

Power Quality Measurements in all voltage levels of the energy utilities up to 150 kHz – Is it possible?

A reliable energy supply has meanwhile become an important location factor for many companies. While power failures and voltage fluctuations were among the most important parameters of supply quality in the past, voltage transients and voltage harmonics are becoming more and more important. This is mainly due to the increasing number of non-linear loads and many decentral renewable energy sources. In order to guarantee uniform standards for electrical energy supply in Europe, the minimum requirements for voltage quality are defined in a European standard. This is EN 50160, which is entitled "Voltage Characteristics in Public Distribution Systems". This standard is to be understood as a product standard for electrical energy and for this reason is also used as a valid product standard in electricity supply contracts. In February 2014 the Federal Court of Justice in Germany made it unequivocally clear that electricity is also subject to the Product Liability Act. The distribution network operator is thus liable for damage to electrical consumers that can be traced back to poor voltage quality on the part of the distribution network operator. For this reason, many measuring device manufacturers now offer measuring devices that prepare automated quality reports in accordance with EN 50160. Digital billing meters are also increasingly offering power quality functions in accordance with EN 50160. While the measuring devices can process the voltage directly in the low voltage range, we rely on voltage transformers or voltage sensors in the medium and high voltage range. The voltage quality is usually measured on older already existing systems. However, the built-in voltage transformers usually do not give any indication of the transmission behavior at higher frequencies on the rating plate. The devices are only specified for the 50 Hz fundamental frequency of the network. However, measurements according to EN 50160 require a frequency range of up to 2 kHz. We want to investigate the question of whether the existing devices are suitable for measurements up to 2 kHz.

Almost without exception, the built-in voltage transformers have an inductive transformer as active part of the unit that works according to the transformer principle.

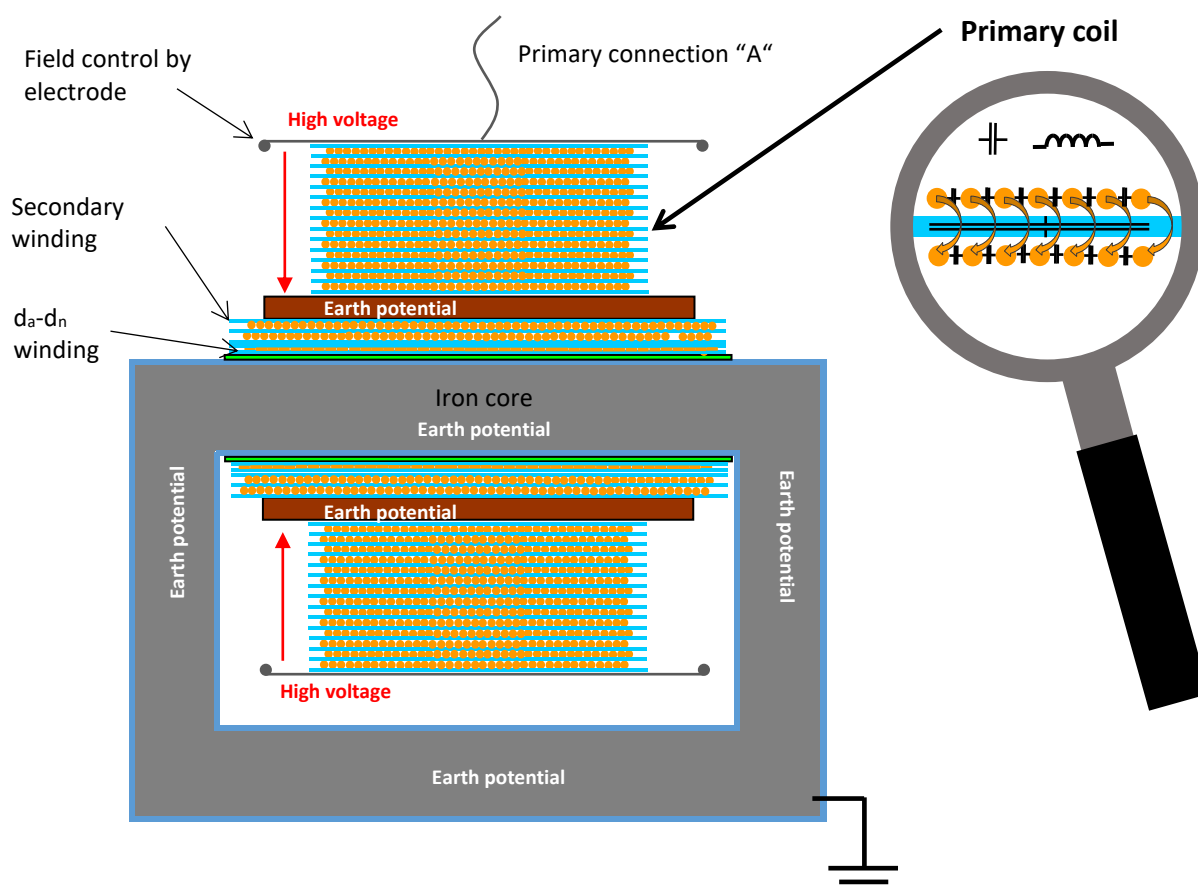


Figure 1: Model of the active part of a MV voltage transformer

In detail, the primary coil not only consists of inductive copper windings, but capacities also result from the individual layers isolated from one another. The capacities between the individual turns also contribute to the total capacitance of the primary coil. This results in a resonant circuit made up of inductance, capacitance and ohmic resistance, which must also have a corresponding resonance frequency.

In order to find this resonance frequency, a commercially available 10 kV voltage transformer is now tested with the "frequency sweep method" with 6,400 measuring points up to 10 kHz.

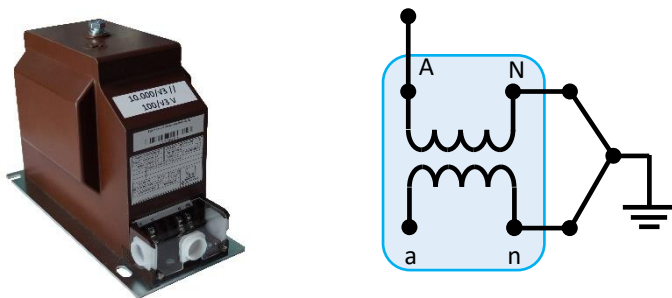


Figure 2: Inductive single pole 10 kV voltage transformer (VTS12M11-T)

We found it!

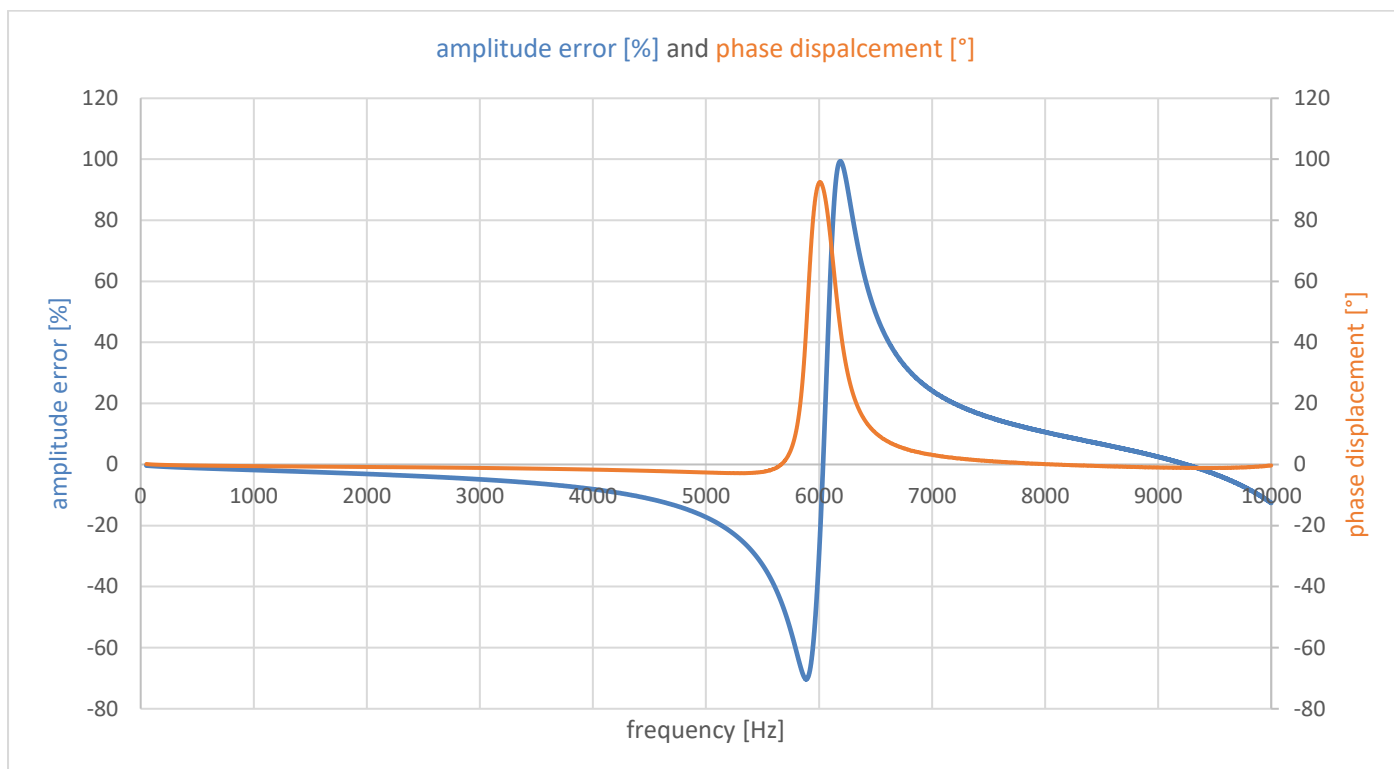


Figure 3: Amplitude error and phase displacement of a 10 kV voltage transformer

A resonance point can be seen at approx. 6 kHz. While the voltage transformer transmits the primary signal acceptably up to approx. 5 kHz, an amplitude error of approx. 100% and a phase error of 87 ° results at approx. 6 kHz. For example, a reliable PQ analysis up to 9 kHz can therefore not be carried out with this voltage transformer.

Despite the normatively regulated voltage levels, every instrument transformer manufacturer has a large number of different voltage transformers with different primary coils in order to be able to meet the most diverse secondary configurations by the customer. These voltage transformers have already been delivered and installed in measuring fields. The manufacturer can only carry out a rough calculation of the first resonance point in connection with the archived production documents. However, the resonance point measured in practice can often deviate from the calculation result by a few kHz. It is therefore very difficult for instrument transformer manufacturers to make reliable statements for devices that have already been delivered.

A contribution from the technical and scientific organization CIGRE / CIREN offers the measuring point operators good support. A guideline for power quality measurements was published here, which provides a meaningful table with regard to the frequency transmission behavior of inductive voltage transformers.

| | Voltage level | Single harmonic order | | |
|-----|---------------|------------------------------------|-------------------------------------|--------------------------------------|
| | | 2 nd to 7 th | 8 th to 20 th | 21 st to 50 th |
| MV | 10 kV | Yes | Yes | Yes |
| | 20 kV | Yes | Yes | Uncertain |
| | 30 kV | Yes | No | No |
| HV | 60 kV | Yes | Yes (?) | Uncertain |
| | 110 kV | Yes | Uncertain | No |
| EHV | ≥ 220 kV | Uncertain | No | No |

Figure 4: Suitability of inductive transformers for harmonic measurements (Source: CIGRE / CIREG Guidelines for Power Quality Monitoring WG C4.112 TECHNICAL BROCHURE 596)

It can be seen that 10 kV voltage transformers up to the 50th harmonic (2.5 kHz) can generally be used for PQ measurements. This statement is consistent with our measurement result in Figure 3.

In the 20 kV range, however, according to the table, devices have already been found that do not provide any reliable measured values on the secondary side from the 21st harmonic upwards. In the 30 kV range, there is even a general approval up to the 7th harmonic. We state that only 10 kV voltage transformers can be used in existing systems for reliable EN 50160 measurements. In the voltage levels 20 and 30 kV, information must be provided by the instrument transformer manufacturer.

The voltage transformers examined here are exclusively single-pole devices. Two-pole voltage transformers, which can still be found in older existing installations in medium voltage grids, cannot be used for the analysis of harmonics. This is due to the voltage measurement between the conductors.

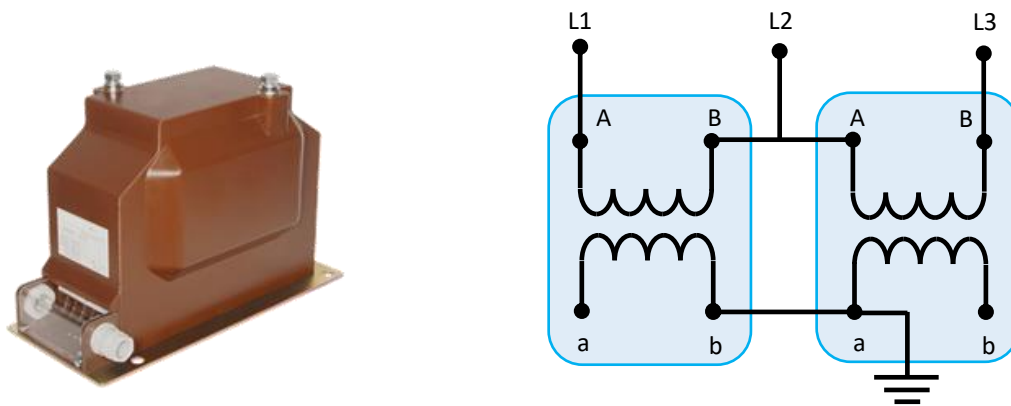


Figure 5: Two-pole voltage transformer with Aron circuit (two-wattmeter circuit)

Despite the 120 ° phase shift of the 50 Hz conductor voltages, the amplitude values of the superimposed 3rd harmonic are not offset and thus cannot generate a voltage difference between the conductors. This generally applies to all harmonics divisible by 3.

Thus, the THDu obtained by the two-wattmeter circuit is reduced by the values of the voltage harmonics divisible by three (3, 6, 9,...).

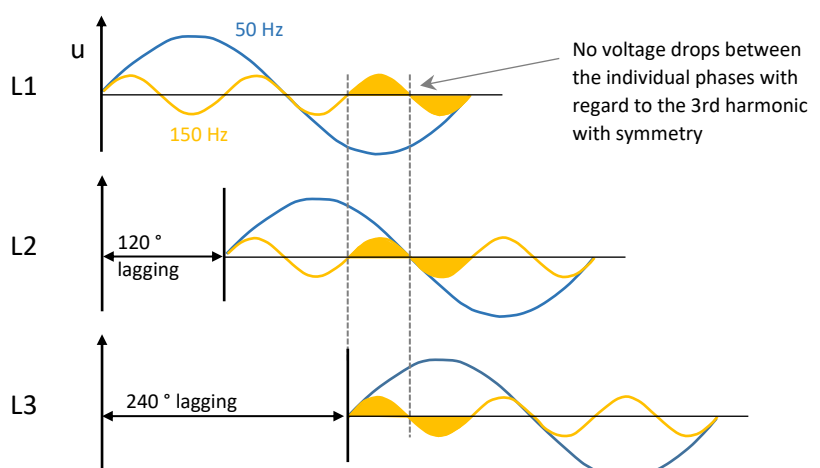


Figure 6: Representation of the 50 Hz fundamental oscillation and the 3rd harmonic

Furthermore, the question arises whether measurements up to 2 kHz are still sufficient. The current IEC 61000-2-2 (Environment - Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems) already specifies limit values for voltages up to 150 kHz.

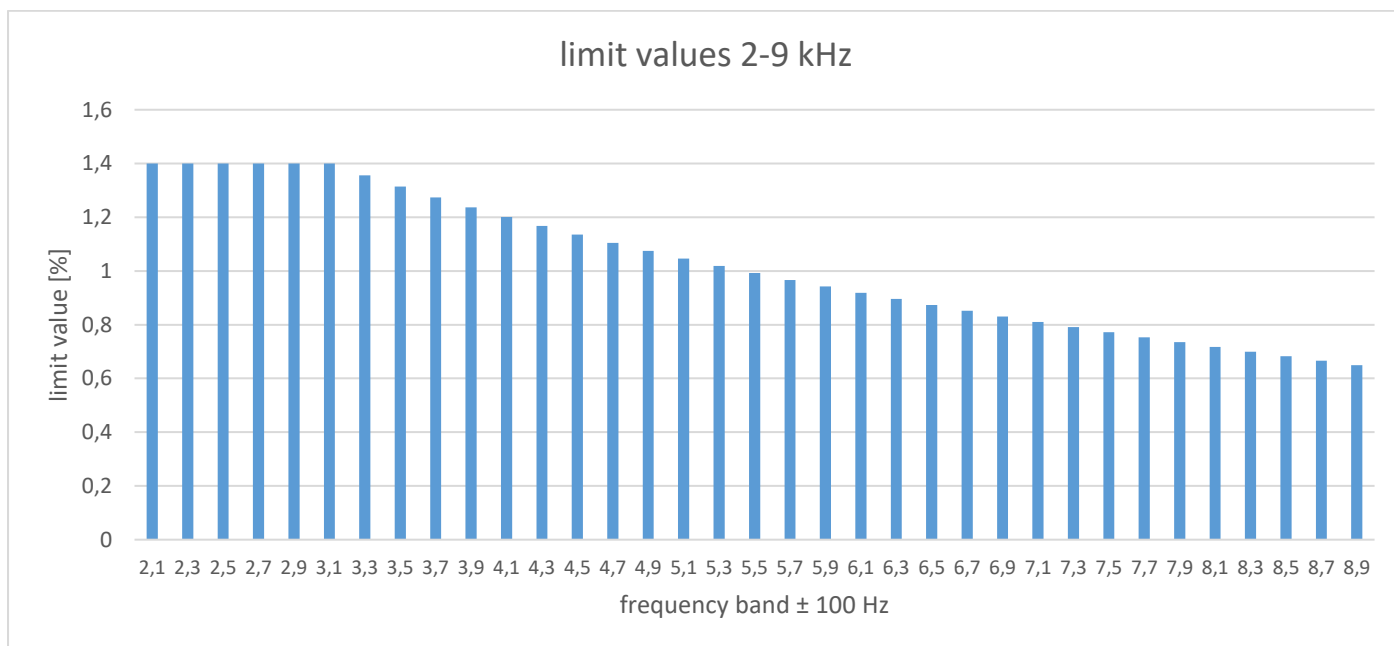


Figure 7: Limits for voltage harmonics from 2 to 9 kHz acc. to IEC 61000-2-2

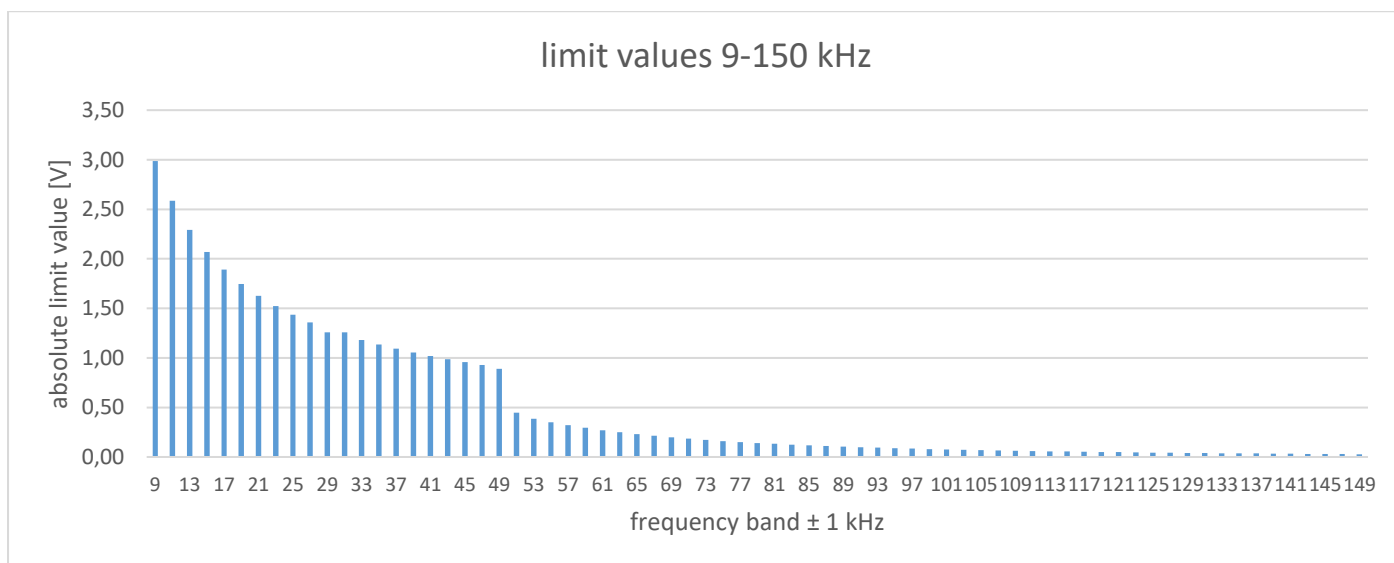


Figure 8: Limits for voltage harmonics from 9 to 150 kHz

The EN 50160 cited in electricity supply contracts has been updated in 2020, but limit values beyond 2 kHz have not yet been bindingly defined. Thus, a voltage measurement up to 2 kHz is sufficient for determining the quality of the electrical energy. However, PQ measurements up to 9 kHz are already required for the grid connection of feed-in plants.

MBS AG therefore offers frequency-optimized voltage transformers up to 24 kV for the measurement range up to 9 kHz. The accuracy requirement for these transformers is defined in IEC 61869-6. The amplitude and phase errors are as follows.

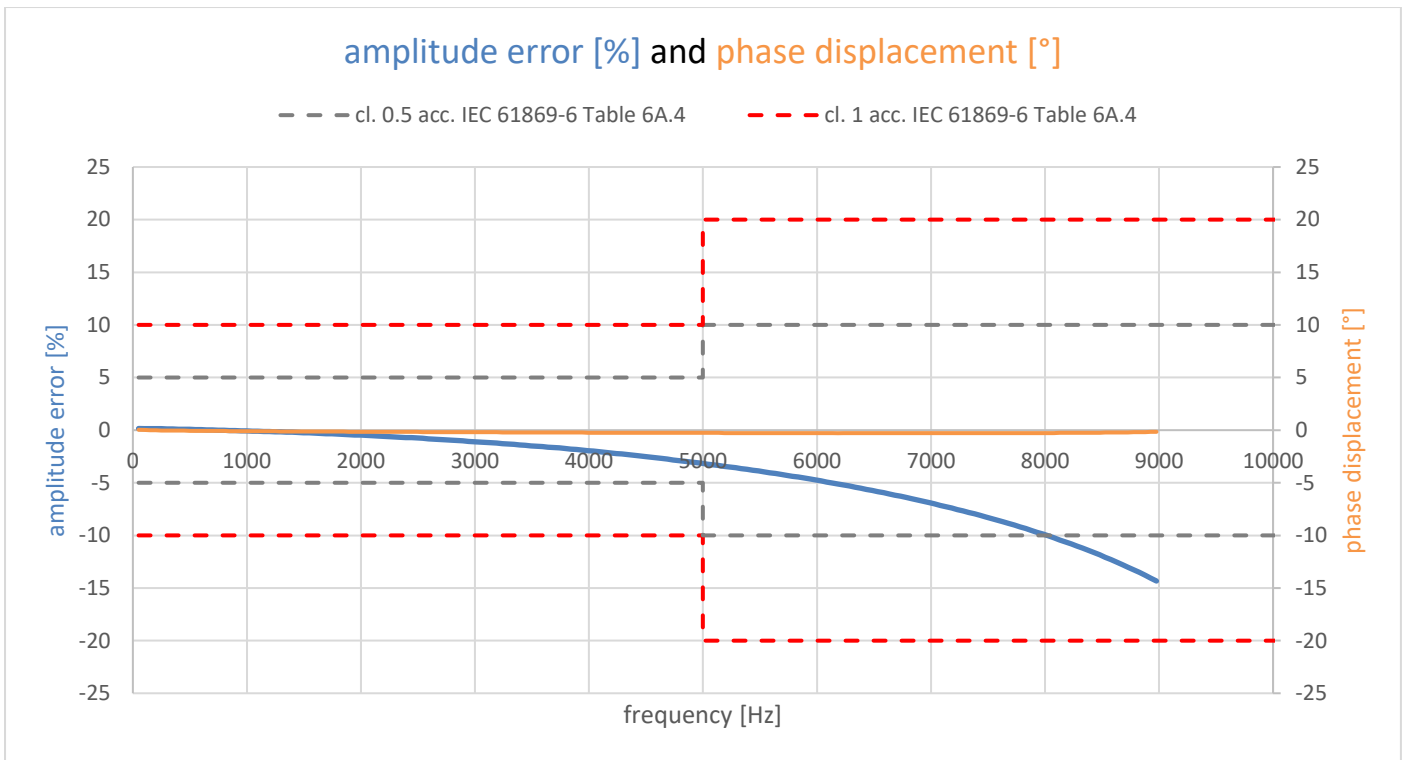


Figure 9: Frequency-optimised 24 kV voltage transformer VTS24M32-T from MBS AG (amplitude error and phase displacement)

The transformer maintains class 0.5 up to approx. 8 kHz. From 8 kHz, class 1 is still clearly maintained. These voltage transformers thus enable reliable PQ measurement up to 9 kHz and, like all other medium-voltage transformers from MBS AG, are also SF₆-free.

Many experts are already assuming that PQ measurements up to 150 kHz will also be carried out in the medium voltage in the future. Even some of the current mobile PQ analysers already measure up to at least 150 kHz, which may well be necessary for comprehensive interference analysis.

With inductive voltage transformers, the range up to 150 kHz is not technically feasible. With 24 kV devices, the first resonance point can only be pushed into the range of 10 to 20 kHz. Voltage sensors based on the voltage divider principle offer an alternative. As a reminder, the basic principle is shown here once again.

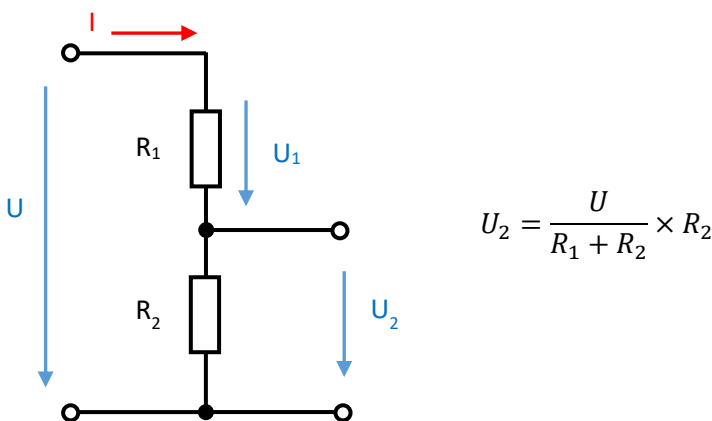


Figure 10: Principle of the voltage divider

Already today, voltage sensors are mainly installed in existing local network stations that require an additional voltage measurement on the medium voltage side. Measuring fields with conventional inductive voltage transformers can only be retrofitted in rare cases for reasons of space. A proven method is to mount sensors in so-called T-connectors. This solution is space-saving and the installation is carried out by trained personnel within a reasonable time window. While the cone of the symmetrical connector is standardised according to IEC 50181, the cone of the compact T-connector has slightly different dimensions depending on the manufacturer. However, due to

its patented design, the VAPxx-S voltage sensor intended for the compact T-connector can be used in the slightly different T-connectors of all well-known manufacturers without having to fear partial discharges. For the new type of compact T-connector from Nexans (480 TB), there is already the matching sensor with the VCPxx-S.

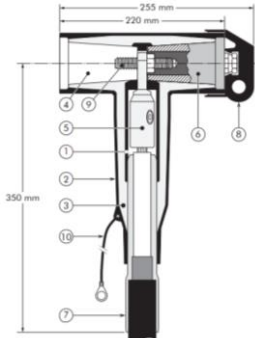

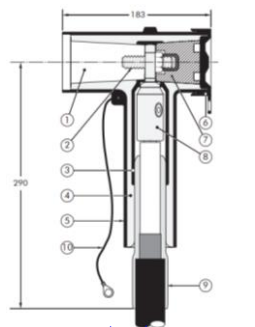

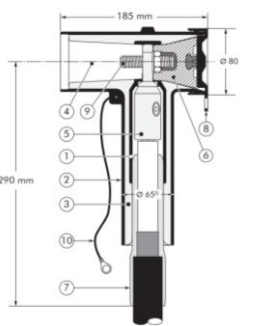

| | | |
|---|---|---|
| <p>Type C interface acc. IEC 50181</p> <p>→ VSPxx-S</p> |  <p>Source: http://www.nexans-power-accessories.com/</p> |  |
| <p>Sensor with short insulating plug (compact-T-connector), compatible with Nexans (430TB), nkt, Tyco, Südkabel, Cellpack</p> <p>→ VAPxx-S</p> |  <p>Source: http://www.nexans-power-accessories.com/</p> |  |
| <p>new Nexans compact-T-connector 480TB</p> <p>→ VCPxx-S</p> |  <p>Source: http://www.nexans-power-accessories.com/</p> |  |

Figure 11: Currently available connector types with the corresponding voltage sensors for the 12 and 24 kV insulation series

The sensors shown in Figure 11 can be used up to a maximum of 24 kV. A 36 kV version is already planned.

For air-insulated switchgears or measuring fields, MBS AG has a sensor that is already being used in new systems as well as for retrofitting.



Figure 12: Voltage sensor VSIxx-S for air-insulated switchgears

While the accuracy class at 50 Hz is noted on each sensor rating plate and is thus the responsibility of the manufacturer, manufacturers often do not provide protocols or reliable statements for measurements beyond 50 Hz. In the market, end users often think that ohmic dividers can generally transmit harmonics very well. This will be investigated in the following.

A resistive divider basically consists of two almost ohmic resistors, but these resistors always have parasitic inductive and capacitive components. A capacitance also forms around the high-voltage resistor, so that the technical literature does not speak of ohmic dividers, but of ohmic-capacitive dividers.

Air insulated voltage sensor (VSI)



Voltage sensor as termination insert of the T-connector (VAP)

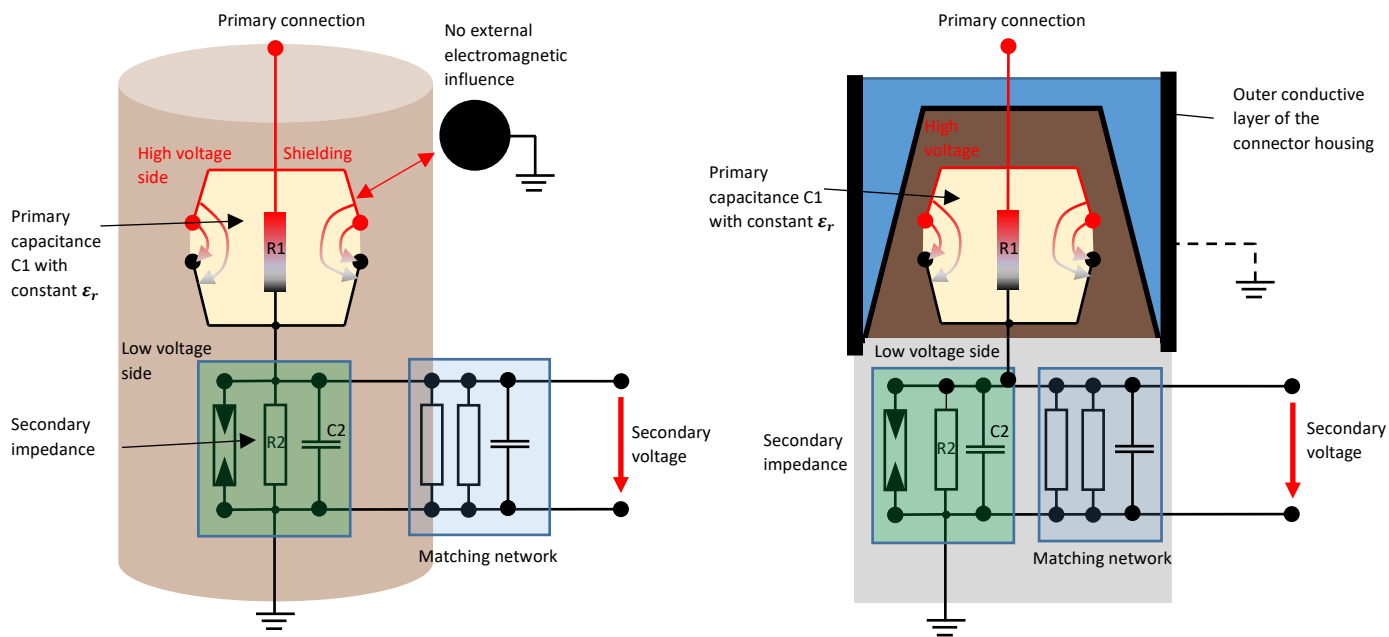
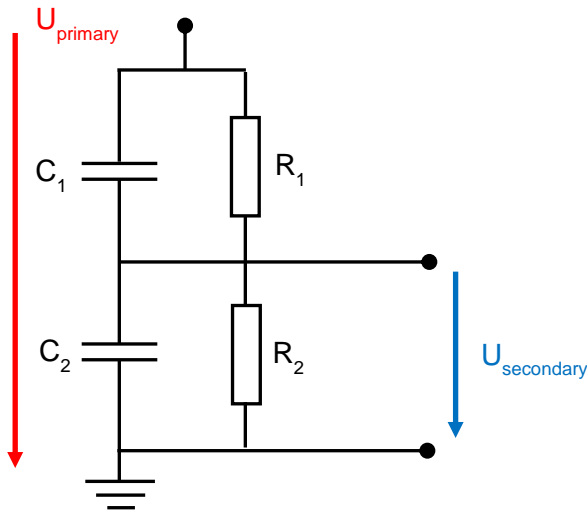


Figure 13: Schematic diagrams of an air-insulated voltage sensor (VSIxx-S) and a voltage sensor as termination insert of the T-connector (VAPxx-S)

A simplified equivalent circuit can be derived from the figure above.



The secondary voltage $U_{\text{secondary}}$ as a function of the primary voltage U_{primary} and the resistance and capacitance values result in the following equation:

$$\frac{U_s}{U_p} = \frac{R_2}{R_2 + R_1 \frac{1 + R_2 j \omega C_2}{1 + R_1 j \omega C_1}} = \frac{C_1}{C_1 + C_2 \frac{1 + 1/j \omega C_2 R_2}{1 + 1/j \omega C_1 R_1}}$$

Hereby applies:

- for $\omega \ll 1$: $\frac{U_s}{U_p} = \frac{R_2}{R_1 + R_2}$,
- for $\omega \gg 1$: $\frac{U_s}{U_p} = \frac{C_1}{C_1 + C_2}$

Figure 14: Simplified equivalent circuit diagram of the RC divider

For the frequency independence of U_s/U_p , the following condition applies to the above equation

$$R_1 C_1 = R_2 C_2.$$

The question now arises whether ohmic-capacitive sensors in the medium voltage can be used for PQ measurements without further ado. In the following figure, a competitor's and MBS's own 50 Hz sensor have been measured from 50 to 150 kHz with respect to amplitude and phase errors.

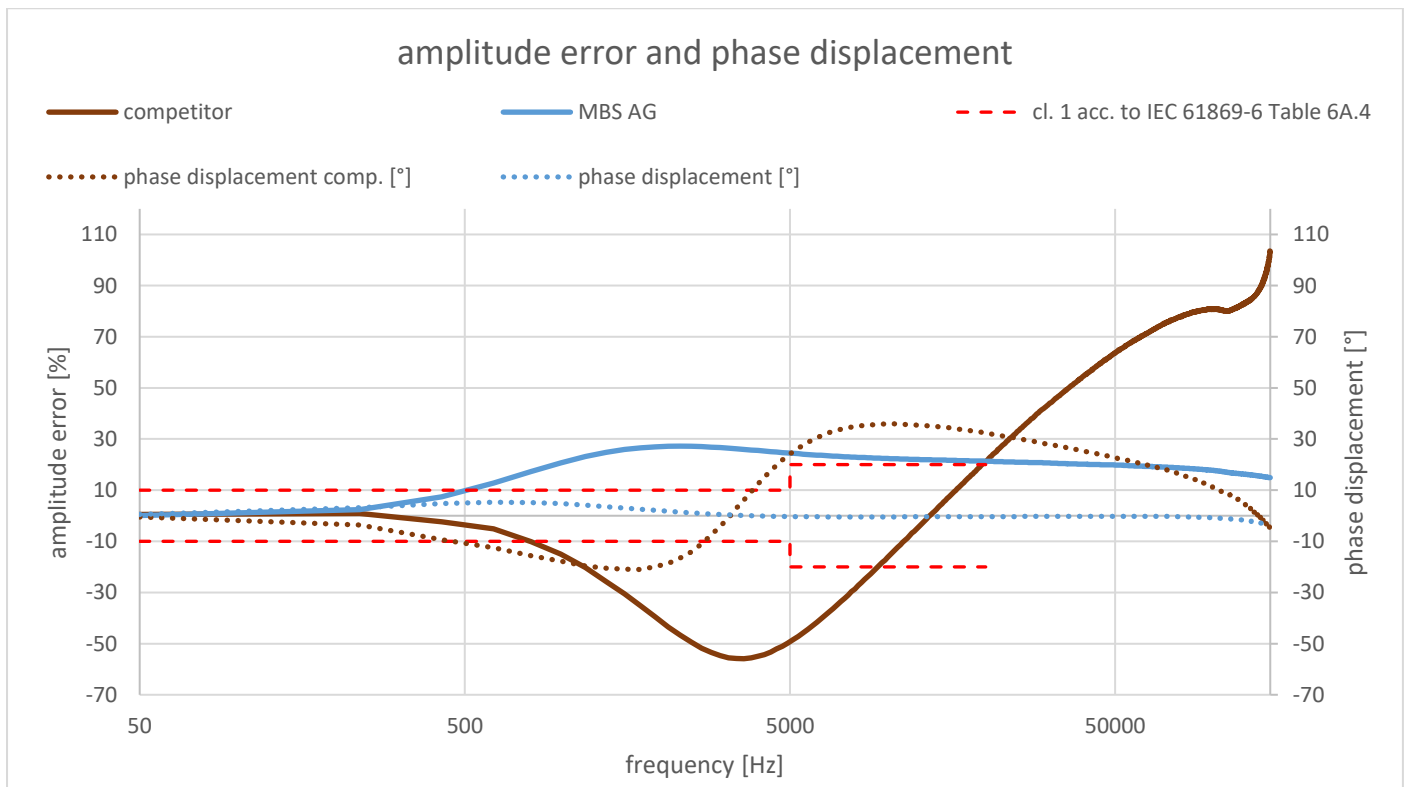


Figure 15: Amplitude error and phase displacement of two 50 Hz voltage sensors (X-axis logarithmically scaled)

Both sensors are outside the minimum requirements of class 1 for PQ measurements according to IEC 61869-6. For optimum transmission behaviour, the alignment network must also be optimized for higher frequencies.

MBS AG can currently provide voltage sensors for T-connectors and for air-insulated systems with optimized transmission behaviour up to 150 kHz.

For PQ measurements, frequency-optimized sensors are absolutely necessary in order to comply with the minimum requirement (class 1 according to IEC 61869-6). Transfer curves from current customer projects are shown in the following figure.

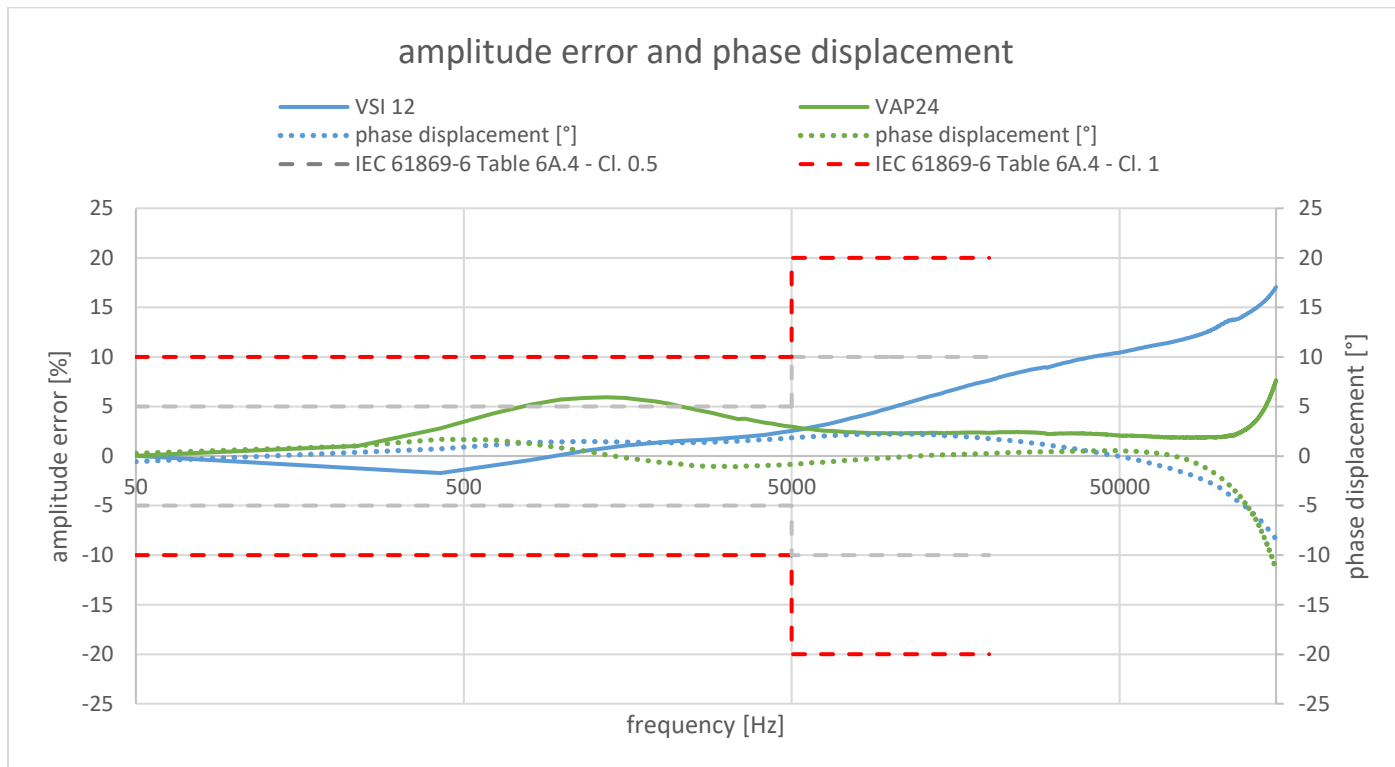
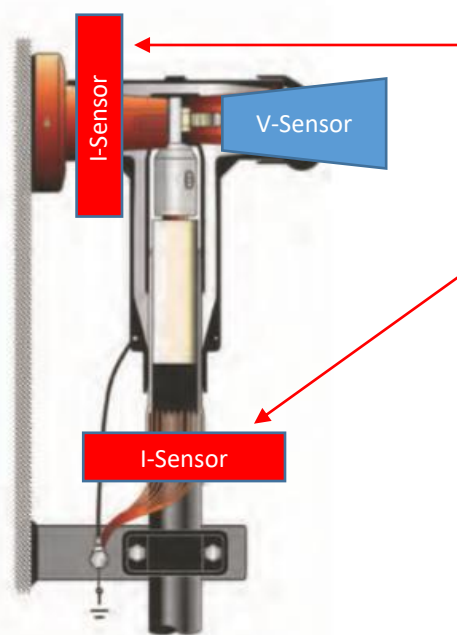


Figure 16: Amplitude error and phase displacement of the frequency-optimized sensors VAP and VSI (X axis logarithmically scaled)

The voltage sensors are usually installed with corresponding current sensors. Unlike conventional current transformers, a voltage signal is output on the secondary side. However, broadband Rogowski coils can also be used.



source:
<http://www.nexans-power-accessories.com/>



Current measurement with current sensors or Rogowski coils can be carried out in those areas of the connector where no cable shielding is realised

or the shielding is led back through the sensor. In this way, the current on the shielding is not measured.

source:
<http://www.nexans-power-accessories.com/>

Figure 17: Current and voltage measurement on the medium voltage side at MV cable feeders

Various cable connector manufacturers also offer adapters for the external cone A. Thus, voltage measurements can be realised directly at the transformers in a space-saving way.

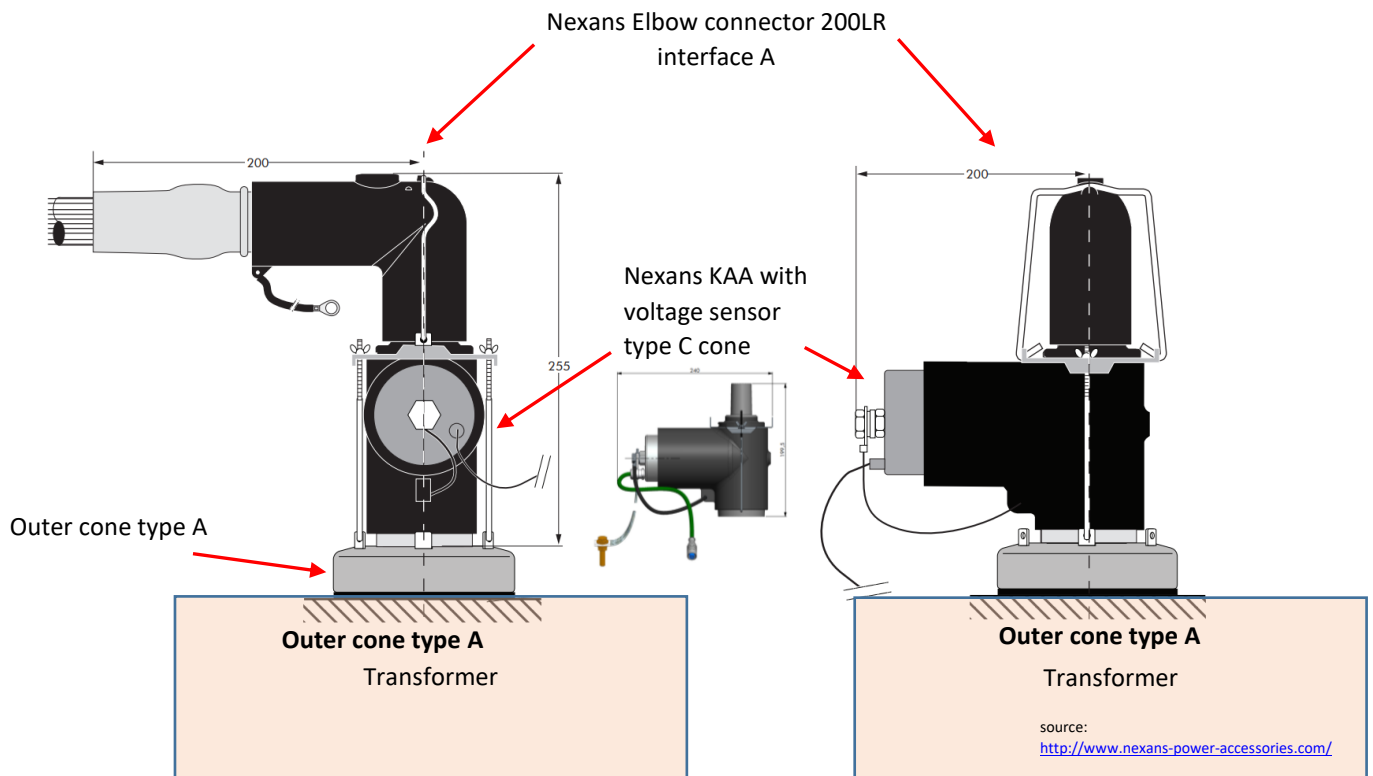


Figure 18: Nexans KAA with voltage sensor + Elbow connector 200LR with interface A

When selecting the measuring device, it should be noted that the voltage sensors addressed here can provide a maximum of $10/\sqrt{3}$ volts on the secondary side. In Germany, the standard $3.25/\sqrt{3}$ V has already become established. For current sensors, 225 or 333 mV are usually used.

Here, a problem often arises for the utility company when purchasing a mobile power quality analyser. In contrast to the traditional inductive voltage transformers with $100/\sqrt{3}$ V, the voltage sensors only give a small signal up to a maximum of $10/\sqrt{3}$ V. In the low-voltage range the voltage is measured directly. Frequency-optimised high-voltage sensors, which are designed also as RC dividers, usually provide $100/\sqrt{3}$ V like conventional voltage transformers. This results in a wide variety of secondary voltages in the environment of energy supply companies.

| Voltage converter | Possible bandwidth | Output signal | Possible input impedances of the meter |
|--|-----------------------------------|---|--|
| NS → direct measurement | Limitation by the meter (500 kHz) | $400/\sqrt{3}$ V | 200 kΩ - 10 MΩ |
| MV-voltage transformer (frequency optimized) | 9 kHz (10, 20, 30 kV) | $100/\sqrt{3}$ V resp. $110/\sqrt{3}$ V | 200 Ω - 10 MΩ |
| MV-RC-divider (frequency optimized) | 150 kHz (10, 20, 30 kV) | $3.25/\sqrt{3}$ V (standard EU) maximum $10/\sqrt{3}$ V | 200 kΩ - 10 MΩ |
| HV-RC-divider (frequency optimized) | approx. 30 kHz | $100/\sqrt{3}$ V resp. $110/\sqrt{3}$ V | 1 MΩ - 10 MΩ |

Figure 19: Measuring voltages on the voltage side of a utility

In order to be able to guarantee sufficient resolution and accuracy, a mobile PQ measuring device should be designed for these different measuring voltages.

The only mobile measuring device that currently meets these requirements is the PQA 8000H-P from NEO MESSTECHNIK. It has switchable voltage inputs for 600 V_{peak} and 10 or 20 V_{peak}. With this option, it is possible for the utility company to carry out high-quality PQ measurements in the different voltage levels.



- FFT analysis up to 500 kHz (voltage & current) in 2 kHz bands (according to international standard IEC61000-4-30)
- Scope View with 1 MS/s
- 4x voltage measurements / up to 8x current measurements
- Display and recording of the digital PLC data stream
- Two voltage measuring ranges (switchable) of 600 Vp and 10 Vp
- All voltage inputs isolated (CAT III 1000 V / CAT IV 600 V)
- Power supply of the current sensors directly from the unit

Figure 20: Mobile PQ meter PQA8000H-P with switchable voltage inputs especially for utility companies

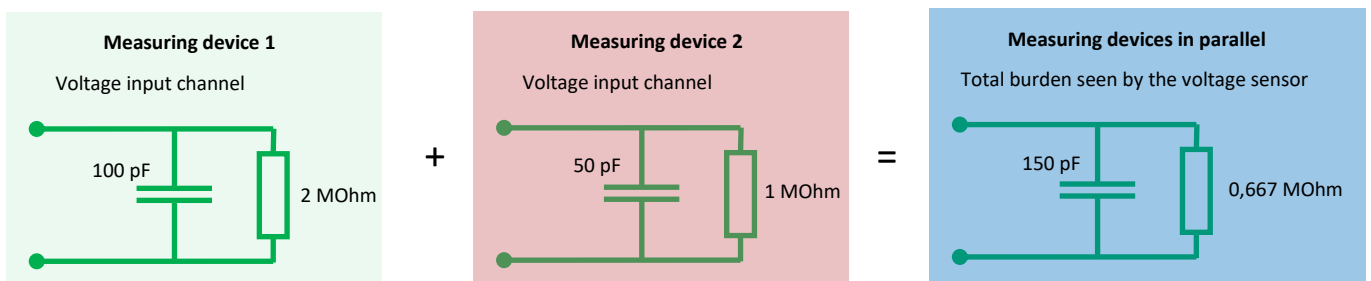
The input impedance of the voltage channels is 10 MOhm || 2 pF. Conventional voltage transformers in medium voltage are specified in terms of class accuracy with a burden power in VA. Values between 5 and 20 VA are common. The class noted on the rating plate applies to 25 to 100 % of this power. The power requirement of the mobile PQ unit is vanishingly small at the usual secondary output voltage of 100/√3 V.

$$P = \frac{U^2}{R} = \frac{100/\sqrt{3}^2 V^2}{10 MOhm} = 0.33 mVA$$

The measuring device can therefore be operated in parallel to the connected measuring devices without affecting the accuracy.

The situation is different with the sensors in the medium and high voltage. Here, the RC dividers are precisely calibrated to the load resistance. In the high voltage, therefore, an extra terminal is often designed for the PQ measuring device. In medium voltage, the sensor must be precisely matched to the measuring device. However, measuring devices can also be operated in parallel here. By using parallel additional resistors, the PQ meter can be simulated when not in use.

For the parallel connection of resistors apply: $R_{total} = \frac{R_1 \times R_2}{R_1 + R_2}$ $C_{total} = C_1 + C_2$



The total burden of the voltage sensor should be between 200 kΩ and 10 MΩ.

Figure 21: Calculation of the total burden seen by the voltage sensor

When using several measuring devices in different measuring stations, a convenient connection to the ENA SCADA system is possible.



Figure 22: SCADA System ENA SCADA for the control room

It can be stated that by using ohmic-capacitive voltage sensors in the medium voltage in connection with a switchable mobile PQ analyser, measurements up to 150 kHz can also be carried out. With RC dividers in the high voltage, a measuring range of up to 30 kHz can currently be covered. From a technical point of view, there is no obstacle to adopting the limit values from the current IEC 61000-2-2 into EN 50160 for low and medium voltage. Only in the high voltage level the bandwidth is limited to 30 kHz.

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