lines, according to IEC accuracy class 0.2 for measuring and metering applications. In the same figure, the behaviour of the corresponding phase displacement with green colored curves and different line styles for identification is shown. The limits are also marked as dashed *purple* lines which corresponds to the call 0.2.

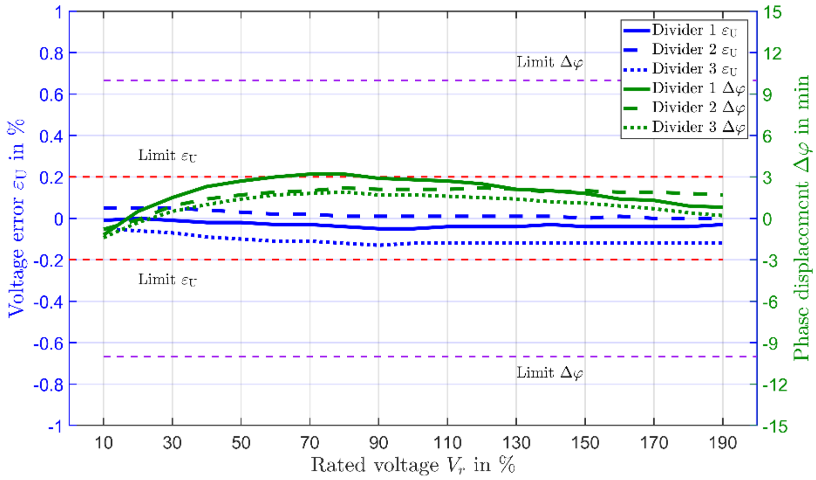


Figure 8: Voltage linearity performance based on accuracy $\varepsilon_U(f)$(blue) and phase displacement $\Delta\varphi(f)$(green)

All three types of RC-dividers show very good performance with respect to the linearity of the voltage error as well as the linearity of the phase displacement. This guaranties a correct signal analysis of low voltage as well as high voltage superimposed signals on the fundamental system voltage.

Another important aspect is the transient voltage measurement for monitoring purposes. The measurement of impulse voltage signals in test laboratories has been realized using voltage dividers for many decades. One of the best types of divider is the CR-divider, also well known as Zaengl-divider, where the capacitor elements and the resistors are connected in series. This kind of connection is important to prevent voltage oscillations. Also, the secondary device is optimized for fast or very fast transient voltage signals.

Based of the discussions in section 4, the theoretical bandwidth of an RC-divider seems to be close to infinity. In reality, each component, especially the primary capacitive part, has a self-inductance. This parasitic circuit element will limit the frequency response of the RC-divider. In cases of acceptable transmission quality of transient signals in terms of voltage peak and wave shape, RC-dividers could be used as a monitoring device in common high voltage networks. Transient voltage impulses up to 1.5 MHz would cover typical lightning impulses according to IEC with a rise-time of 1.2 µs.
For the determination of the behaviour of an RC-divider, lightning impulse tests and/or step response tests were performed and measured directly at the secondary terminal output, according to IEC60060-1 and -2 procedures as well as IEC61869-11.

Figure 9 shows a lightning impulse test on a GIS RC-divider type RGK400DC. The measured peak voltage of the RC-divider (*red* curve) is 506 kVpeak compared to 500 kVpeak of the reference impulse divider (*blue* curve). The measurement error is + 1.2 %, which is a very good result. The time until any significant oscillation disappeared is around 6 µs.

Figure 9: Lightning impulse behaviour – GIS type RGK 400DC [11]

Figure 10 illustrates a step-response behaviour of an AIS RC-divider type RGF 320DC. Based on the new international standards for RC-dividers, in this figure the step response test shows two significant time areas. The first step response time is τ_{RS1} and specifies the crossing point of the RC-divider (*red* curve) with the voltage curve of the reference impulse divider (*blue* curve). A step response time of τ_{RS1} = 2.19 µs was measured. This first step response time can be used protection function.

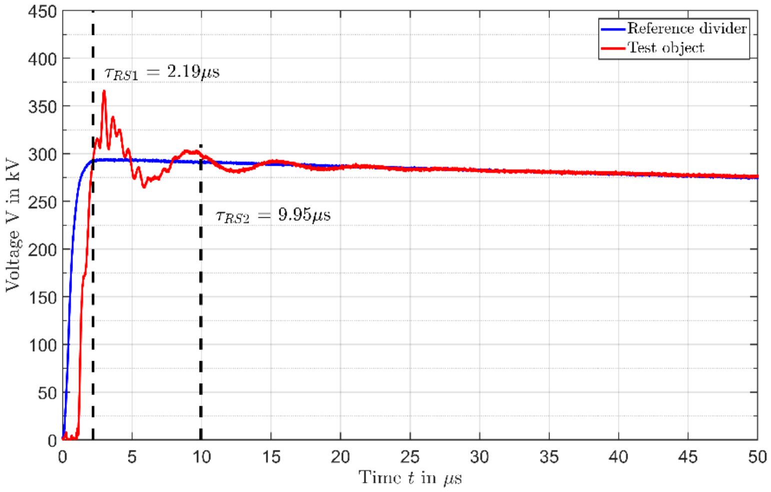


Figure 10: Step response behaviour – AIS type RGF 320DC

The second step response time is τ_{RS2} and specifies the crossing of the tolerance band of ± 3 % of the reference impulse divider curve (*blue*). The tested RC-divider has a second response time of τ_{RS2} = 9.95 µs. The second step response time can be used monitoring or analysis function in the network. Especially for calculation of the probability of the aging of the installed high voltage equipment in the substation or in the network.

The oscillation in the rising voltage curve shown in figure 10 seems to be a reflection phenomenon. First reason: this RC-divider measuring system, including the design of the secondary equipment and the connection to the oscilloscope, was not specially optimized for impulse voltage measurement. The second important point is non-series damping. When a series damping resistor is used, the behaviour can be improved.

6. Conclusions

This paper is a contribution on the possibilities of measuring power quality parameters in electrical high-voltage networks using a non-conventional instrument transformer with a very high accuracy starting from DC up to MHz. The theoretical aspects are described as well as the technical solutions which explain the behaviour of this kind of technology. In the case of hybrid networks, with a combination of AC and DC power transmission in the same corridor, an expected DC offset on the AC part can be measured to a high accuracy. The linearity of accuracy, independent of primary voltage amplitude as well as of the performance of impulse voltage measurement, confirms very high performance. Transient impulses can be measured to a sufficient accuracy for the peak voltage level. As a summary of the discussions above, the wide frequency range, as shown in figure 1, can be measured to a high degree of accuracy using this technology.

In comparison with conventional inductive instrument transformers with their resonances, this technical solution has a much better performance when measuring harmonics to a high level of accuracy up to high frequencies for all voltage networks.

Up to now, accuracy classes for instrument transformers with their ratio error and phase displacement limits are only related to the rated system frequency (see relevant standard). For the definition of new accuracy classes for frequencies other than the rated frequency, applications have a large influence.

The demands placed by metering, measurement or protection applications vary. Also, the consequences on the network, as well as for the operator, vary depending on requirements. It is therefore necessary to define useful classes which cover the various functions. Because of the complexity of this subject, several technical committees of IEEE and IEC need to work together.

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