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TECHNICAL REPORT

colour inside

Instrument transformers – The use of instrument transformers for power quality measurement

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

INSTRUMENT TRANSFORMERS – THE USE OF INSTRUMENT TRANSFORMERS FOR POWER QUALITY MEASUREMENT

FOREWORD

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IEC 61869-103, which is a technical report, has been prepared by IEC technical committee 38: Instrument transformers.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
38/402/DTR	38/409/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all the parts in the IEC 61869 series, published under the general title *Instrument transformers*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability dateindicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
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INSTRUMENT TRANSFORMERS – THE USE OF INSTRUMENT TRANSFORMERS FOR POWER QUALITY MEASUREMENT

1 Scope

This part of IEC 61869 is applicable to inductive and electronic instrument transformers with analogue or digital output for use with electrical measuring instruments for measurement and interpretation of results for power quality parameters in 50/60 Hz a.c. power supply systems.

This part of IEC 61869 aims at giving guidance in the usage of HV instrument transformers for measuring power quality parameters.

The power quality parameters considered in this document are power frequency, magnitude of the supply voltage and current, flicker, supply voltage dips and swells, voltage interruptions, transient voltages, supply voltage unbalance, voltage and current harmonics and interharmonics, mains signalling on the supply voltage and rapid voltage changes.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60044-8:2002, *Instrument transformers – Part 8: Instrument transformers: Electronic current transformers*

IEC 61000-2-1:1990, *Electromagnetic compatibility (EMC) – Part 2-1: Environment – Description of the environment – Electromagnetic environment for low-frequency conducted disturbances and signalling in public power supply systems*

IEC 61000-2-2:2002, *Electromagnetic compatibility (EMC) – Part 2-2: Environment – Compatibility for low frequency conducted disturbances and signalling in public low-voltage power supply systems*

IEC 61000-4-7:2002, *Electromagnetic compatibility (EMC) – Part 4-7: Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto*

IEC 61000-4-15:2010, *Electromagnetic compatibility (EMC) – Part 4-15: Testing and measuring techniques – Flickermeter – Functional and design specifications*

IEC 61000-4-30:2008, *Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques – Power quality measurement methods*

IEC 60359:2001, *Electrical and electronic measurement equipment – Expression of performance*

IEC 61557-12:2007, *Electrical safety in low voltage distribution systems up to 1 000 V a.c. and 1 500 V d.c. – Equipment for testing, measuring or monitoring of protective measures – Part 12: Performance measuring and monitoring devices (PMD)*

EN 50160:2007, *Voltage characteristics of electricity supplied by public distribution networks*

3 Terms and definitions

For the purpose of this document, the terms and definitions given in IEC 61000-4-30:2008 and the following apply.

3.1
dip threshold
voltage magnitude specified for the purpose of detecting the start and the end of a voltage dip

3.2
flicker
impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time

[SOURCE: IEC 60050-161:1990, 161-08-13]

3.3
fundamental component
component whose frequency is the fundamental frequency

[SOURCE: IEC 60050-101:1998, 101-14-49, modified definition]

3.4
fundamental frequency
frequency in the spectrum obtained from a Fourier transform of a time function, to which all the frequencies of the spectrum are referred

[SOURCE: IEC 60050-101:1998, 101-14-50, modified definition]

Note 1 to entry: In case of any remaining risk of ambiguity, the fundamental frequency may be derived from the number of poles and speed of rotation of the synchronous generator(s) feeding the system.

3.5
harmonic component
any of the components having a harmonic frequency

[SOURCE: IEC 61000-2-2:2002, definition 3.2.4]

Note 1 to entry: Its value is normally expressed as an r.m.s. value. For brevity, such a component may be referred to simply as an harmonic.

3.6
harmonic frequency
frequency which is an integer multiple of the fundamental frequency

Note 1 to entry: The ratio of the harmonic frequency to the fundamental frequency is the harmonic order (recommended notation: n) (IEC 61000 2-2, definition 3.2.3).

3.7
influence quantity
quantity which is not the subject of the measurement and whose change affects the relationship between the indication and the result of the measurement

[SOURCE: IEC 60050-311:2001, 311-06-01]

Note 1 to entry: This quantity is generally external to the measurement equipment.

3.8
interharmonic component
component having an interharmonic frequency

[SOURCE: IEC 61000-2-2:2002, definition 3.2.6]

Note 1 to entry: Its value is normally expressed as an r.m.s. value. For brevity, such a component may be referred to simply as an interharmonic.

3.9
interharmonic frequency
any frequency which is not an integer multiple of the fundamental frequency

[SOURCE: IEC 61000-2-2:2002, definition 3.2.5]

Note 1 to entry: By extension from harmonic order, the interharmonic order is the ratio of an interharmonic frequency to the fundamental frequency. This ratio is not an integer (recommended notation m).

Note 2 to entry: In the case where $m < 1$ the term subharmonic frequency may be used.

3.10
interruption
reduction of the voltage at a point in the electrical system below the interruption threshold

3.11
interruption threshold
voltage magnitude specified for the purpose of detecting the start and the end of a voltage interruption

3.12
measurement uncertainty
parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand

[SOURCE: IEC 60050-311:2001, 311-01-02, VIM 2.26]

3.13
nominal voltage
U_n
voltage by which a system is designated or identified

3.14
overdeviation
the absolute value of the difference between the measured value and the nominal value of a parameter, only when the measured value of the parameter is greater than the nominal value

3.15
power quality
characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters

[SOURCE: IEC 60050-617:2009, 617-01-05]

Note 1 to entry: These parameters might, in some cases, relate to the compatibility between electricity supplied on a network and the loads connected to that network.

3.16
r.m.s. (root-mean-square) value
square root of the arithmetic mean of the squares of the instantaneous values of a quantity taken over a specified time interval and a specified bandwidth

[SOURCE: IEC 60050-101:1998, 101-14-16, modified definition]

3.17
r.m.s. voltage refreshed each half-cycle
$U_{rms(1/2)}$
value of the r.m.s. voltage measured over 1 cycle, commencing at a fundamental zero crossing, and refreshed each half-cycle

Note 1 to entry: This technique is independent for each channel and will produce r.m.s. values at successive times on different channels for polyphase systems.

Note 2 to entry: This value is used only for voltage dip, voltage swell and interruption detection and evaluation, in Class A.

Note 3 to entry: This r.m.s. voltage value may be a phase-to-phase value or a phase-to-neutral value.

3.18
r.m.s. voltage refreshed each cycle
$U_{rms(1)}$
value of the r.m.s. voltage measured over 1 cycle and refreshed each cycle

Note 1 to entry: In contrast to $U_{\mathrm{rms}(1/2)}$, this technique does not define when a cycle commences.

Note 2 to entry: This value is used only for voltage dip, voltage swell and interruption detection and evaluation, in Class S.

Note 3 to entry: This r.m.s. voltage value can be a phase-to-phase value or a phase-to-neutral value.

3.19
residual voltage
U_{res}
minimum value of $U_{\mathrm{rms}(1/2)}$ or $U_{\mathrm{rms}(1)}$ recorded during a voltage dip or interruption

Note 1 to entry: The residual voltage is expressed as a value in volts, or as a percentage or per unit value of Udin

3.20
sliding reference voltage
Usr
voltage magnitude averaged over a specified time interval, representing the voltage preceding a voltage-change type of event (e.g. voltage dips and swells, rapid voltage changes)

3.21
supply voltage
the voltage which a distribution undertaking maintains at the consumer's point of supply

[SOURCE: IEC 60050-604:1987, 604-01-16]

Note 1 to entry: If a supply voltage is specified, for instance in the supply contract, then it is called "declared (supply) voltage".

3.22
swell threshold
voltage magnitude specified for the purpose of detecting the start and the end of a swell

3.23
underdeviation
the absolute value of the difference between the measured value and the nominal value of a parameter, only when the value of the parameter is lower than the nominal value

3.24
voltage dip
temporary reduction of the voltage magnitude at a point in the electrical system below a threshold

Note 1 to entry: Interruptions are a special case of a voltage dip. Post-processing may be used to distinguish between voltage dips and interruptions.

Note 2 to entry: A voltage dip is also referred to as sag. The two terms are considered interchangeable; however, this standard will only use the term voltage dip.

3.25
voltage swell
temporary increase of the voltage magnitude at a point in the electrical system above a threshold

3.26
voltage unbalance
condition in a polyphase system in which the r.m.s. values of the line voltages (fundamental component), and/or the phase angles between consecutive line voltages, are not all equal

[SOURCE: IEC 60050-161:1990, 161-08-09, modified definition and notes]

Note 1 to entry: The degree of the inequality is usually expressed as the ratios of the negative- and zero-sequence components to the positive-sequence component.

Note 2 to entry: In this document, voltage unbalance is considered in relation to 3-phase systems.

4 Nature of the problem

Instrument transformers have been used up to now for protection and metering purpose, providing a secondary signal suitable for protection relays and measurement instruments with the required accuracy.

Attention has been focused on the measurement of current, voltage, power frequency and power: instrument transformers have been conceived, standardized, designed, manufactured, tested mainly, if not exclusively, for this purpose.

Nowadays, there is a growing demand for investigating the characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters; in other words, for measuring the Power Quality (PQ) at that point of the system.

The development of a lot of applications sensitive to PQ issues, from domestic to industrial field, requires technical and normative criteria, in order to protect the parts involved.

Aspects related to PQ measurement methods (and relevant accuracy classes) are defined in detail in the Standard IEC 61000-4-30:2008. In low voltage applications, instruments are available, able to perform measurements with a high degree of accuracy and complying with measurement classes prescribed by IEC 61000-4-30:2008. For high voltage applications, voltage and current transformers have to be inserted in measurement chain, but the information available about their impact on the measurement is not yet consolidated.

For power frequency, a homogeneous behaviour within the whole instrument transformer population belonging to the same class is expected; however, at other frequencies, the transformers behaviour may change, not only from type to type, but even between different samples of the same type.

The present technical report aims to provide the relevant information available at the present about the subject, to give, where possible, indications about the methods and the arrangements to be used and to define the issues that have to be solved and the aspects to be investigated.

In the following chapter, power quality parameters according to IEC 61000-4-30:2008 are described. The possible impact of instrument transformers on the measurement chain is also considered.

5 Power quality parameters according to IEC 61000-4-30:2008

5.1 General

The IEC 61000 family of standards on electromagnetic compatibility standardizes most aspects of power quality. Namely, these standards provide definition for the various disturbances, acceptable emission, susceptibility and compatibility levels as well as measurement methods. The most relevant standards necessary to understand the influence of instrument transformers on power quality parameters are:

- IEC 61000-2-1:1990, *Electromagnetic compatibility (EMC) – Part 2-1: Environment – Section 1: Description of the environment – Electromagnetic environment for low-frequency conducted disturbances and signalling in public power supply systems*
- IEC 61000-2-2:2002, *Electromagnetic compatibility (EMC) – Part 2-2: Environment – Compatibility for low-frequency conducted disturbances and signalling in public low-voltage power supply systems*
- IEC 61000-4-7:2002, *Electromagnetic compatibility (EMC) – Part 4-7: Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto*
- IEC 61000-4-15:2010, *Electromagnetic compatibility (EMC) – Part 4-15: Testing and measurement techniques – Flickermeter – Functional and design specifications*
- IEC 61000-4-30:2008, *Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques – Power quality measurement methods*
- IEC 60359:2001, *Electrical and electronic measurement equipment – Expression of performance*
- IEC 61557-12:2007, *Electrical safety in low voltage distribution systems up to 1 000 V a.c. and 1 500 V d.c. – Equipment for testing, measuring or monitoring of protective measures – Part 12: Performance measuring and monitoring devices (PMD)*

The first two standards listed provide a definition of the power quality disturbances and their acceptable levels in power system. The remaining three documents define how these disturbances are measured. IEC 61000-4-30:2008 is the main document and is completed by IEC 61000-4-7:2002 and IEC 61000-4-15 which address the specific requirements for harmonics and flicker. It is important to note that IEC 61000-4-30:2008 addresses disturbances relevant to voltage only, while IEC 61000-4-7:2002 also includes current. This implies that, at present, voltage transformers influence has to be considered taking into account the measurement of all quantities identified by IEC 61000-4-30:2008, while the analysis of the impact of current transformers could be limited to harmonics and interharmonics.

5.2 Power quality measurement chain

To determine and quantify the influence of instrument transformers on the overall uncertainty on power quality measurements, it is necessary to simultaneously consider the electrical behaviour of an instrument transformer for a given disturbance and the measurement method as they constitute a measurement chain. This is shown schematically in Figure 1.

NOTE The measurement chain shown in Figure 1 is the same illustrated in clause 4.2 of IEC 61000-4-30:2008, where “Measurement transducers” has been replaced with “Instrument transformers”, in order to be consistent with the terminology used by IEC TC 38.

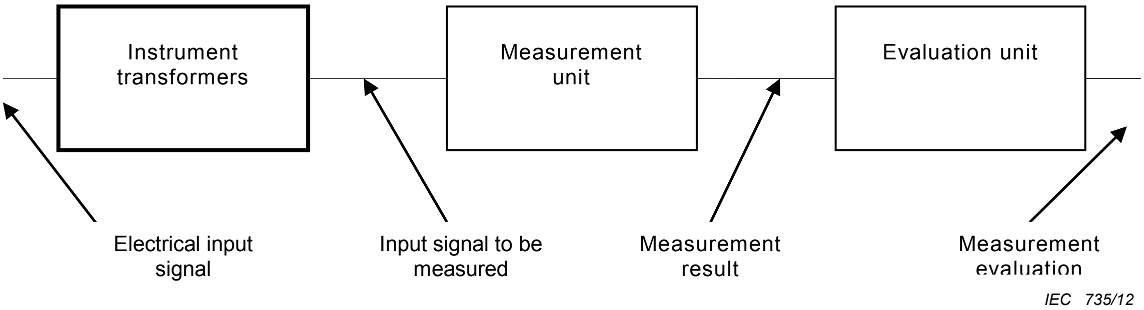

Figure 1 – Measurement chain (From h)[1], modified)

The impact of instrument transformers on the overall uncertainty can be quantified as an added uncertainty that combines with the uncertainty of the measuring system as illustrated in Figure 2.

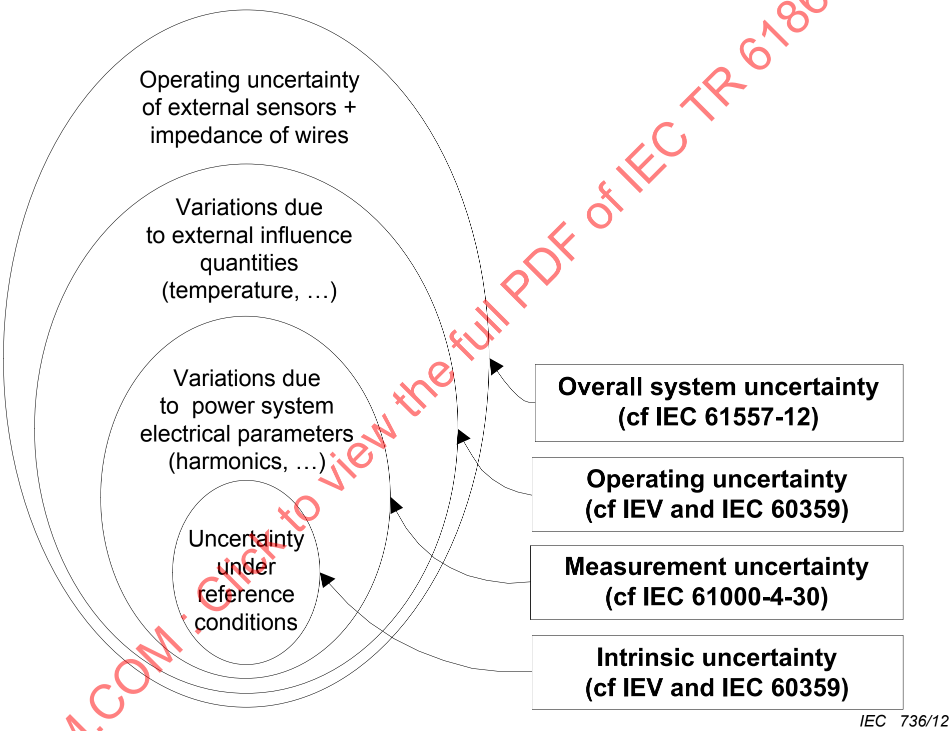

Figure 2 – Contribution of instrument transformers in overall measurement uncertainty (from i), modified)

5.3 Signal processing according to IEC 61000-4-30:2008

The signal from the instrument transformer is digitised and processed over several time intervals in a class A or S power quality analyser:

- Measure of r.m.s. voltage over 1 cycle refreshed each half-cycle ($U_{\text{rms(1/2)}}$)
- Measures over a period of 10/12 cycles for 50/60 Hz
- 150/180 cycles aggregation for 50/60 Hz of 10/12 cycles measurement
- 10 minutes aggregation of 10/12 cycles measurement
- 2 hours aggregation of 10/12 cycles measurement

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1 Numbers in square brackets refer to the Bibliography.

Aggregation is the combination of several sequential values of a parameter measured over 10/12 cycles time intervals to provide a value for a longer time interval. Aggregation is performed using the square root of the arithmetic mean of the squared input values.

In Table 1 are listed all the power quality disturbances for which IEC 61000-4-30:2008 provides a measurement method and time intervals:

Table 1 – Power quality disturbances and measurement interval as per IEC 61000-4-30:2008

Disturbance	1 Cycle	10/12 Cycles	150/180 Cycles	10 min	2 hrs	Other
Power frequency						10 s
Magnitude of voltage		x	x	x	x	
Flicker				x	x	1 min
Dips and swells	x					
Voltage interruptions	x					
Voltage unbalance		x	x	x	x	
Voltage harmonics		x	x	x	x	
Voltage interharmonics		x	x	x	x	
Main signalling		x				
Rapid voltage changes	x					
U/O deviation parameters		x	x	x	x	

In the following sections all the disturbances are reviewed and the possible influences of the transformers on the measurements are identified.

5.4 Power frequency

As the frequency measurement is based on an integer number of cycles (using the zero crossing of the fundamental) the IT does not introduce any additional uncertainty.

5.5 Magnitude of the supply voltage

The r.m.s value of voltage is computed over 10 cycles of the fundamental frequency and takes into account the full spectrum of the signal. Thus any attenuation / amplification introduced by the ITs will directly impact the r.m.s uncertainty. Due to this relatively long time interval, the phase response of the ITs has little impact on the computation of the r.m.s. voltage. In summary, the important characteristic required from ITs is good magnitude accuracy for frequencies other than the power one (up to the 50th harmonic).

5.6 Flicker

Flicker can be caused by voltage fluctuations, harmonic fluctuations and by interharmonics. The measure of flicker is the most complicated of all the disturbances as it must predict the annoyance experimented by humans from light intensity fluctuations caused by the variation of the power system voltage.

An example of a voltage fluctuation which can cause flicker is given in Figure 3.

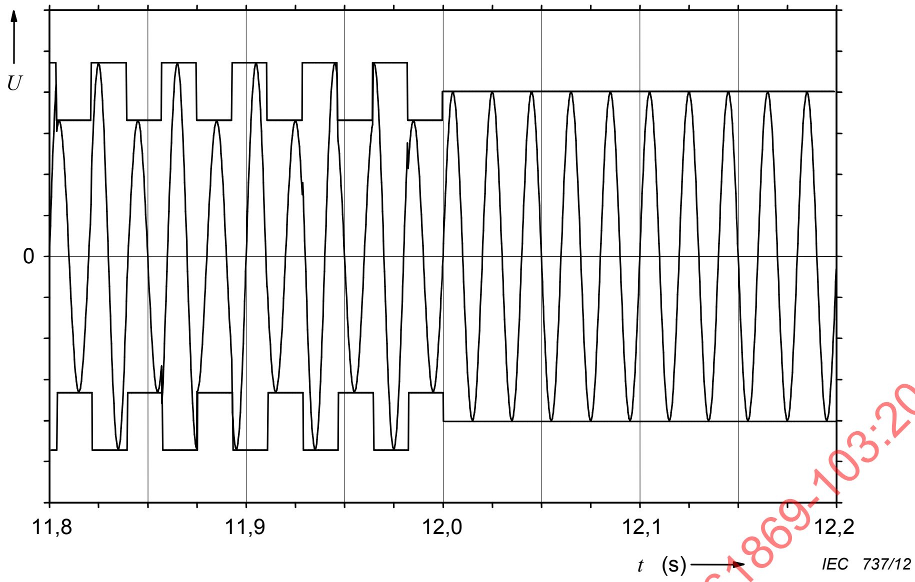


Figure 3 – Example of voltage fluctuation causing flicker

The presence of flicker in a power system leads to apparition of side bands around the power frequency. The equation below illustrates this for the case of a power waveform modulated in amplitude by another sine wave (flicker):

$$v(t) = \hat{V} \times \sin(\omega t) \times (1 + \alpha \times \sin(\omega_f t)) = \hat{V} \times \sin(\omega t) + \frac{\hat{V} \times \alpha}{2} \cos(\omega t - \omega_f t) - \frac{\hat{V} \times \alpha}{2} \cos(\omega t + \omega_f t)$$

where:

V is the nominal voltage

ω is the power frequency

ω_f is the Flicker frequency

α is the ΔV/V fluctuation

Human beings are capable to perceive light fluctuation at frequencies of up to about 35 Hz, the spectrum of the power waveform spectrum can thus contain frequency components between 15 Hz to 85 Hz. To avoid any degradation of the accuracy of the flicker measurement, voltage transformers must neither attenuate nor amplify these frequencies. A further requirement is the need for a symmetrical frequency response around the fundamental frequency. This requirement is dictated by the demodulation process within the IEC flickermeter shown in Figure 4.

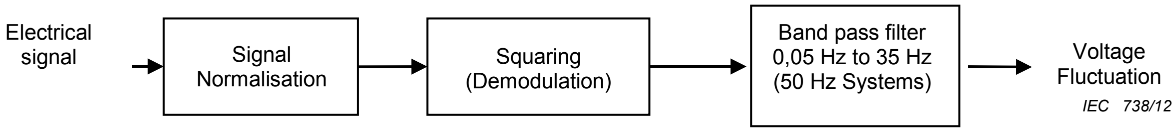


Figure 4 – Demodulation within the IEC flickermeter

It can be shown that the combination of the squaring and band pass filter extracts the flicker frequency through a beat of the fundamental frequency with ω - ωf and ω + ωf components of the spectrum. The magnitude of the flicker modulation corresponds to the sum of the magnitude of ω - ωf and ω + ωf components which add as two vectors. Thus any dissymmetry in the frequency response around the fundamental frequency can directly impact the accuracy of the flicker measurement.

5.7 Supply voltage dips and swells

Dip and swell evaluations are based on the $U_{rms(1/2)}$. So similarly to the magnitude of the supply voltage, the frequency response influences this one cycle r.m.s calculation. With this successive values of $U_{rms(1/2)}$, the various dip and swell characteristics are established:

- Start time the time where $U_{rms(1/2)}$ goes below / above a set reference value
- Stop time the time where $U_{rms(1/2)}$ returns to its normal value
- Duration time between the start and stop time
- Depth difference between reference voltage and residual voltage of a dip
- Maximum largest $U_{rms(1/2)}$ value during a swell

As dips and swells are characterised by a rapid voltage and phase change, the transient behaviour of the voltage transformer could impact the waveshape seen by the measurement unit and thus the computation of $U_{rms(1/2)}$ and of the above parameters could be affected.

An example of voltage dip is shown in Figure 5.

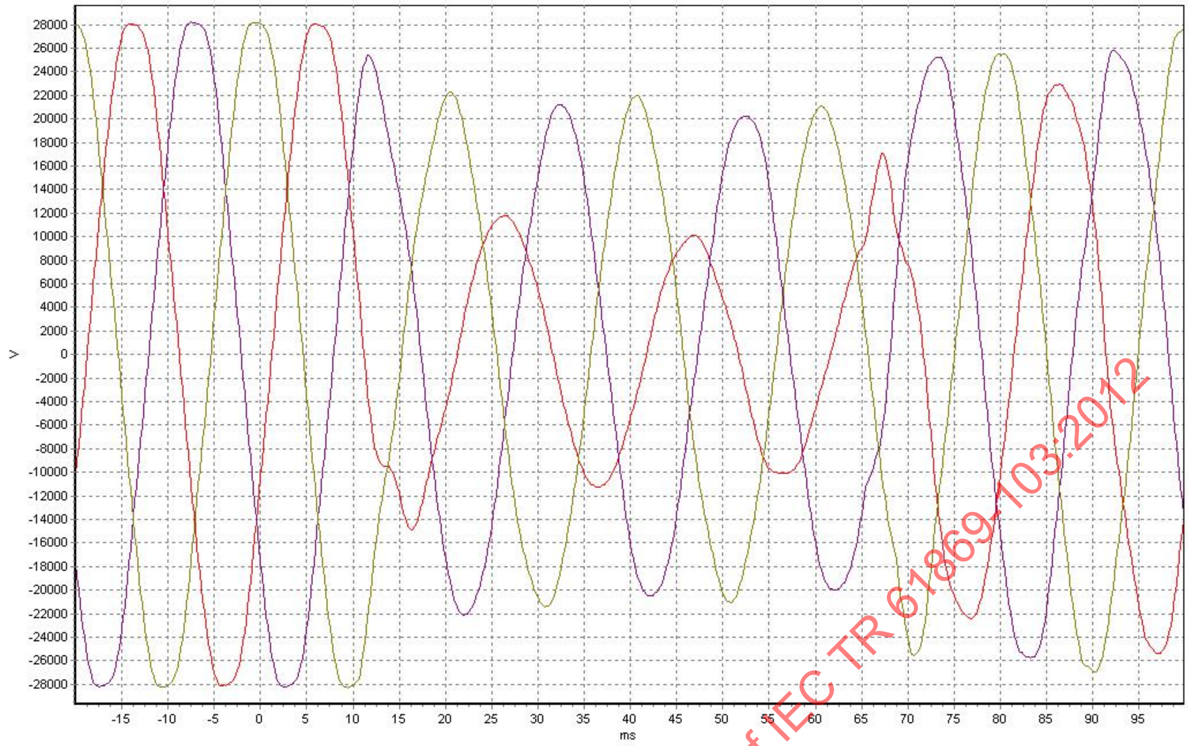


Figure 5 – Example of voltage dip (courtesy of Italian distribution network monitoring system – QuEEN)

5.8 Voltage interruptions

An example of voltage interruption is shown in Figure 6.

Instrument transformers have a similar impact on the measurement as for the dips and swells.

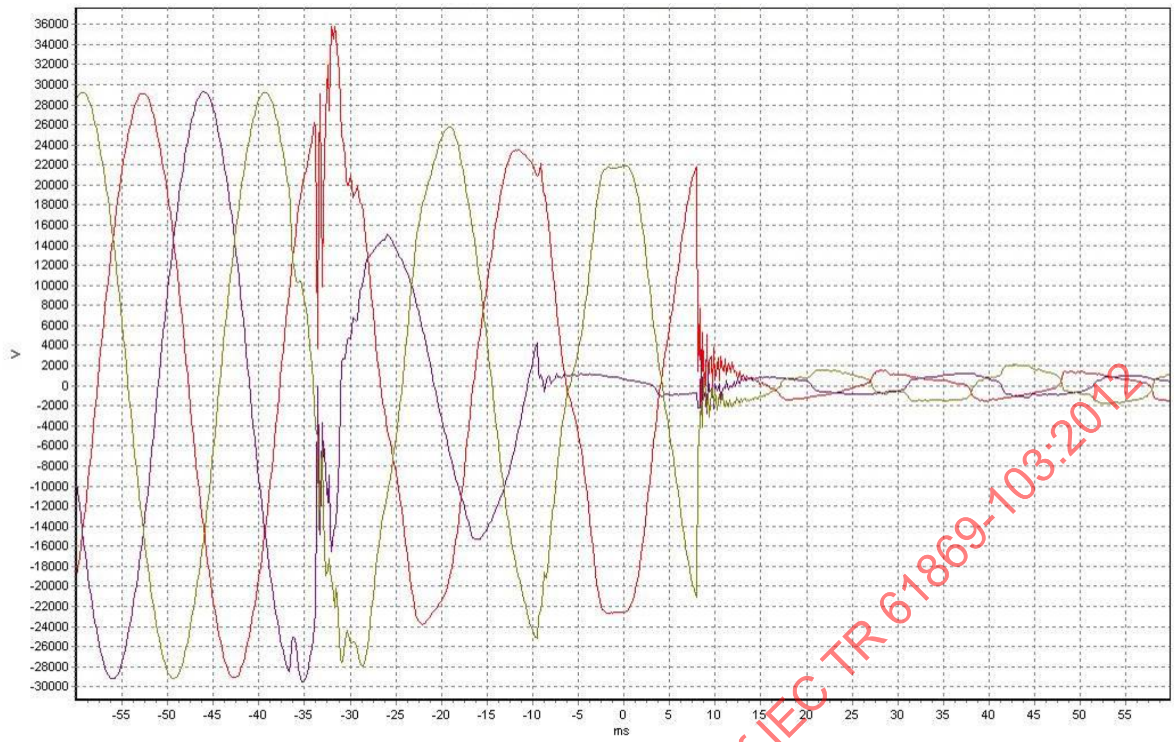


Figure 6 – Example of voltage interruption (courtesy of Italian distribution network monitoring system – QuEEN)

5.9 Transient voltages

IEC 61000-4-30:2008 (Clause A.4) provides only information about the measure of current and voltage transient occurring in the LV systems and does not cover HV systems. In addition, the standard contains no normative information on how to process and quantify these disturbances.

5.10 Supply voltage unbalance

Unbalance is measured only at fundamental frequency. As voltage transformers are specified at power frequency, their impact on the measure of unbalance is only influenced by their magnitude and phase error and possibly mismatch. An example of voltage unbalance is shown in Figure 7.

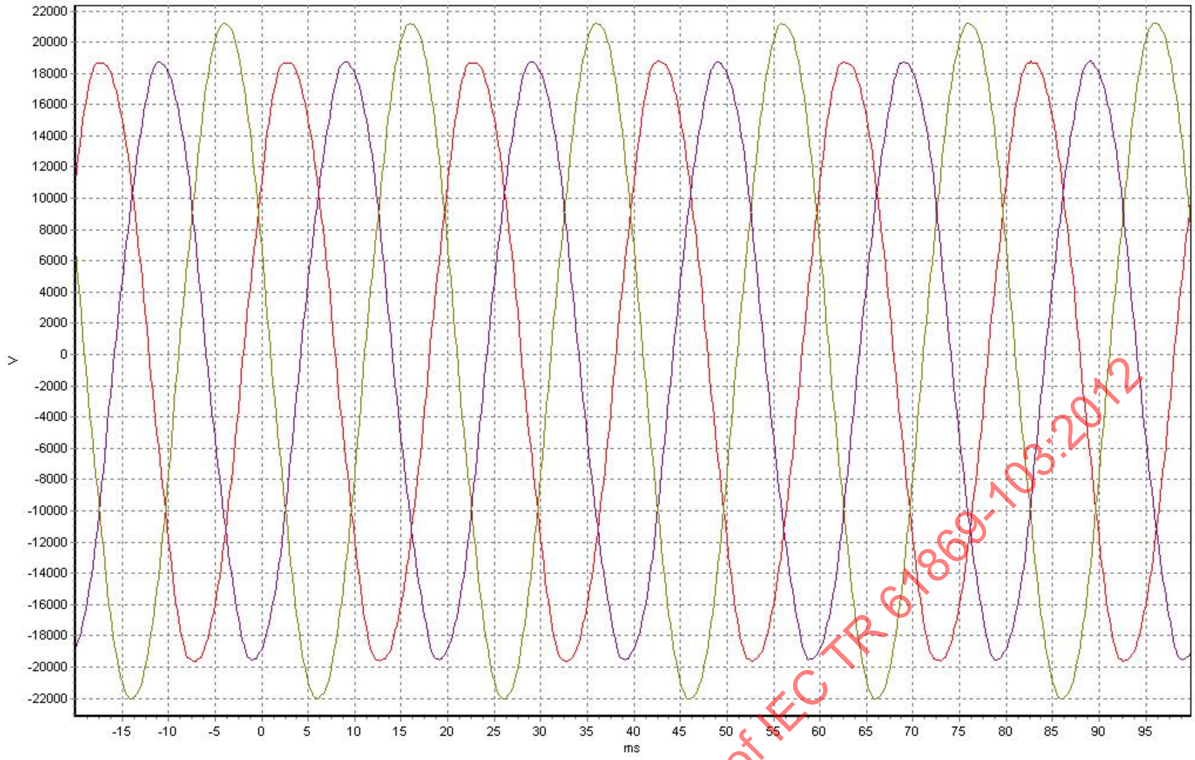


Figure 7 – Example of voltage unbalance (courtesy of Italian distribution network monitoring system- QuEEN)

5.11 Voltage harmonics

The measure of harmonics is made over 10 cycles according to IEC 61000-4-7:2002. Class A requires measurements of at least up to the 50th (2 500 Hz or 3 000 Hz) harmonics while class S requires 40th (2 000 Hz or 2 400 Hz) order. The frequency response, magnitude and phase of the ITs' impact thus directly the accuracy on the measurement of harmonics.

NOTE An example of voltage harmonics is shown in Figure 8, where a simulated case is given in order to illustrate the contribution of the single harmonic components.

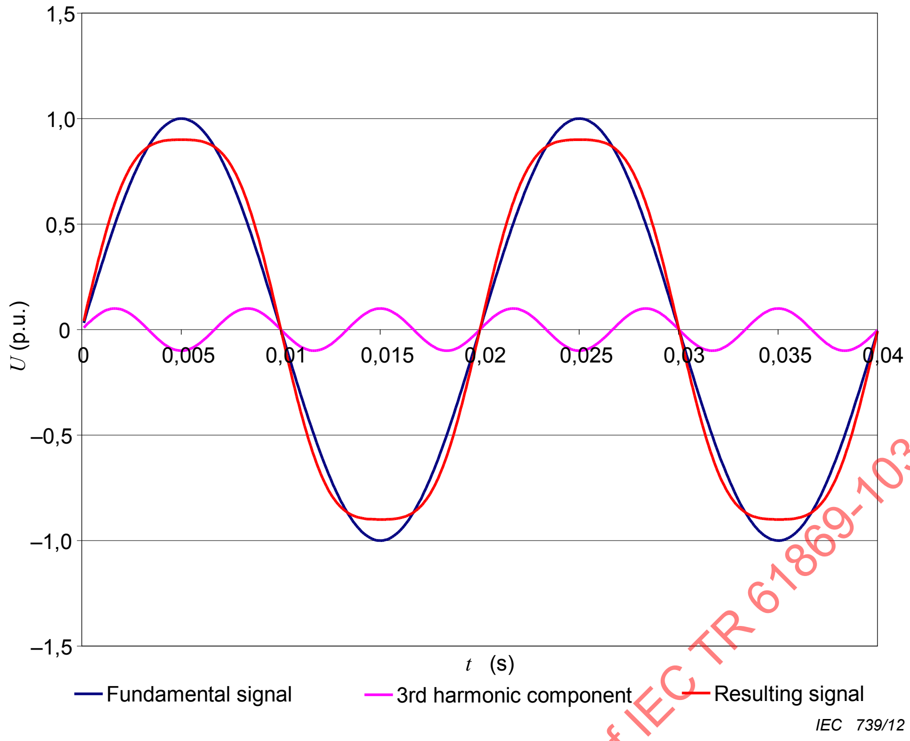


Figure 8 – Example of voltage harmonics

5.12 Voltage inter-harmonics

The measure of harmonics is computed over 10 cycles according to IEC 61000-4-7:2002. Class A requires measures of at least up to the 50^{th} (2 500 Hz or 3 000 Hz) order while class S requires the 40^{th} (2 000 Hz or 2 400 Hz) order. The measuring method, however, specifies “Grouping” of adjacent frequency bins of the FFT. Thus the phase response of the ITs do not represent an issue. Only magnitude accuracy is important in regard to the overall uncertainty.

5.13 Mains Signalling Voltages on the supply voltage

Main signalling voltage can be considered as interharmonic if its frequency is less than 2 500 Hz. Instrument transformer can possibly impact the magnitude of the main signalling voltage seen by the instrument.

5.14 Rapid voltage changes

IEC 61000-4-30:2008 is not normative for rapid voltage changes, but provides some information. It can be assumed that rapid voltage changes can be captured with $U_{\text{rms}(1/2)}$. The impact of voltage transformers is similar to the dips and swells case. However, since the magnitude changes are much lower, the impact of the transformers may not be as severe.

5.15 Measurement of underdeviation and overdeviation parameters

Underdeviations and overdeviations are based on 10/12 cycles and are thus subject to the same influence as the magnitude of supply voltage.

5.16 Summary of the requirements placed by the measure of power quality parameters

In summary, the measure of power quality disturbances measured according to IEC 61000-4-30:2008 requires improved frequency response (magnitude and phase) as well as transient response from the transformers. In Table 2 is shown the relation between these requirements and the power quality disturbances.

Table 2 – Transformer parameters influencing power quality measurement

Disturbance	Magnitude	Phase	Transients
Power frequency			
Magnitude of voltage	x	x	
Flicker	x	x	
Dips and swells	x	x	x
Voltage interruptions	x	x	x
Voltage unbalance	x	x	
Voltage harmonics	x	x	
Voltage interharmonics	x		
Main signaling	x		
Rapid voltage changes	x		x
U/O deviation parameters	x	x	

6 Impact of instrument transformers on PQ measurement

6.1 General

The impact of instrument transformers on PQ measurements is tied to technology adopted and to design and manufacturing details.

Instrument transformers are used in order to provide to power quality measurement instruments a signal suitable for their input channels and containing all the relevant information needed from primary signals. Such information may be the accurate reproduction of the primary signal or may give to the instrument the relevant information in order to reconstruct the power quality parameters of the primary signal.

At present, knowledge about instrument transformers measurement behaviour for PQ measurement is not homogeneous: more information is available (or can be inferred from a theoretical point of view) for electronic instrument transformers, often based on well-known sensors commonly used for laboratory application. Many electronic instrument transformer technologies may be considered linear both with amplitude and with frequency in a certain frequency range (i.e. up to 3 000 Hz): principle of superposition of causes and effects may then be applied and linearity with amplitude and with frequency may be assessed separately.

Information is available about CVTs too, leading to consider them in principle unadvisable or unsuitable for PQ-measurements, provided that no further expedient is adopted.

A comparable level of knowledge would be highly desirable for inductive instrument transformers, due to their worldwide availability and diffusion: anyway, at present little experience is available, very far from what would be needed in order to perform totally reliable power quality measurements.

This low level of experience is more often tied to the difficulties tied with the assessment of their behaviour than to the technology adequacy for the purpose.

Inductive instrument transformers up to now have been designed in order to have behaviour mostly linear in the range of primary signal amplitudes and at rated power frequency: outside these ranges, their behaviour is not standardised, even if linearity characteristics may extend beyond the rated ranges.

However, inductive instrument transformer may not in principle be considered linear neither with the change of the primary signal amplitude nor with the frequency: this fact affects more the instrument transformer characterisation than measurement performance.

Non linearity may in fact be taken into account within measurement instruments, but must be previously assessed: superposition principle cannot be applied in this case and effects of power frequency signal and PQ parameters must be assessed by applying them at the same time.

For this reason, at present no standardised laboratory method is available for this purpose, suitable for inductive instrument transformers, due to technical limits: in fact, such tests have been, up to now, out of scope of standard laboratory equipment and new, special test set up have to be conceived in order to correctly assess behaviour. Further, subsidiary information can be inferred from field experience, by comparison within measurements made by means of inductive instrument transformers and data made available by purposely characterised linear sensors.

At this proposal, many contributions are available in technical literature about frequency response of instrument transformers; such information can be useful in order to assess instrument transformers behaviour when they are used for the measurement of power quality parameters but could also be misleading, since it may not be representative of the real behaviour of the sensor, when higher voltages and currents are involved. For this reason, in the present document information available about instrument transformer frequency response and measurement behaviour was separated into different chapters.

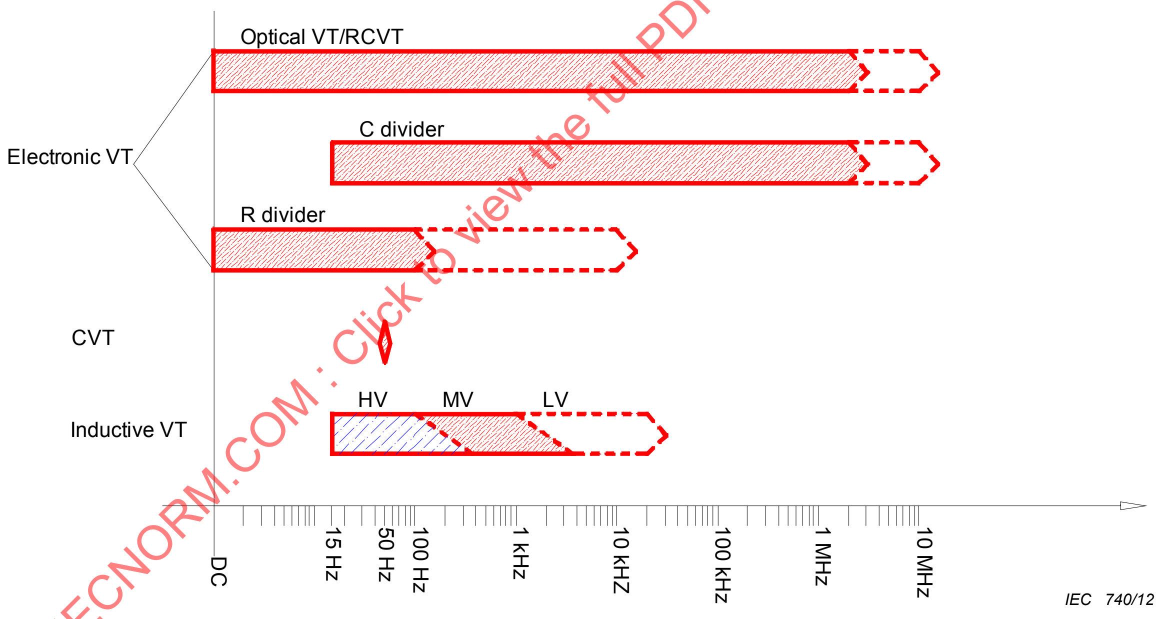


Figure 9 – Voltage transformer technologies frequency range according to present experience

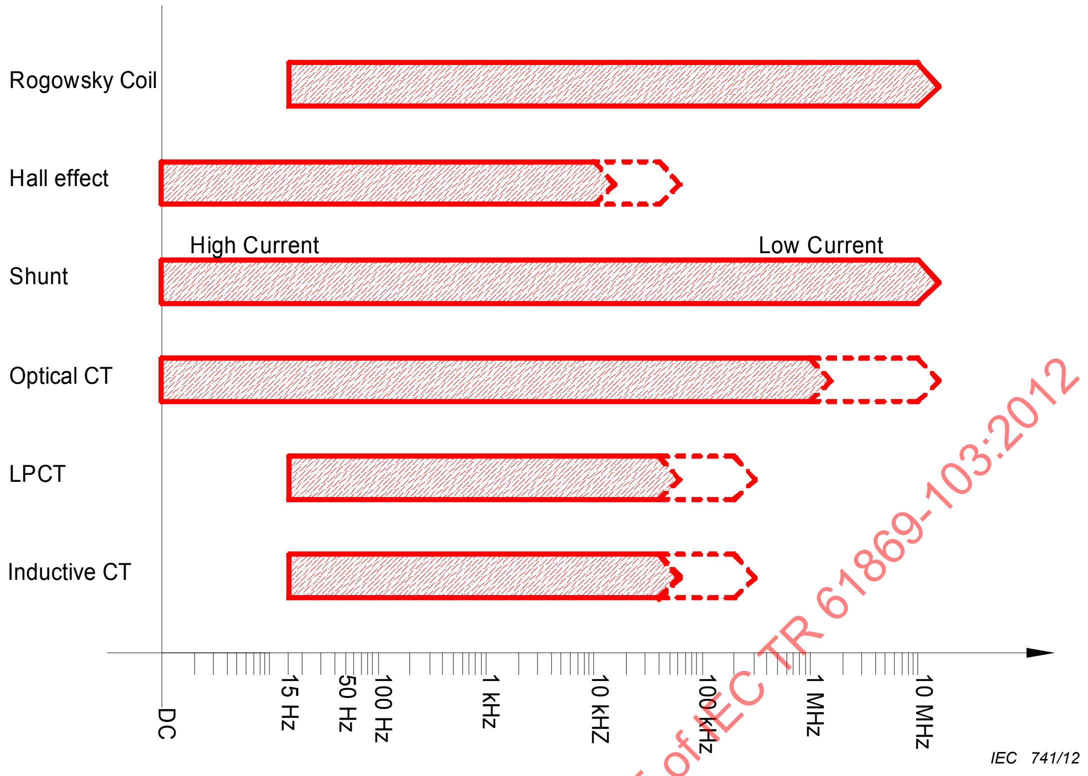


Figure 10 – Current transformer technologies frequency range according to present experience

In the following, state of art of knowledge about behaviour of available instrument transformers technologies is presented.

The charts in Figure 9 and 10 show an approximate overview of the useful frequency range of today available instrument transformer technologies. In the figures the main features of each technology like size, material/technology of the active part or of the sensor, temperature and voltage coefficients and so on are not considered, so the charts give only a rough overview. Due to the fact that, even within the same technology, the limits depend on numerous parameters, they were not represented as continuous lines but they are drawn with dotted lines.

6.2 Inductive instrument transformers

Magnetic error is tied to flux into instrument transformer magnetic core, necessary for normal operation conditions.

Since flux is a non-linear function of magnetising current, magnetic error is non-linear and is a function of burden, frequency and rated ratio. At power frequency, magnetic error is the main component of instrument transformer error, whereas, at higher frequencies, capacitive error is the main cause of deviation. Capacitive error is tied to windings geometry and is due to distributed capacitances within instrument transformer, supplied by voltages applied or induced. Distributed capacitances may be located within a winding, between windings or between windings and shields. Their contribution to error components increases with frequency. Magnetic error decreases as frequency increases, its contribution to total error becomes negligible and capacitive error becomes prevailing. Moreover, for inductive CTs, error variation with secondary current and residual magnetisation effects become less significant at higher frequencies. Usually capacitive error is a complex function of many parameters, with ratio and phase angle components varying like the square of power and power respectively. Capacitive error in inductive CTs is usually lower than in inductive VTs due to a lower flux (lower voltage applied or induced in windings): usually inductive CTs have a better behaviour with frequency than inductive VTs. Finally, the burden itself could be a function of the frequencies, affecting therefore the magnetic error.

In Subclause 6.2.1, information about inductive instrument transformers is featured and behaviour is collected, in order to provide a reference for further investigation activity. At this proposal, it must be underlined that frequency response is not linear, for inductive instrument transformers, neither with frequency nor with amplitude; information available in literature about frequency response of inductive instrument transformers must therefore be carefully examined and assessed before usage: special attention must be paid on methods used for frequency behaviour assessment, as shown, for example, in a): errors measured using the superposition approach are larger than the ones obtained with the frequency response approach.

The same care has to be taken with equivalent circuits available in technical literature, mainly developed for calculations performed with EMTP or similar software applications. Attention must be paid to methods used for the assessment of these models and to the purpose for which they have been developed, in order to avoid results and conclusions which could be misleading. The circuits and diagrams in the following clauses are shown for reference only but they are generally not applicable in presence of power quality disturbances.

6.2.1 Inductive voltage transformers

6.2.1.1 General

Inductive voltage transformers are based on electromagnetic coupling between primary and secondary circuits.

A simplified equivalent circuit for an inductive voltage transformer is shown in Figure 11, in order to put into evidence the parameters having impact on measurements in presence of harmonics or other PQ events.

With reference to the usual representation, it must be considered that the behaviour of the instrument transformer is influenced by the following parameters:

- Magnetizing inductance L_{10} is characterized by a non-linear, hysteretic behaviour: hysteresis cycle shape and area are function of signal amplitude and frequency;
- Capacitances between windings and among windings and ground are determined by the geometrical features of the transformer: their impact increases with frequency.

The same simplified equivalent circuit can be used also in order to illustrate the behaviour of inductive current transformers.

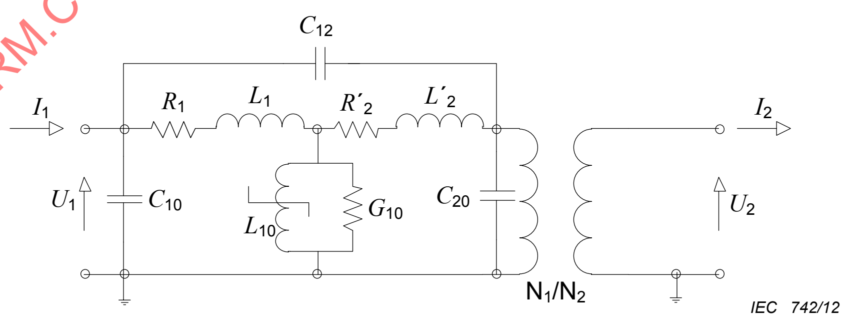


Figure 11 – Example of equivalent circuit for an inductive voltage/current transformer

6.2.1.2 Inductive VTs for voltages over 1 kV and up to 52 kV

6.2.1.2.1 Architecture

Table 3 – Main components of an inductive voltage transformer for voltages over 1 kV and up to 52 kV

Primary winding	The primary winding may be phase-to-phase connected or phase-ground connected. It is located on one section of the magnetic core and generally it is made out with a layer winding and a supplementary insulation between the layers. The primary winding can be done in one or more parts to optimize the VTs architecture or the electric field concentration.
Secondary winding	The VTs have one or more secondary windings for measurement and/or protection application. The secondary winding is located between the primary winding and the magnetic core; it is a linear winding type and it can have one or more sections when different transformation ratios are required.
Magnetic core	The VTs have only one magnetic core, even if several secondary windings are requested, made by mainly Si-iron or nickel iron. Other materials are also possible (i.e. nanocrystaline iron) The VT is generally single-phase device but three-phase VTs using a single common magnetic core are used in some countries.
MV insulation	For indoor and outdoor applications synthetic resins (i.e. epoxy resin) are used for the insulation and to withstand to mechanical strength at the terminals of the VT.

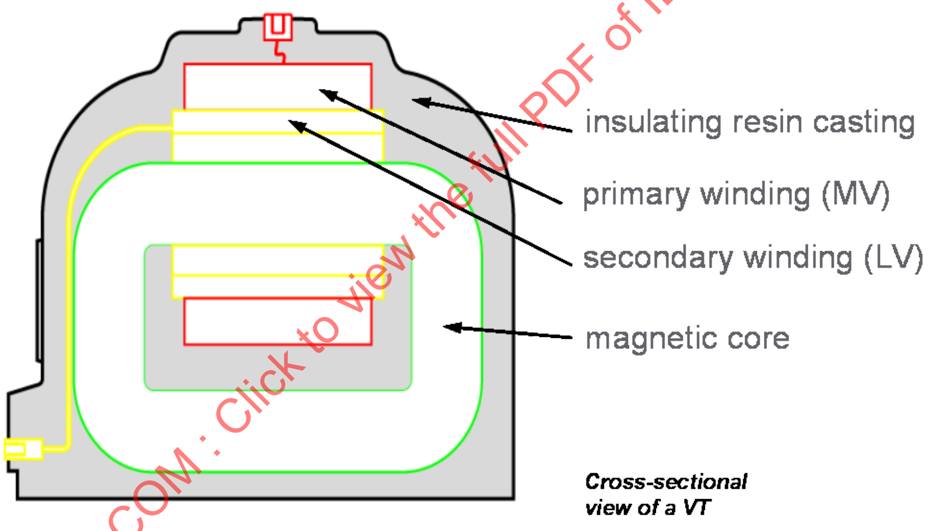


Figure 12 – Cross-section view of an inductive voltage transformer for voltages over 1 kV and up to 52 kV (courtesy of Schneider Electric)

In Figure 12, the Cross-section view of an inductive voltage transformer is shown. A suitable equivalent circuit of layer windings of a VT, showing earthed screens, can be found in b).

6.2.1.2.2 Frequency Response Behaviour

The frequency response becomes unacceptable at about 1 kHz (or even lower), well below the frequency limit established in the relevant standards. The achievable frequency limit increases for lower voltage class units but worsens for higher voltage class units.

According to IEC 61000-4-30:2008, frequency response for a common metering class voltage transformer depends on its type and on burden. With a high impedance burden, the response is usually adequate to at least 2 kHz but it can be less.

At higher voltages, resonances can be encountered at lower frequencies, since inductances and capacitance values vary with insulation and manufacturing requirements. Exact response of a single sample unit is function of manufacturing characteristics.

Also burden has an impact on frequency response: as burden decreases, useful frequency range decreases to c).

Test campaigns d) show that it is possible to state that, for medium voltage, all VTs perform accurately up to 1 kHz but only about 60 % is suitable up to 2 500 Hz. These figures further decrease to 700 Hz and 50 % respectively, if accuracy requirements for phase are considered.

Table 4 – Inductive voltage transformers for voltages over 1 kV and up to 52 kV: impact on the measurements of PQ Parameters

Power Frequency	No impact
Magnitude of the supply voltage	No impact
Flicker	To be investigated
Supply voltage dips and swells	To be investigated
Supply voltage unbalance	To be investigated
Harmonics and interharmonics	LV voltage transformers are suitable for the harmonic frequency range of interest. If amplitude accuracy only is required, MV voltage transformers seem to be generally suitable up to 1 kHz; about 60 % of all voltage transformers is suitable for the whole harmonic range of interest; if also phase angle accuracy is required, MV voltage transformers seem to be suitable up to 700 Hz; about 50 % of all VTs cover the whole frequency range of interest.
Main signalling on the supply voltage	To be investigated
Rapid voltage changes	To be investigated
Voltage interruptions	To be investigated
Transient voltages	For transient measurements, voltage transformers should be designed in order to avoid saturation conditions due to measured events: for low frequency, the knee of saturation curve must be at twice the rated system voltage at least.

6.2.1.3 Inductive VTs for voltages over 52 kV and up to 1 100 kV

6.2.1.3.1 Architecture

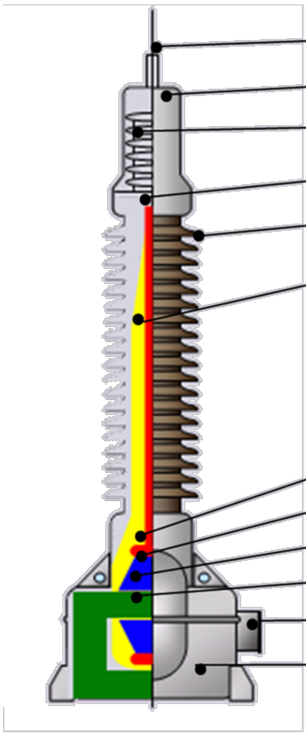


Figure 13 – Cross-section view of a freestanding High Voltage VT (courtesy of Trench Switzerland AG)

In Figure 13, the cross-section view of a freestanding high voltage VT is shown.

The outer insulation is either made by a porcelain insulator or by a glass fibre reinforced epoxy resin tube with silicone sheds (silicon insulator). Inductive VTs for high voltage applications may have the inner insulation either made by a SF_6 gas insulation system or by an oil/paper insulation system. To lead the high voltage from the top terminal to high voltage connection of the transformer, a conductor is necessary. The conductor is part of the bushing. To avoid high electrical field stress on the outer insulator an internal grading is necessary. This grading may be done just with some few grading layers (rough grading) or with a high number of grading layers (fine grading).

6.2.1.3.2 Frequency response behaviour

Due to the resonance of the inductance of the winding and the stray capacitance between the winding layers there are big errors in the measurement of the amplitude and big phase displacements for higher frequencies. The higher the system voltage, the higher is the effect, so that the frequency response becomes unacceptable around 1 kHz e), f) or even lower d).

Manufacturing features can strongly affect this behaviour: core grounded VTs would have a better behaviour up to 2 kHz than the insulated core ones, unsuitable above 1 kHz g).

Sensitivity to secondary burden is low for the main part of interesting frequency range, except for resonance peaks proximities f).

Error correction techniques may in principle be used in order to improve frequency behaviour of VTs for measurement of harmonics.

Different conclusions among authors may be explained with different core groundings or other manufacturing methods or with test and methods used, from harmonics superposition to the fundamental frequency e) to impulses f).

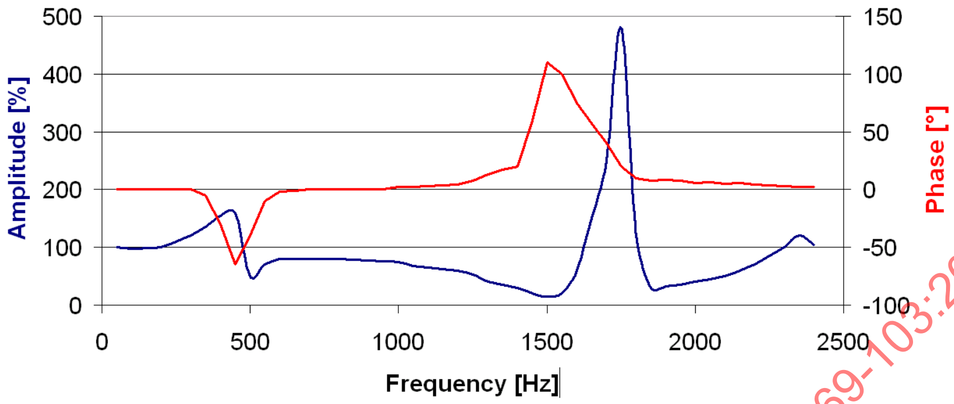


Figure 14 – Frequency response of a typical inductive VT 420 kV (courtesy of Trench Switzerland AG)

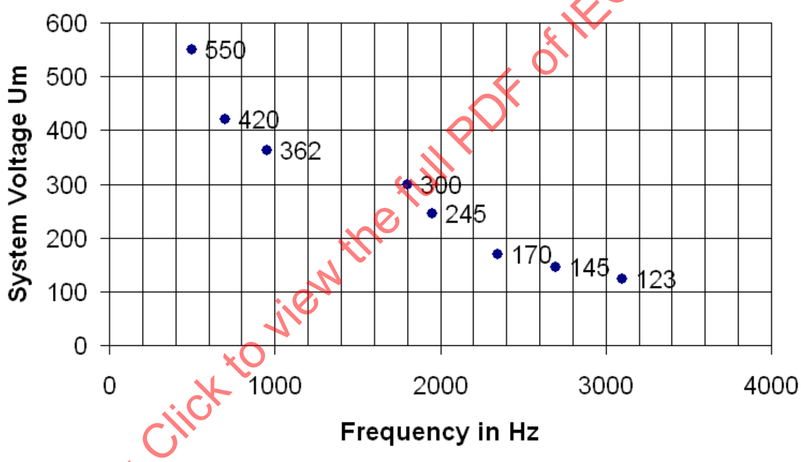


Figure 15 – First resonance peak depending on the system voltage U_m (courtesy of Trench Switzerland AG)

6.2.1.3.3 Impact on the measurements of PQ Parameters

For high voltages, instrument transformers behaviour deteriorates for frequencies above 500 Hz. Common inductive transformers do not give accurate information for frequencies above the 5th harmonic h).

Table 5 gives the impact on the measurements of PQ parameters of inductive voltage transformers for voltages over 52 kV and up to 1 100 kV.

Table 5 – Inductive voltage transformers for voltages over 52 kV and up to 1 100 kV: impact on the measurements of PQ parameters

Power Frequency	No impact
Magnitude of the supply voltage	No impact
Flicker	To be investigated
Supply voltage dips and swells	To be investigated
Supply voltage unbalance	To be investigated
Harmonics and interharmonics	HV voltage transformers are generally suitable only up to 500 Hz. If particular design and manufacturing cares are adopted, voltage transformers may cover the total harmonic range: this should be more probable for more recent transformers. Voltage transformers having rated primary voltage above 275 kV seem not suitable for harmonic measurements above 250 Hz; if particular care is adopted in design, errors should be acceptable up to at least 1 kHz.
Main signalling on the supply voltage	To be investigated
Rapid voltage changes	To be investigated
Voltage interruptions	To be investigated
Transient voltages	To be investigated

6.2.2 Inductive CTs

6.2.2.1 General

An inductive CT with a toroidal and ferromagnetic core is characterised by a low primary dispersion inductance and a low primary winding resistance. In normal service conditions, the primary current is lower than the saturation one and the CT operates on the linear part of magnetization curve. The frequency response of the inductive CTs is tied to transformer capacitances and inductances. Both capacitances between turns, windings and stray capacitances are present. According to tests performed, capacitances may have a significant effect at high frequency but impact is negligible up to the 40th harmonic or even higher. Beneath harmonics, primary current may contain a dc component; if present, such a component is not transferred to secondary winding but it will cause an offset of magnetic flux in transformer core. Such a condition could happen due to remnant flux present in transformer core after a switching operation. When the presence of a DC component or of core residual flux is possible, a CT having a core with air gap may be used. This attenuates DC component effect by increasing core reluctance and allows a linear behaviour. Since CT burden increases with frequency, corresponding power factor decreases as frequency increases and the transformer output will result in a harmonic voltage higher than with a pure resistive burden. Further increase of magnetization current will cause even higher errors. In order to measure harmonic currents in frequency range up to 10 kHz, common CTs used for protection and measurement purpose have accuracy better than 3 %. If CT burden is inductive, a small phase displacement will occur. Current clamps are available in order to obtain direct connection to an instrument.

If many secondary outputs are available, use of higher ratio one is recommended (lower magnetizing current); CT burden should be low, in order to decrease voltage and, by consequence, magnetizing current.

According to j), from CTs belonging to the 0,6 accuracy class defined in IEEE Std C57.13-1993 k) or better it is possible to obtain harmonic current amplitudes reasonably accurate but phase displacement may be affected by not acceptable errors: resonances between windings inductances and stray capacitances cause high phase angle errors near resonance frequencies, usually higher than harmonics order to be measured. Phase angle error is due to magnetizing current: the lower the magnetic core permeability, the higher the magnetizing current; the bigger the air gap in a current clamp, the higher the magnetizing current and harmonics in output current, also for a perfectly linear CT. Special CTs, operating with no flux and in absence of magnetizing currents, are very expensive and available to specialized laboratories only.

Burden power factor shall be as high as possible, in order to avoid impedance increase with frequency and the consequent magnetizing current enhancement. If possible, it is advisable to short-circuit CT output and measure output current with an accurate current clamp.

Frequency response for current transformers varies according to the accuracy class, type, manufacturer, turns ratio, core material and cross section and the secondary circuit load. Usually, the cut-off frequency of a current transformer ranges from 1 kHz to a few kHz and the phase response degrades as the cut-off frequency is approached d).

An example of simplified equivalent circuit for an inductive CT is shown in Figure 11.

6.2.2.2 Inductive CTs for voltages over 1 kV up to 52 kV

6.2.2.2.1 Architecture

Table 6 gives the main components of an inductive current transformer for voltages over 1 kV up to 52 kV.

Table 6 – Main components of an inductive current transformer for voltages over 1 kV up to 52 kV

Primary winding	The CTs may have or not the primary winding as an integral part of the structure. The CTs have the primary winding with one or more turns and one or more sections that, properly connected, vary the transformation ratio (i.e. primary winding with two sections: series connection Ip - parallel connection 2xIp) and the terminals are positioned at the top and/or sides of the device. If the primary winding is external to the structure it may be an insulated conductor (i.e. MV bushing or MV cable) or non-insulated conductor (i.e. busbar switchgear) and, in this case, the MV insulation can be assured by the CT or by the distance between the conductor and the CT.
Secondary winding	CTs have one or more secondary windings for measuring or protective application, each with its own magnetic core. The secondary winding may have one section or one or more intermediate tapping to obtain different transformation ratio.
Magnetic core	Magnetic core is generally toroidal type, and is evenly covered by the secondary winding. There are some applications where the magnetic core has different forms and the secondary winding is located only on a part of it. The magnetic core is generally made by FeSi grain oriented steel but different alloys (FeNi, amorphous materials …) are used for special applications.
MV insulation	For MV indoor and outdoor applications synthetic resins are mainly used which provide MV insulation and mechanical strength to the CT. CTs exist with other MV insulation types for specific applications (i.e. oil-paper insulated CTs for outdoor applications).

Figure 16 shows a cross-section view of a current transformer.

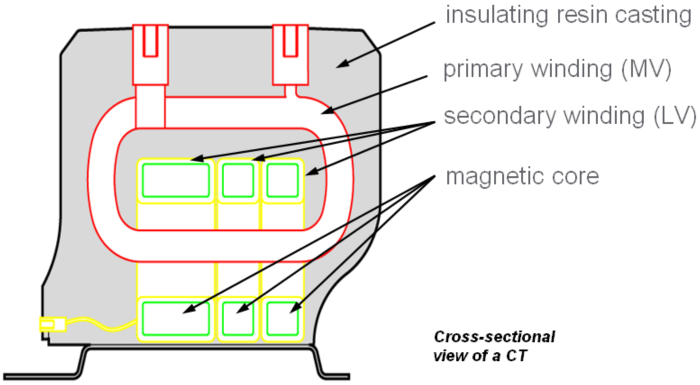


Figure 16 – Cross-section view of a current transformer (courtesy of Schneider Electric)

6.2.2.2.2 Frequency Response Behaviour

Many tests on inductive current transformers have been performed a)l)j)m)n)o) but information available is controversial, depending on equipment tested and test methods applied. According to g), coil type CTs accuracy is good (error less than 5 % for all frequencies up to 5 kHz both for ratio and phase angle), in other cases j) above the 40th harmonic measurement quality decays rapidly, also for very low burdens. In some cases, ratio error increases with frequency o), in other cases j)m) decreases. Phase displacement increases with frequency j).

6.2.2.2.3 Impact on the measurements of PQ Parameters

Table 7 gives the impact on the measurements of PQ parameters of inductive CTs for voltages over 1 kV up to 52 kV.

Table 7 – Inductive CTs for voltages over 1 kV up to 52 kV: impact on the measurements of PQ parameters

Power Frequency	Not applicable
Magnitude of the supply voltage	Not applicable
Flicker	Not applicable
Supply voltage dips and swells	Not applicable
Supply voltage unbalance	Not applicable
Harmonics and interharmonics (current)	According to IEC, LV current transformers are suitable for the harmonic frequency range of interest. All MV current transformers are suitable for measurements of amplitude in the harmonic range; in the case of phase angle measurements, the range is limited to about 1,5 kHz.
Main signalling on the supply voltage	Not applicable
Rapid voltage changes	Not applicable
Voltage interruptions	Not applicable
Transient currents (?)	For transient measurement, Standard metering class CTs are generally adequate for frequencies up to 2 kHz (phase error becoming significant beyond this limit). For higher frequencies, window type CTs with a high turns ratio should be used.

6.2.2.3 Inductive CTs for voltages over 52 kV up to 1 100 kV

6.2.2.3.1 General

In inductive CTs for voltages over 52 kV up to 1 100 kV, different behaviours were found not only among different manufacturing types of the same transformer but also among different samples of the same transformer f): this is probably due to small variations in resonance frequency which generate large errors in frequency response. Anyway, CT accuracy seems to be suitable for the measurement of the first 25 harmonics, since frequency response amplitude is nearly constant and phase displacement between input and output is negligible up to at least 2500 Hz. According to f) when transfer function does not show steep variations caused by resonances, it would be possible to characterise representative transformers; otherwise it should be necessary to characterise each transformer sample.

A high accuracy was found up to 5 kHz, additionally no phase shift between primary and secondary voltage has been observed visually up to 20 kHz.

6.2.2.3.2 Architecture

Table 8 gives the main components of an inductive current transformer for voltages above 52 kV up to 1 100 kV.

Table 8 – Main components of an inductive current transformer for voltages above 52 kV up to 1 100 kV

Primary winding	The CTs may have or not the primary winding as an integral part of the structure. The CTs have the primary winding with one or more turns and one or more sections that, properly connected, vary the transformation ratio (i.e. primary winding with two sections: series connection Ip - parallel connection 2xIp) and the terminals are positioned at the top and/or sides of the device
Secondary winding	CTs have one or more secondary windings for measuring or protective application, each with its own magnetic core. The secondary winding may have one section or one or more intermediate tapping to obtain different transformation ratio
Magnetic core	Magnetic core is generally square type, and is evenly covered by the secondary winding. There are some applications where the magnetic core has different forms and the secondary winding is located only on a part of it. The magnetic core is generally made by FeSi grain oriented steel but different alloys (FeNi, amorphous materials …) are used for special applications
HV insulation	For HV indoor and outdoor applications oil/paper or SF_6 are mainly used which provide HV insulation and mechanical strength to the CT. There are CTs with other HV insulation types for specific applications (i.e. oil-paper insulated CTs for outdoor applications)

A cross-section view of a freestanding current transformer may be found in b).

6.2.2.3.3 Frequency response behaviour

In Figure 17 and 18, the results obtained for a CT 245 kV, 2400 /1 A, 30 VA, accuracy class 0,5 are shown; measurements were taken between 45 Hz and 20 kHz. In the figures is represented the output obtained by supplying the CT with the superposition of a 400 Hz, 107 A signal and a 50th harmonic component (13 A at 20 kHz).

6.2.2.3.4 Impact on the measurements of PQ parameters

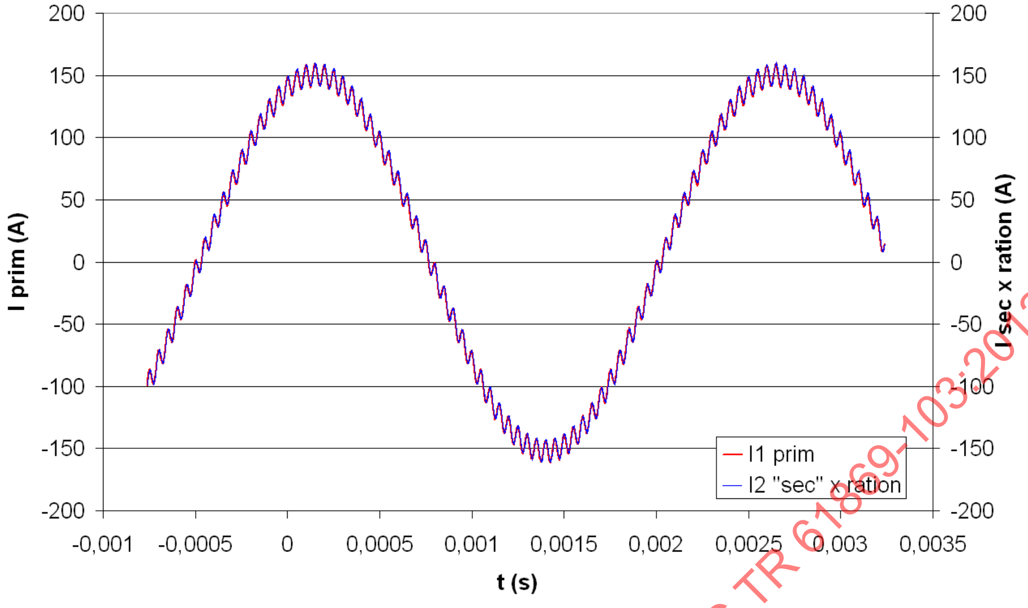


Figure 17 – Results obtained for a 245 kV CT (courtesy of Trench Switzerland AG)

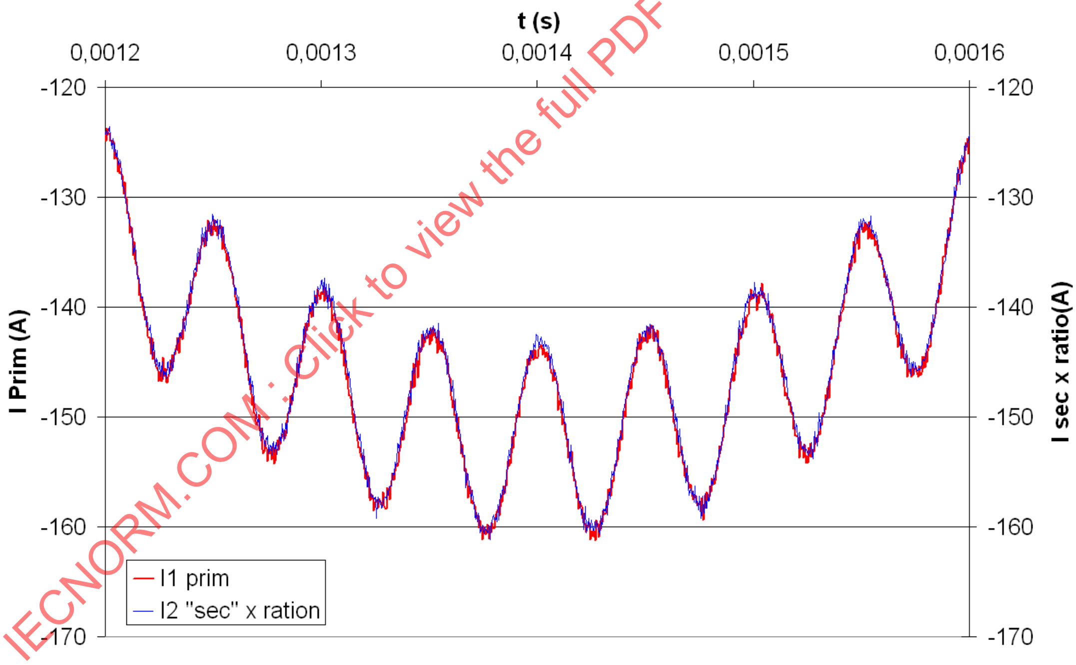


Figure 18 – Results obtained for a 245 kV CT: detail (courtesy of Trench Switzerland AG)

Table 9 gives the impact on the measurements of PQ parameters of inductive CTs for voltages over 52 kV up to 1 100 kV.

Table 9 – Inductive CTs for voltages over 52 kV up to 1 100 kV: impact on the measurements of PQ parameters

Power Frequency	Not applicable
Magnitude of the supply voltage	Not applicable
Flicker	Not applicable
Supply voltage dips and swells	Not applicable
Supply voltage unbalance	Not applicable
Harmonics and interharmonics	To be investigated
Main signalling on the supply voltage	Not applicable
Rapid voltage changes	Not applicable
Voltage interruptions	Not applicable
Transient voltages	Not applicable

6.3 Capacitive voltage transformers (CVTs)

6.3.1 Standard application

6.3.1.1 Architecture

The architecture for a Capacitive Voltage Transformer is represented in Figure 19.

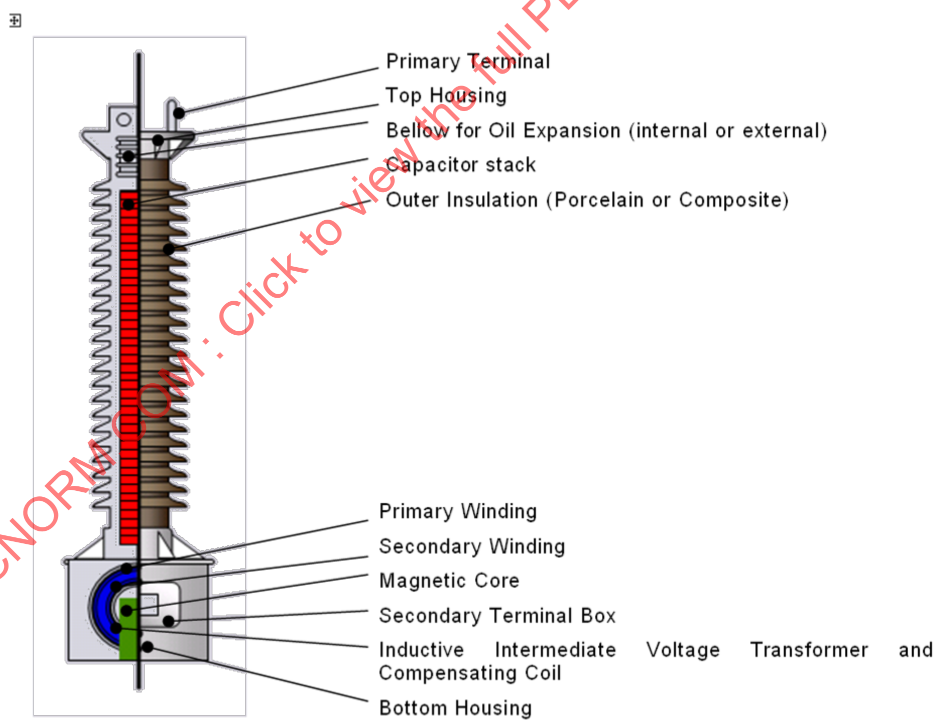


Figure 19 – Cross-section view of a capacitive voltage transformer (Courtesy of Trench Switzerland AG)

The CVT consists of a capacitive voltage divider (CVD) and an intermediate electromagnetic unit (EMU).

The CVD-active part is made of stacked flat capacitor elements which are connected in series. The dielectric material of the elements can be paper only or paper with film or film only. The CVD is impregnated and filled with mineral, synthetic oil or with SF_6 gas. Each CVD unit is mounted in a hermetically sealed insulator (porcelain or composite). Volume changes of the insulating liquid due to temperature variations are compensated by a stainless steel bellows. For gas insulated units a gas monitoring system is necessary. The CVD is mounted onto the base box and connected through the intermediate bushing with the EMU in the base box. The base box is usually hermetically sealed from the outside and provided with an air cushion.

The EMU consist of a compensation coil, transformer unit and a damping system to avoid mainly ferroresonance and overvoltages.

The transformer unit has one or more secondary windings for measurement or protection application.

A suitable representation of the electrical scheme of a capacitive voltage transformer at power frequency is shown, along with its burden Z, in Figure 20.

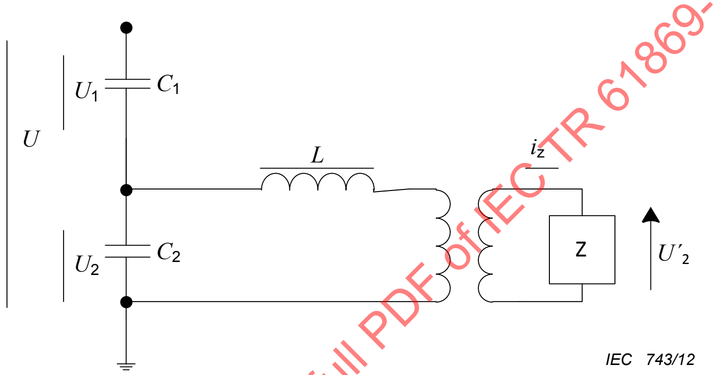


Figure 20 – CVT: Equivalent circuit at power frequency

The CVT is mainly based on the following elements:

– A capacitor divider (C_1 and C_2);
– A voltage transformer;
– A compensating reactor L.

If the capacitor divider only is considered, the following ratio is obtained between total voltage U and voltage drop on capacitance C_2.

$$\frac{U}{U_2} = \frac{C_1 + C_2}{C_1}$$

The ratio is constant provided that no current is drained out of C_2.

If the compensating reactor would not be present, the simplified Thevenin equivalent circuit for the CVT shown in Figure 21 could be used.

The voltage U'_2 differs in this case from U_2, due to the voltage drop on the equivalent capacitance C_1+C_2.

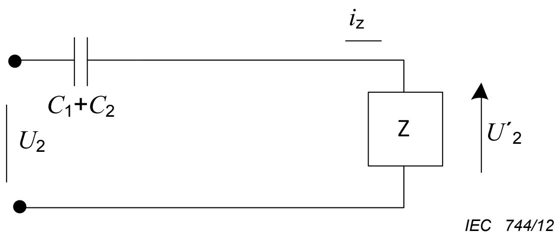


Figure 21 – Simplified CVT Thevenin equivalent circuit at power frequency without compensating reactor

In order to obtain a suitable voltage U'_2 and a constant ratio between U and U'_2 when a burden is present, it is necessary to add a compensating reactor L, as shown in Figure 22.

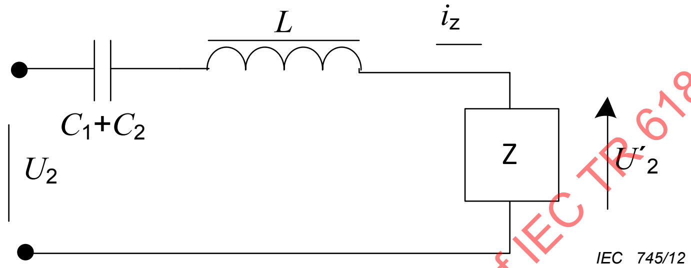


Figure 22 – Simplified CVT Thevenin equivalent circuit at power frequency

The error is therefore compensated by inserting an impedance in order to obtain, at power frequency:

$$\omega L = \frac{1}{\omega (C_1 + C_2)}$$

It is now possible to give the complete equivalent circuit for the CVT shown in Figure 23, where:

U_2	secondary voltage which can be measured in no load conditions across C_2.
C_1+C_2	voltage divider capacitance
L	compensating inductance
L_1 and L_2	leakage inductances of the voltage transformer
R_1 and R_2	resistances of the windings of the voltage transformer
R_c	resistance keeping into account the losses of the capacitors
R_{1c}	resistance keeping into account the losses of the compensating reactance (copper and iron)
L_0	magnetization inductance of the transformer
R_0	resistance keeping into account the iron losses of the transformer
U'_2	voltage transformer secondary voltage
Z	burden

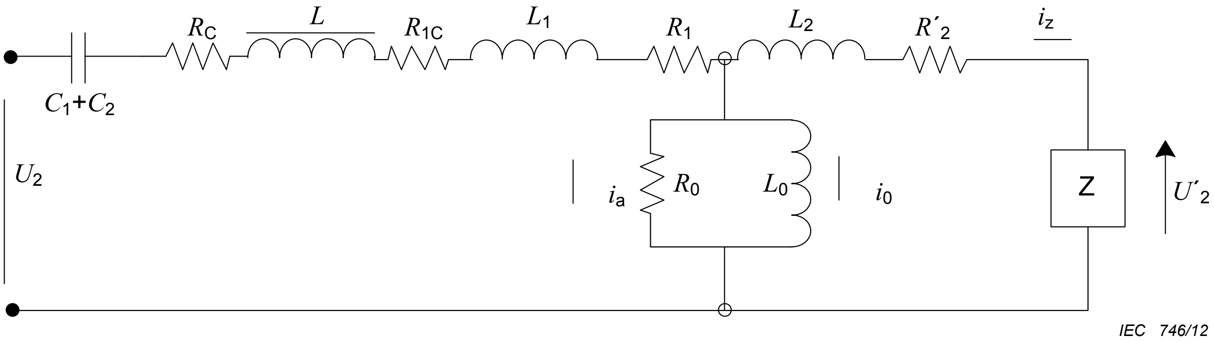


Figure 23 – Complete CVT Thevenin equivalent circuit at power frequency

The reactances are tuned in order to obtain, at power frequency, a resonant circuit,

$$\omega(L + L_1 + L_2) = \frac{1}{\omega(C_1 + C_2)}$$

For a given burden, error is function only of the sum of the resistances. At frequencies different than the power one, the inductive reactance does not compensate perfectly the capacitive one and the error increases.

The equivalent circuit shown is therefore applicable only at power frequency; an example suitable of equivalent circuit applicable when frequencies different from the power one are involved is shown in kk).

6.3.1.2 Frequency response behaviour

The CVT components are tuned in such a way that the capacitive voltage divider and the electromagnetic unit are in resonance at rated frequency. Due to this fact, a small shift from the rated frequency causes big errors both in amplitude and in phase. The linear portion of frequency response is limited to ±10 Hz from the rated frequency g) and the frequency response becomes unacceptable at above the second harmonic order:

CVTs are affected by high errors at frequencies of some hundreds of Hertz; in the frequency range of interest, errors between 80 % and 1200 % of the measurand have been found, with errors depending on resonance peak frequency which is usually located at some hundreds of Hz and may decrease up to 200 Hz e). Some authors e)p) suggest that CVTs may be characterised; attention must be paid since behaviour is not homogeneous within the same population and also characterisation method must be taken into account: Tests performed on the same samples at low and high excitation voltage show a strongly non-linear response, sensitive to magnetisation curve specific of the tested sample.

As excitation voltage increases, useful bandwidth is considerably reduced, due to input impedance of ferroresonance suppression circuit. The load due to the circuit increases a lot as excitation voltage increases, mainly for higher frequencies. Output voltage is therefore considerably attenuated.

6.3.1.3 Impact on the measurements of PQ parameters

Table 10 gives the impact on the measurements of PQ parameters of capacitive voltage transformers.

Table 10 – Capacitive voltage transformers: impact on the measurements of PQ parameters

Power Frequency	No impact between 80 % and 120 % of the nominal voltage.
Magnitude of the supply voltage	No impact between 80 % and 120 % of the nominal voltage.
Flicker	To be investigated
Supply voltage dips and swells	To be investigated
Supply voltage unbalance	To be investigated
Harmonics and interharmonics	Not suitable above the 2nd order of harmonics
Rapid voltage changes	To be investigated
Voltage interruptions	To be investigated
Transient voltages	To be investigated
Main signalling on the supply voltage	To be investigated

6.3.2 Special measurement techniques

6.3.2.1 General

As mentioned before, output of CVTs is not suitable for PQ measurement in the frequency range of interest. If compared to the conventional output, other quantities seem to be more interesting and some measurement methods were developed.

The more immediate method in order to allow harmonics measurement is inductive part disconnection, in order to use the CVT as a pure divider for harmonic measurements on site, measuring the signal at inductive part input using an instrument having a high input impedance and, if necessary, by the addition of a second divider in order to obtain a suitable output signal. This way, it is possible to obtain a frequency response linear up to 100 kHz or even 150 kHz but it is not possible to use the CVT for its primary purpose in the meanwhile g), if a suitable terminal is not made available, as described in 6.3.2.2.

Another interesting quantity seems to be the transconductance ratio between capacitive current derived towards ground by the divider and input voltage: transconductance ratio frequency response seems almost linear and it is easily predictable for frequency band of interest, from the power one up to about 2,5 kHz q). A development of this principle is described in 6.3.2.3.

6.3.2.2 Capacitive voltage transformer with harmonic measurement terminal

6.3.2.2.1 Principle

In order to measure the voltage across LV capacitance and to allow at the same time CVT usage for its primary purpose, suitable terminals can be made available, obtaining the principle scheme shown in Figure 24, where the measurement of harmonics is carried on across capacitance C3 (see also p) for reference). This construction allows an accurate measurement of the amplitude of the output voltage, up to 2 000 Hz. There are in any case heavy influences onto the phase angle over the whole frequency range with this type of measuring system.

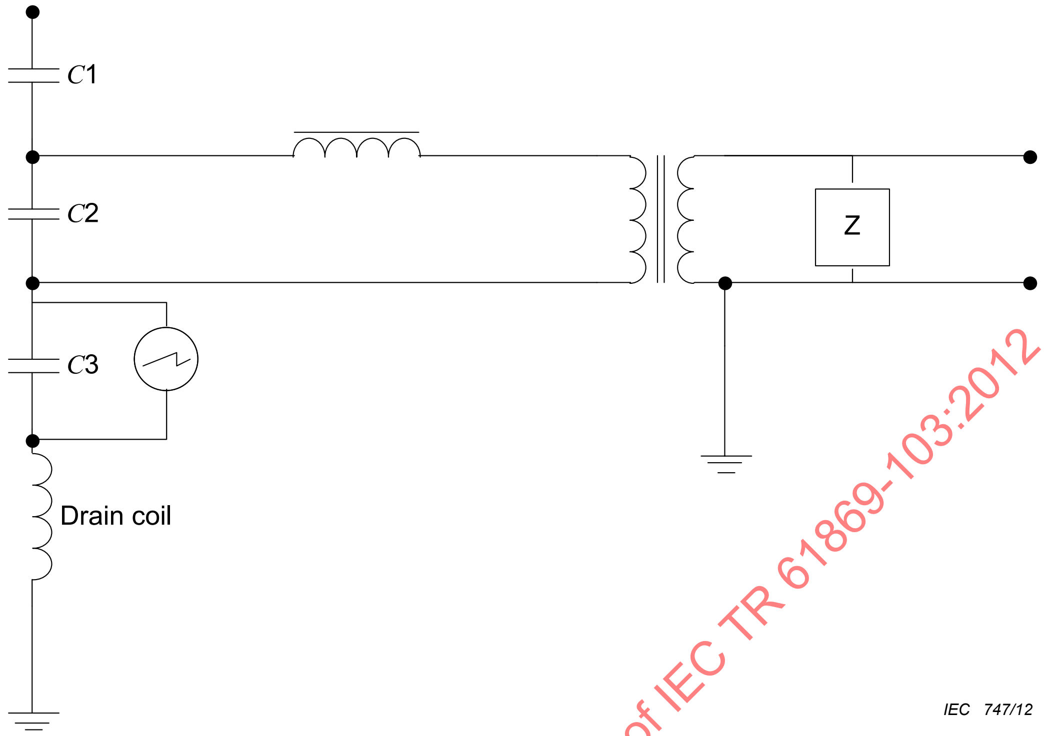


Figure 24 – Measurements performed by means of a CVT with harmonic measurement terminal

6.3.2.2.2 Frequency response behaviour

Figure 25 gives a comparison of different measurements with and without harmonic monitoring terminal.

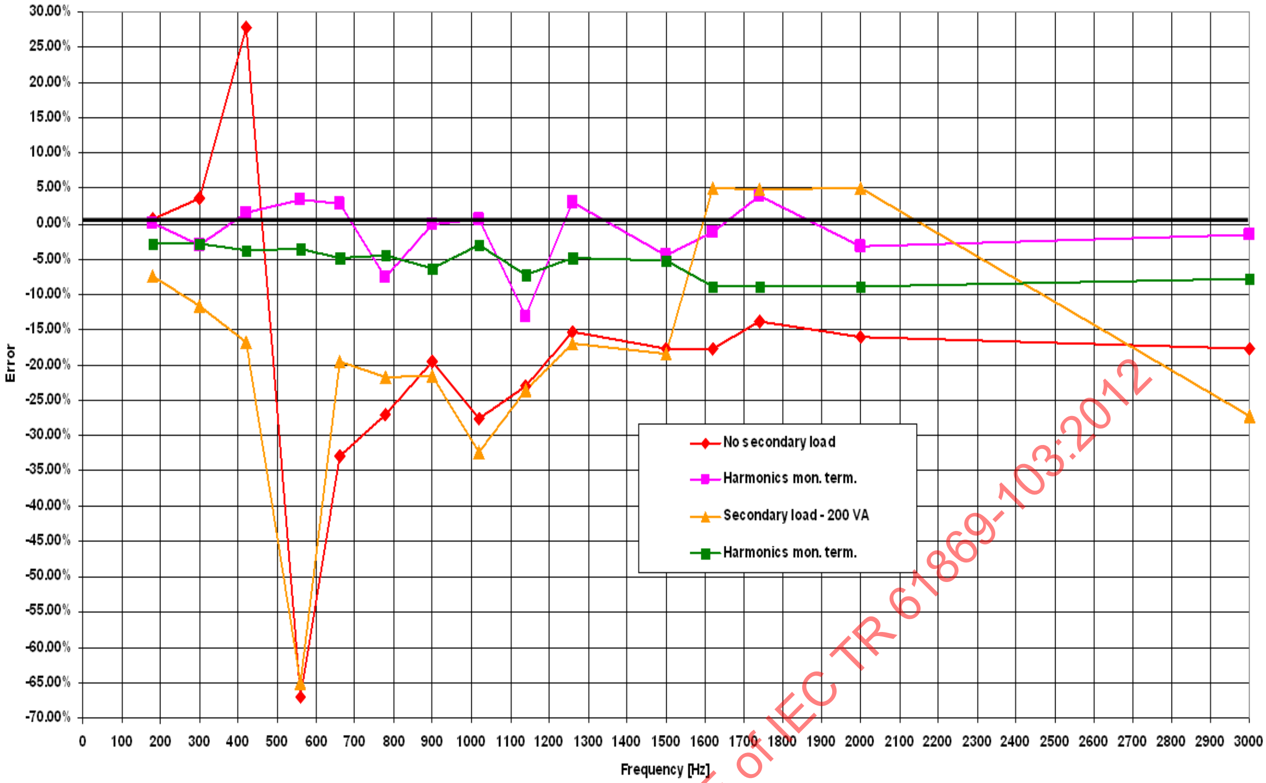


Figure 25 – Comparison of different measurements with and without harmonic monitoring terminal (Courtesy of Trench Switzerland AG, based on p))

6.3.2.2.3 Impact on the measurements of PQ parameters:

Table 11 gives the impact on the measurements of PQ parameters of a capacitive voltage transformer with harmonic measurement terminal.

Table 11 – Capacitive voltage transformer with harmonic measurement terminal: impact on the measurements of PQ parameters

Power Frequency	No Impact on the amplitude but impact on the phase angle
Magnitude of the supply voltage	No Impact on the amplitude but impact on the phase angle
Flicker	No Impact on the amplitude but impact on the phase angle
Supply voltage dips and swells	No Impact on the amplitude but impact on the phase angle
Supply voltage unbalance	No Impact on the amplitude but impact on the phase angle
Harmonics and interharmonics	No Impact on the amplitude but impact on the phase angle
Main signalling on the supply voltage	No Impact on the amplitude but impact on the phase angle
Rapid voltage changes	No Impact on the amplitude but impact on the phase angle
Voltage interruptions	No Impact on the amplitude but impact on the phase angle
Transient voltages	No Impact on the amplitude but impact on the phase angle

6.3.2.3 Capacitive voltage transformer with additional equipment for PQ measurement

6.3.2.3.1 Principle

Equipment able to make CVTs, both new and in-service since long time, suitable for power quality measurements has been recently made available as a patented application. This equipment is based on simultaneous measurements of current, one immediately after LV capacitance and the other one on the earth connection. Further information about the measurement method is given in r) ÷ t).

6.3.2.3.2 Frequency response behaviour

According to data sheet declared by the Manufacturer, the useful frequency range starts from 5 Hz up to approximately 13 kHz (DC is not measurable). Within this range, the phase displacement is less than 1,5° up to 3 kHz and less than 3° at 5 kHz. Ratio error is minor than 2 % at 5 kHz, no information is available for lower frequencies.

6.3.2.3.3 Impact on the measurements of PQ parameters

Table 12 gives the impact on the measurements of PQ parameters of a capacitive voltage transformer with additional equipment for PQ measurement.

Table 12 – Capacitive voltage transformer with additional equipment for PQ measurement: impact on the measurements of PQ parameters

Power Frequency	No impact
Magnitude of the supply voltage	No impact
Flicker	To be investigated
Supply voltage dips and swells	To be investigated
Supply voltage unbalance	To be investigated
Harmonics and interharmonics	See data declared by the Manufacturer for reference
Main signalling on the supply voltage	To be investigated
Rapid voltage changes	To be investigated
Voltage interruptions	To be investigated
Transient voltages	To be investigated

6.4 Electronic instrument transformers

6.4.1 General

Electronic instrument transformers behaviour for power quality measurements is already considered in IEC Standards.

In Subclause 6.4.2, requirements given by IEC 60044-8:2002, Annex D, about accuracy for harmonics measurements are quoted for reference.

6.4.2 Common accuracy classes

Due to the use of specific devices (non-linear loads, FACTS, railway) harmonics can be generated on the network. The amount of harmonics depends on the network and the voltage level. Harmonics are of interest for metering, quality and protection purposes. Accuracy classes to each specific need are given. The accuracy requirements on electronic transformers with a digital output are the same as those of the transformers with an analogue output. The frequency response and accuracy requirements on harmonics are described in 60044-8:2002, Annex D.

6.4.2.1 Power metering

Table 13 gives accuracy classes for power metering.

Table 13 – Accuracy classes for power metering

Accuracy class	Percentage (ratio) error (+/–) at harmonics shown below				Phase displacement (+/–) at harmonics shown below							
					Degrees				Centiradians			
	2^{nd} to 4^{th} harmonic	5^{th} and 6^{th} harmonic	7^{th} to 9^{th} harmonic	10^{th} to 13^{th} harmonic	2^{nd} to 4^{th}	5^{th} and 6^{th}	7^{th} to 9^{th}	10^{th} to 13^{th}	2^{nd} to 4^{th}	5^{th} and 6^{th}	7^{th} to 9^{th}	10^{th} to 13^{th}
0,1	1 %	2 %	4 %	8 %	1	2	4	8	1,8	3,5	7	14
0,2	2 %	4 %	8 %	16 %	2	4	8	16	3,5	7	14	28
0,5	5 %	10 %	20 %	20 %	5	10	20	20	9	18	35	35
1	10 %	20 %	20 %	20 %	10	20	20	20	18	35	35	35

With these requirements, the contribution of harmonics measurement errors would add roughly 15 %, in the worst case, on the theoretical error of the corresponding power metering class accuracy (i.e. for a class 0,2 CT with a class 0,2 VT, the accuracy of corresponding power metering class is 0,4 for the energy transported by the 50 Hz wave. Since energy transported by harmonics is also measured, the total error on energy transported by the fundamental and its harmonics would be 0,4 % + 0,15 × 0,40 % = 0,46 %). Such a small error can be accepted.

6.4.2.2 Quality metering

According to EN 50160:2007 and IEC 61000-4-7:2002, for such purposes, harmonics up to the 40^{th} order (in some cases even to the 50^{th} order) are measured. IEC 61000-4-7:2002 specifies that the relative error (related to the measured value) shall not exceed 5 %. If measurements of phase angles have to be performed additionally, the respective error shall not exceed 5°.

Table 14 gives accuracy classes for power quality metering.

Table 14 – Accuracy classes for power quality metering

Accuracy class	Percentage (ratio) error (+/–) at harmonics shown below		Phase error (+/–) at harmonics shown below			
			Degrees		Centiradians	
Special quality metering	1^{st} to 2^{nd} harmonic	3^{rd} to 50^{th} harmonic	1^{st} to 2^{nd} harmonic	3^{rd} to 50 harmonic	1^{st} to 2^{nd} harmonic	3^{rd} to 50^{th} harmonic
	1 %	5 %	1	5	1,8	9

6.4.3 Electronic VTs

6.4.3.1 Optical VTs

6.4.3.1.1 Architecture

6.4.3.1.1.1 General

Optical voltage transformers are based on the Pockels Effect. The signal output from the transformer is a modulated light coming from an optoelectronic source like a LED or a Laser, and passing through a crystal which acts as a modulator of polarisation mathematically linked to the applied voltage, or electrical field.

The transmission medium is composed of one or several optical fibres, assuring a natural insulation from the High Voltage. There is no need of electronic equipment on the primary side and therefore all the electronic equipment is located at ground level.

6.4.3.1.1.2 Pockels effect transformers

Optical voltage transformers operation relies on two fundamental physical properties:

- Pockels Effect (first order electro-optical effect), which is a characteristic effect existing in some crystals
- The consequent definition of an electric potential difference between the two potentials applied on the input and the output faces of the crystal

6.4.3.1.1.3 Basics on Pockels Effect

The Pockels Effect is an electro-optical effect of the first order, describing the influence of the electric field on a transparent crystal.

Crystals typically used for Pockels cells are:

- $LiNbO_3$ (Lithium Niobate)
- KDP (Potassium Dihydrogen Phosphate)
- BGO (Germanate Bismuth Oxide)
- BSO (Silicate Bismuth oxide).

Atom clusters in the crystal are, or become, small dipoles, orienting themselves according to the electric field lines. Non-homogeneity of the density may then occur and it induces a linear birefringence, which alters the polarisation state of a monochromatic light beam.

Different sensitivities can be obtained by using different crystal types, their crystalline orientations with respect to the light polarisation and the direction of application of the electric field.

For instance, for a class 43m cubic crystal, having length dL, used in longitudinal configuration (electric field E collinear with the light beam), it is possible to obtain a phase shift value between ordinary and extraordinary ray waves (in radians):

$$d\Gamma = \frac{2\pi}{\lambda} \times n_0^3 \times r_{41} \times (\vec{E} \times d\vec{L})$$

Where

r_{41} is an electro-optical coefficient of the crystal

n_0 is the ordinary refractive index of the crystal.

6.4.3.1.1.4 Potential Difference

By integrating the electric field along the optical path A to B between the two relevant faces of the crystal it is possible to obtain the following relationship for the total phase shift:

$$\Gamma = \frac{2\pi}{\lambda} \times n_0^3 \times r_{41} \times \int_A^B (\vec{E} \times d\vec{L}) = K \times U_{AB}$$

where U_{AB} is the electric potential difference (or, in other words, the voltage) between the input and the output faces of the crystal.

In that case only, the voltage measured becomes independent of other nearby conductors at any voltage, and of the geometry variations of optical elements.

Figure 26 shows a basic design for a bulk crystal producing a Pockels Effect.

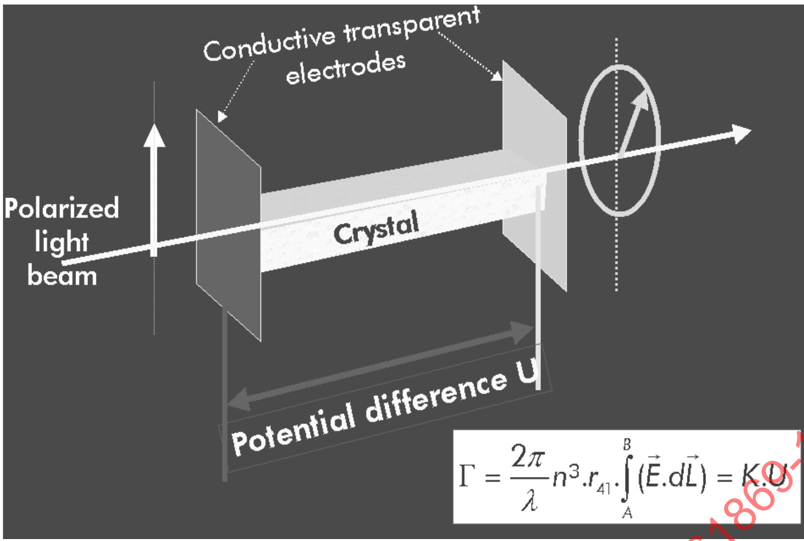


Figure 26 – Basic design for a bulk crystal producing a Pockels Effect (courtesy of Alstom Grid)

Due to economic reasons, the length of the crystal is limited: therefore the acceptable potential difference along a single crystal is also limited, about to 30 kV. Higher voltages need to be partitioned. In order to obtain the partitioning of the voltage, the following devices could be used:

– Conventional Capacitive Dividers (not for DC-measurements)
– Resistive Dividers (only for DC-measurements)
– RC-Dividers (for AC- and DC-measurements)
– Repartition along several sensors without physical dividers, associated with special signal processing

In Figure 27 and 28, possible solutions are shown in order to apply the voltage on the active crystal.

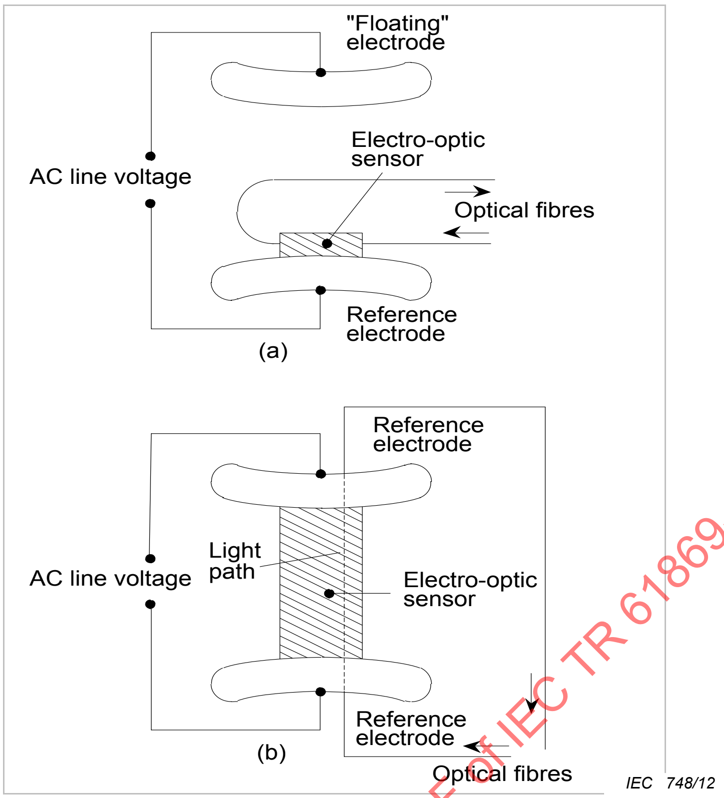


Figure 27 – Various solutions to apply voltage on the active crystal

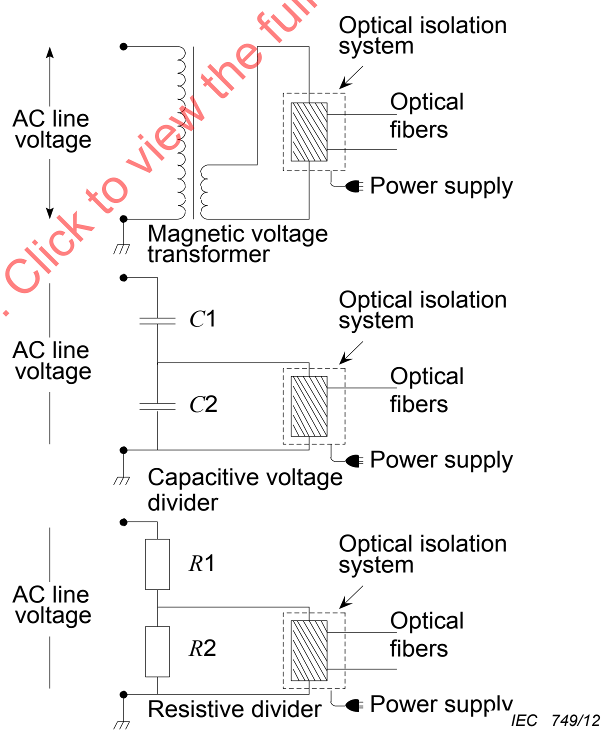


Figure 28 – Various methods to divide the full voltage before applying on the crystal

6.4.3.1.1.5 Bulk Pockels cell and polarimetric detection

The modulation of the polarisation due to the Pockels effect can be managed as a light intensity modulation by adding a polarimetric system made of two polarisers and a phase quarter wave plate.

It has been demonstrated that the light intensity $P_S(t)$, initially constant, leaves the Pockels crystal modulated by the applied voltage, following the mathematical rule:

$$P_s(t) = \frac{1}{2} P_o \times [1 + \sin(K \times U_{AB}(t))]$$

Where

K is the sensitivity constant of the Pockels Effect

U_{AB} is the voltage applied between the faces of the crystal.

The wave shape of the output light intensity is exactly the same that can be obtained with a polarimetric current sensor.

Basic set-up is shown in Figure 29.

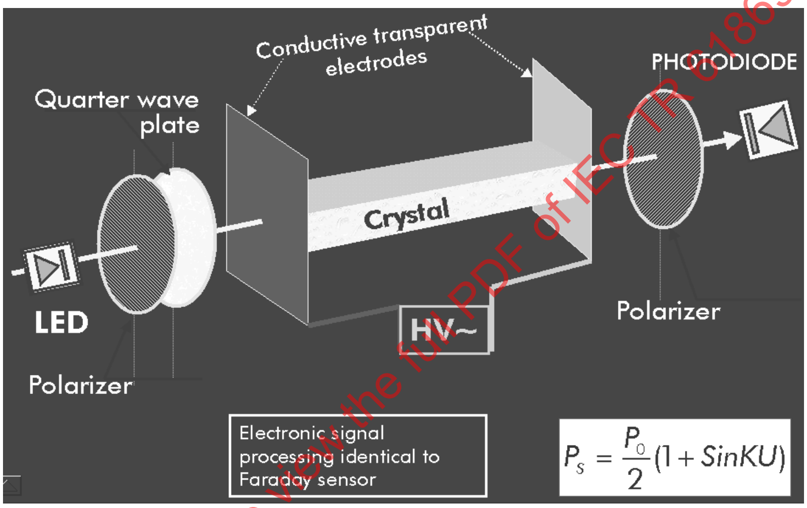


Figure 29 – Basic design for a Pockels sensor (courtesy of Alstom Grid)

Figure 30 shows an industrial bulk Pockels cell.

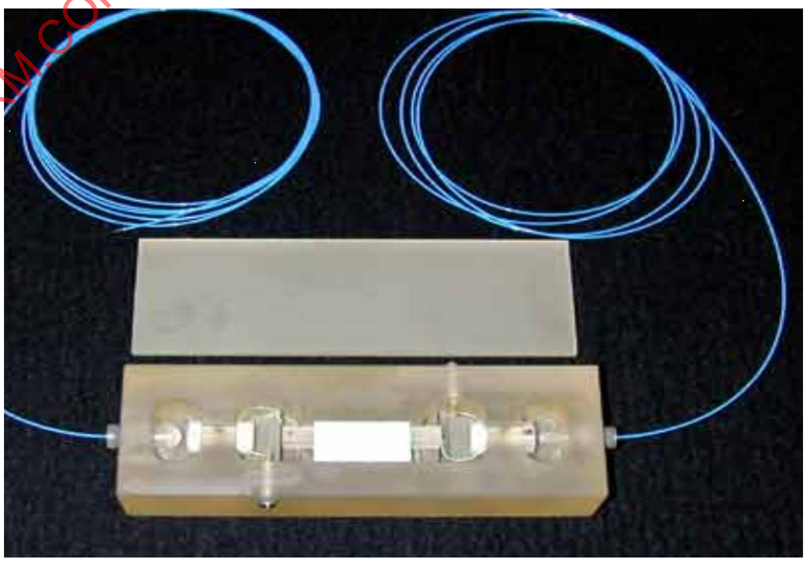


Figure 30 – Industrial bulk Pockels Cell (courtesy of Alstom Grid)

6.4.3.1.2 Frequency Response Behaviour

Figure 31 shows the frequency response calculation for an optical VT.

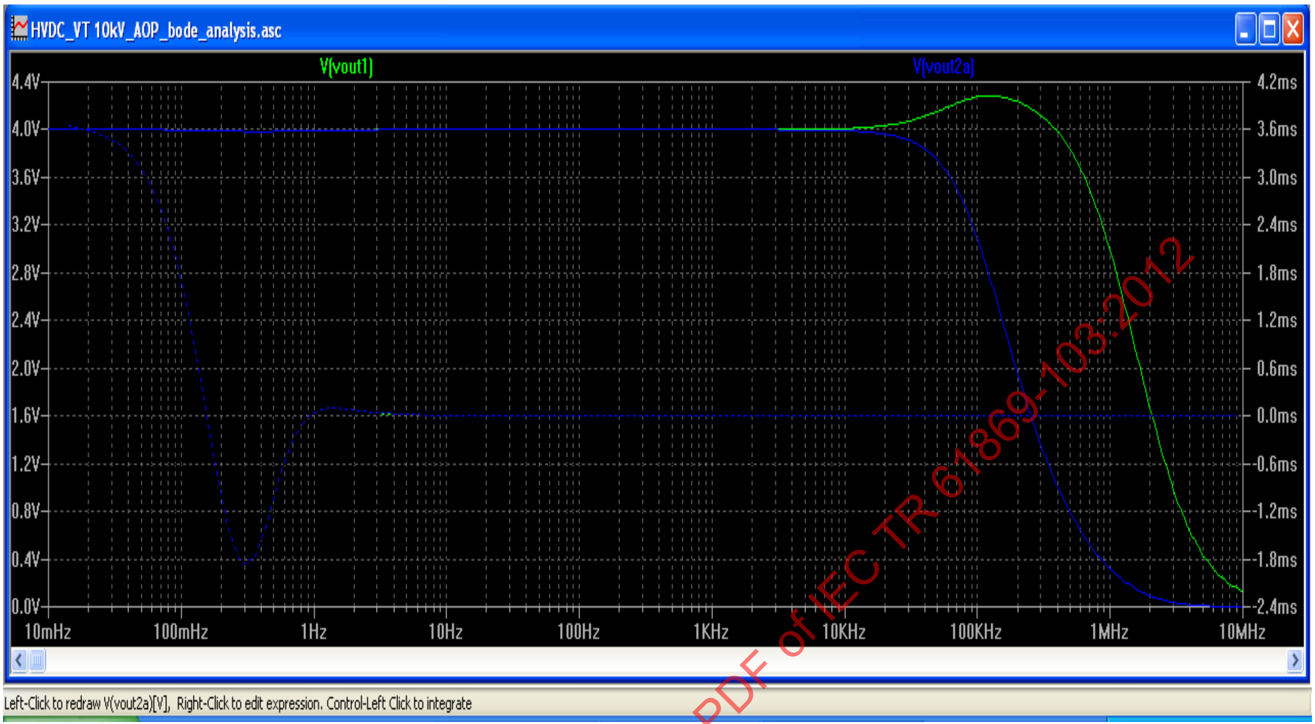


Figure 31 – Frequency response calculation for an optical VT (courtesy of Alstom Grid)

6.4.3.1.3 Impact on the measurements of PQ parameters

Table 15 gives the impact on the measurements of PQ parameters of an optical voltage transformer.

Table 15 – Optical voltage transformer: impact on the measurements of PQ parameters

Power Frequency	Not yet investigated. No effect is expected
Magnitude of the supply voltage	Not yet investigated. No effect is expected
Flicker	Not yet investigated. No effect is expected
Supply voltage dips and swells	Not yet investigated. No effect is expected
Supply voltage unbalance	Not yet investigated. No effect is expected
Harmonics and interharmonics	Not yet investigated. No effect is expected
Main signalling on the supply voltage	Not yet investigated. No effect is expected
Rapid voltage changes	Not yet investigated. No effect is expected
Voltage interruptions	Not yet investigated. No effect is expected
Transient voltages	Not yet investigated. No effect is expected

6.4.3.2 Voltage dividers

6.4.3.2.1 Resistive voltage dividers

6.4.3.2.1.1 Architecture

Figure 32 gives a cross-section view and electrical scheme of a resistive voltage divider.

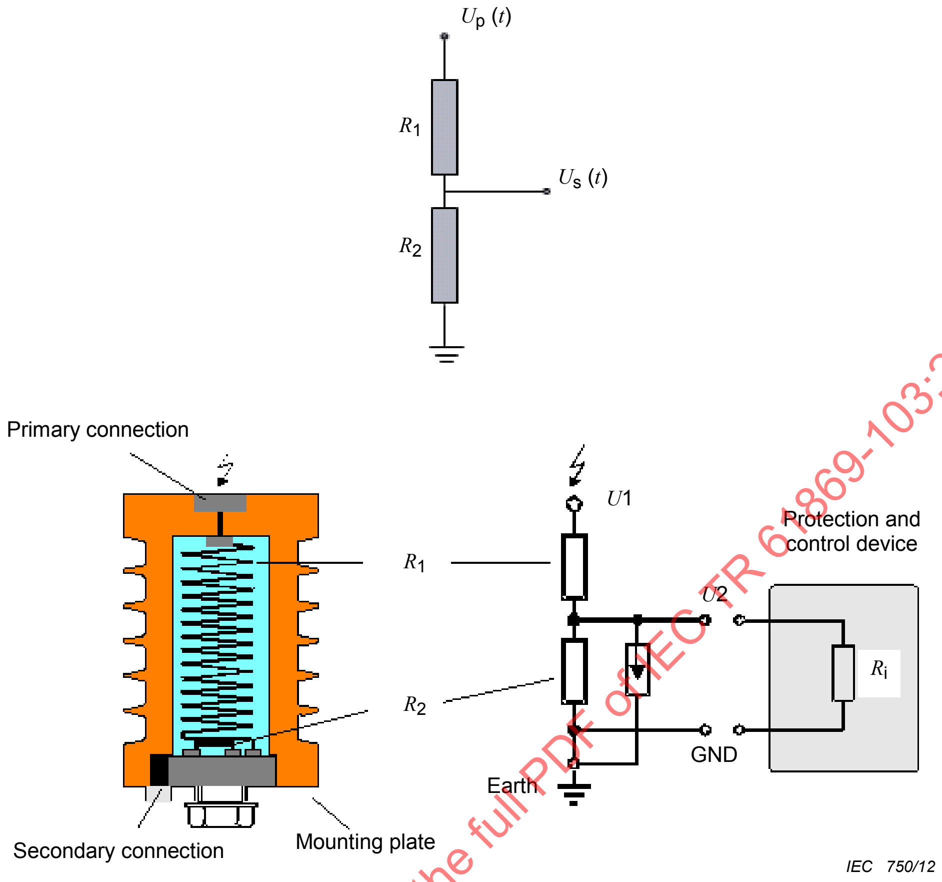


Figure 32 – Cross-section view and electrical scheme of a resistive voltage divider (from v))

Resistive voltage dividers are used in electrical systems for measurements at all voltage levels. The voltage on the secondary side $U_s(t)$ is proportional to the voltage of the primary side $U_p(t)$. The divider ratio is given by the ratio of the primary resistor R_1 and the secondary resistor R_2. The resistors are embedded into an insulating material. This can be resin, oil or gas.

Between the resistors and the housing or the surroundings, there are stray capacitances which limit the bandwidth of this kind of dividers; moreover resistors are never pure, since they always have their own capacitance and inductance: low inductance resistors should therefore be used.

6.4.3.2.1.2 Frequency response behaviour

The frequency response is limited, due to the stray capacitances and to the length of the cable connected to the measurement unit. Resistive voltage dividers have a very good behaviour for the measurements of DC, as shown in Figures 33 and 34.

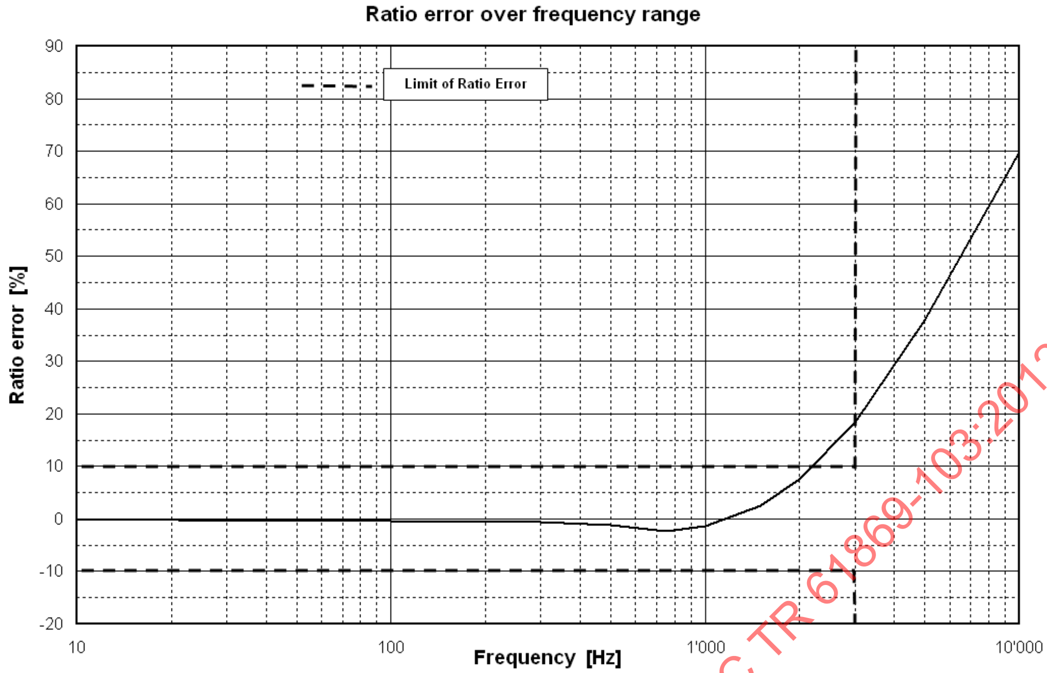


Figure 33 – Ratio error of an MV resistive divider (courtesy of Trench Switzerland AG)

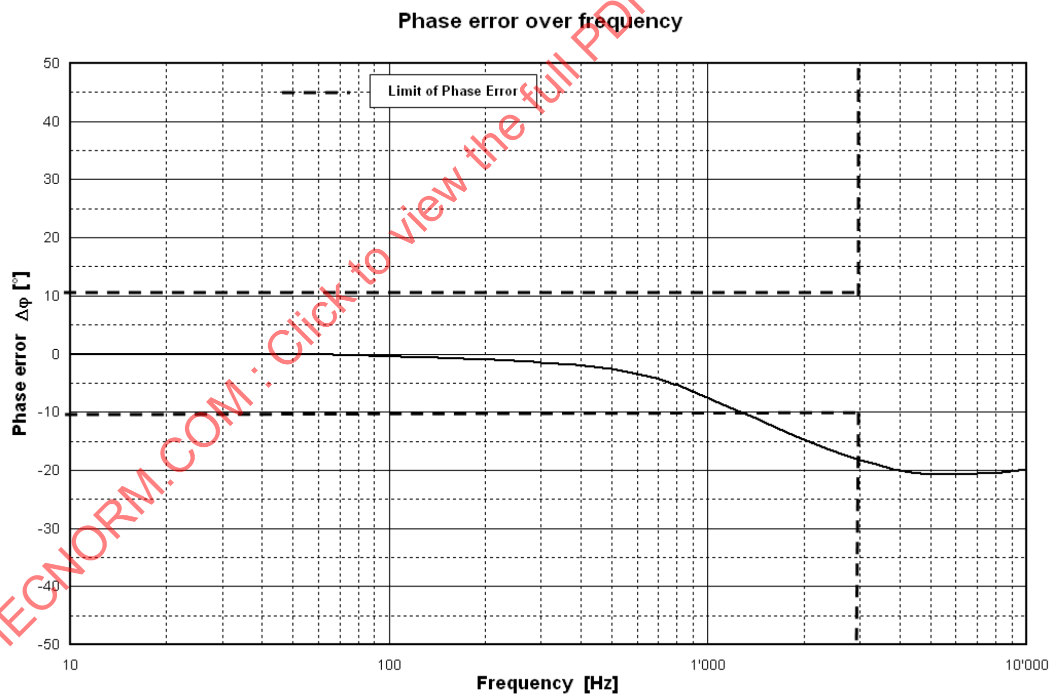


Figure 34 – Phase error of MV resistive divider (courtesy of Trench Switzerland AG)

6.4.3.2.1.3 Impact on the measurements of PQ parameters

Table 16 gives the impact on the measurements of PQ parameters of an MV resistive divider.

Table 16 – MV resistive divider: impact on the measurements of PQ parameters

Power Frequency	No Impact
Magnitude of the supply voltage	No Impact
Flicker	Impact on amplitude and phase angle below 800 Hz
Supply voltage dips and swells	No Impact
Supply voltage unbalance	No Impact
Harmonics and interharmonics	Impact on amplitude and phase angle below 800 Hz
Main signalling on the supply voltage	No Impact
Rapid voltage changes	No Impact
Voltage interruptions	No Impact
Transient voltages	Impact on amplitude and phase angle below 800 Hz

6.4.3.2.2 Capacitive voltage dividers

Figure 35 shows the electrical scheme of a capacitive voltage divider.

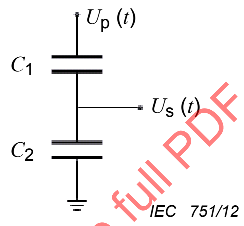


Figure 35 – Electrical scheme of a capacitive voltage divider

6.4.3.2.2.1 Architecture

Capacitive Voltage Dividers (CVDs) are used for measurements on all system voltage levels. The voltage on the secondary side $U_s(t)$ is proportional to the voltage of the primary side $U_p(t)$. The ratio of the divider is given by the ratio of the primary capacitor C_1 and the secondary capacitor C_2 as follows:

$$\frac{U_p(t)}{U_s(t)} = \frac{C_1 + C_2}{C_1}$$

The capacitor itself is manufactured like capacitor units for CVT or in a similar way. The active part is made of stacked flat capacitor elements which are connected in series. The dielectric material of the elements can be paper only or paper with film or film only. The CVD is impregnated and filled with mineral, synthetic oil or with SF_6 gas. Each CVD unit is mounted in a hermetically sealed insulator (porcelain or composite). Volume changes of the insulating liquid due to temperature variations are compensated by a stainless steel bellows. For gas insulated units a gas monitoring system is necessary. The resistors are embedded into an insulating material. This can be resin, oil or gas.

6.4.3.2.2.2 Frequency response behaviour

The frequency response of the C-Divider (capacitor voltage divider) makes it able to accurately monitor voltage transients up to 1 MHz or higher. At lower frequencies, starting from approximately 20 Hz, the C-divider becomes inaccurate, mainly the phase angle showing an error of more than 25 % below 100 Hz. The behaviour depends on voltage level and nominal capacitance of the divider.

6.4.3.2.2.3 Impact on the measurements of PQ parameters

Table 17 gives the impact on the measurements of PQ parameters of capacitive voltage dividers.

Table 17 – Capacitive voltage dividers: impact on the measurements of PQ parameters

Power Frequency	No Impact on the amplitude but impact on the phase angle
Magnitude of the supply voltage	No Impact on the amplitude but impact on the phase angle
Flicker	No Impact
Supply voltage dips and swells	No Impact
Supply voltage unbalance	No Impact on the amplitude but impact on the phase angle
Harmonics and interharmonics	No Impact on the amplitude but impact on the phase angle
Main signalling on the supply voltage	No Impact on the amplitude but impact on the phase angle
Rapid voltage changes	No Impact on the amplitude but impact on the phase angle
Voltage interruptions	No Impact on the amplitude but impact on the phase angle
Transient voltages	No Impact

6.4.3.2.3 Resistive-capacitive voltage dividers (RCVTs)

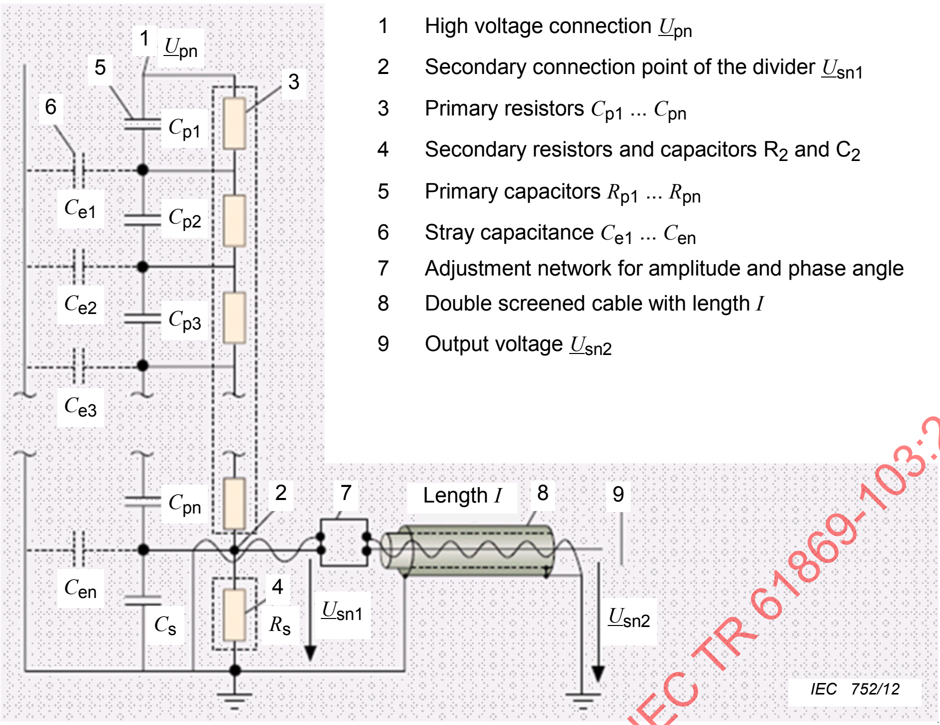
6.4.3.2.3.1 Architecture

The resistive-capacitive voltage transformers are a combination of capacitive voltage dividers and resistive voltage dividers and consist of a primary RC-path with R_1 and C_1 and of a secondary path with R_2 and C_2. R_2 and C_2 include all the capacitances and resistors on the secondary side such as adjusting network, cable, and input impedance of the secondary measuring device. R_1 and R_2 as well as C_1 and C_2 are of a low inductive design.

The primary part of the RCVT is made of stacked capacitor elements which are connected in series and in parallel of series connected resistors. The dielectric material of the capacitor elements is made with paper, film or a combination of both. This primary part is mounted in a hermetically sealed insulator (porcelain or composite) and impregnated and filled with mineral, synthetic oil or with SF_6 gas.

The secondary part is located in the hermetically sealed secondary box. To reach a sufficient temperature coefficient the secondary components are made of similar or identical materials than the primary components. A double screened cable will connect the secondary box with the customer equipment. This cable is pre-mounted by the dividers supplier and integrated in the calibration process.

Figure 36 shows an equivalent circuit of an RC voltage divider.



1 High voltage connection U_{pn}
2 Secondary connection point of the divider U_{sn1}
3 Primary resistors C_{p1} ... C_{pn}
4 Secondary resistors and capacitors R_2 and C_2
5 Primary capacitors R_{p1} ... R_{pn}
6 Stray capacitance C_{e1} ... C_{en}
7 Adjustment network for amplitude and phase angle
8 Double screened cable with length l
9 Output voltage U_{sn2}

Figure 36 – Equivalent circuit of an RC voltage divider (from w), x))

6.4.3.2.3.2 Frequency response behaviour

The measurement of voltages within the frequency range from 0 Hz (DC-voltage) up to 2 MHz is possible only by using a RC-voltage divider for high voltage. The frequency response of the resistive-capacitive voltage divider makes it able to accurately monitor voltage transients up to 1 MHz or even higher. The divider itself can transmit a voltage signal almost independently from the frequency according to its internal build up, by tuning the parallel capacitances and resistances on primary and secondary paths in order to obtain the relation $R_pC_p = R_sC_s$ as shown below (from x)).

Figure 37 shows an equivalent circuit of a balanced RC voltage divider.

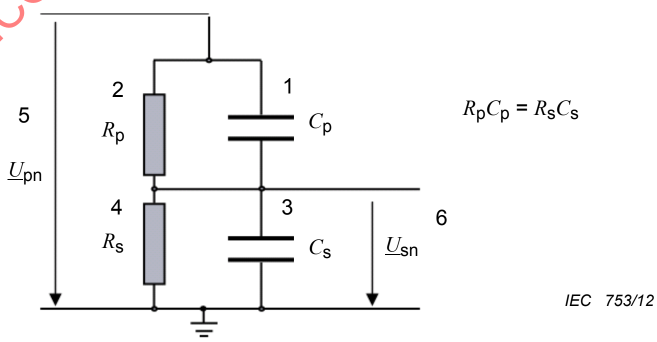


Figure 37 – Equivalent circuit of a balanced RC voltage divider (from x))

$$\frac{U_{sn}}{U_{pn}} = \frac{R_s}{R_s + R_p \dfrac{1 + R_s \times j\omega C_s}{1 + R_p \times j\omega C_p}} \qquad \omega << 1: \frac{U_{sn}}{U_{pn}} = \frac{R_s}{R_p + R_s}$$

$$= \frac{C_p}{C_p + C_s \times \dfrac{1 + 1/\mathrm{j}\omega C_s R_s}{1 + 1/\mathrm{j}\omega C_p R_p}} \qquad \omega >> 1: \frac{\underline{U}_{sn}}{\underline{U}_{pn}} \cong \frac{C_p}{C_p + C_s}$$

If the complete measuring system is considered, the above mentioned average frequency response up to 2 MHz could be affected by additional connection equipment like cable, clamps and secondary equipment. The behaviour of the divider is therefore defined by all those components, which will lead in a frequency response upper limit varying from 400 kHz up to 2 MHz.

Figure 38 gives the frequency response of a RC voltage divider.

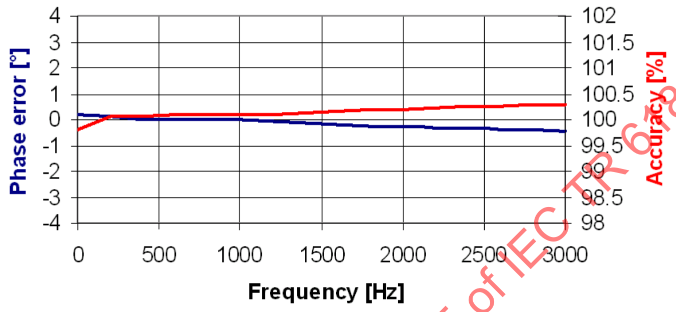


Figure 38 – Frequency response of an RC voltage divider (courtesy of Trench Switzerland AG)

Figure 39 shows the measurements done on an RC voltage divider with a voltage level of 145 kV with a cable length of 150 m.

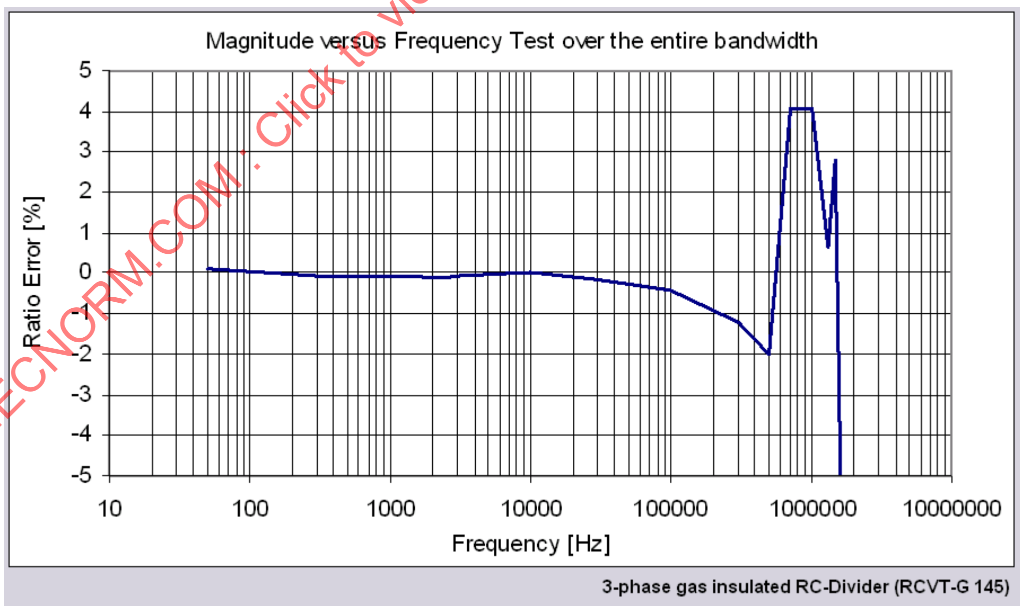


Figure 39 – Measurements done on an RC voltage divider with a voltage level of 145 kV with a cable length of 150 m (courtesy of Trench Switzerland AG)

6.4.3.2.3.3 Impact on the measurements of PQ parameters

Table 18 gives the impact on the measurements of PQ parameters of an RC voltage divider.

Table 18 – RC voltage divider: impact on the measurements of PQ parameters

Power Frequency	No Impact
Magnitude of the supply voltage	No Impact
Flicker	No Impact
Supply voltage dips and swells	No Impact
Supply voltage unbalance	No Impact
Harmonics and interharmonics	No Impact
Main signalling on the supply voltage	No Impact
Rapid voltage changes	No Impact
Voltage interruptions	No Impact
Transient voltages	No Impact

6.4.4 Electronic CTs

6.4.4.1 Optical CTs

6.4.4.1.1 Architecture

The principle adopted in order to measure the current differs significantly from conventional techniques.

The signal used by the sensor is the light coming from an optoelectronic source, like a LED, a Laser Diode (LD) or a Superluminescent Diode (SLD or SLED).

The transmission medium is composed of one or several optical fibres, assuring a natural insulation from the High Voltage. There is no need of primary electronics at the HV and hence all electronics are located at ground potential (at the base of the device or in the control room).

Depending on the sensing medium choice, various industrial solutions are proposed. For such design, two fundamental physical properties are used and two optical detection methods are possible.

The two physical properties are:

– the Faraday Effect (magneto-optic effect of 1st order), which reveals itself in transparent optical mediums such as glasses or crystals,

– The Ampère's theorem, law from electromagnetism theory.

Figure 40 shows the principle of optical CT measurement.

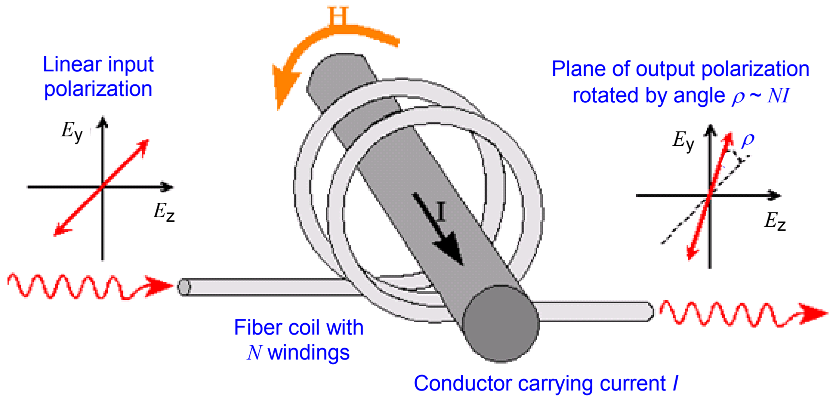


Figure 40 – Principle of optical CT measurement (from v))

The two optical detection methods are based on:

– Polarimetric systems, using polarisers;
– Interferometric systems, using interference of two light beams having a phase shift induced by Faraday Effect.

All combinations are theoretically possible; some industrial designs are described in the following:

– "Ring-Glass" or "Bulk Glass" and "Polarimetric detection"
– "Fibre-Coil" and "Interferometric detection"

Figure 41 shows the principle of optical CT measurement.

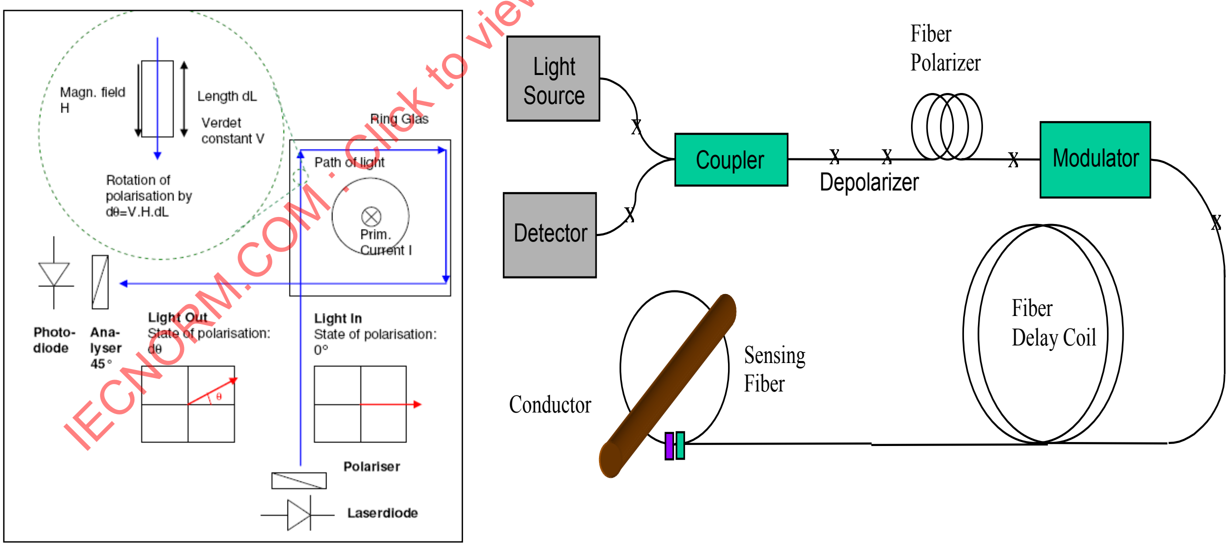


Figure 41 – Principle of optical CT measurement (Courtesy of Alstom Grid)

6.4.4.1.2 Frequency response behaviour

In both cases, the frequency response bandwidth of the coil, or of the ring glass is very high, typically from DC to several GHz. The limitation is given by the time of propagation of the light in the medium from the source to the detector.

The bandwidth limitation is due to the electronics involved in the signal processing, to the sampling rate and to the digital communication.

The typical bandwidth that can be achieved without any resonances (0 kHz to 100 kHz (3dB)) is shown in Figure 42.

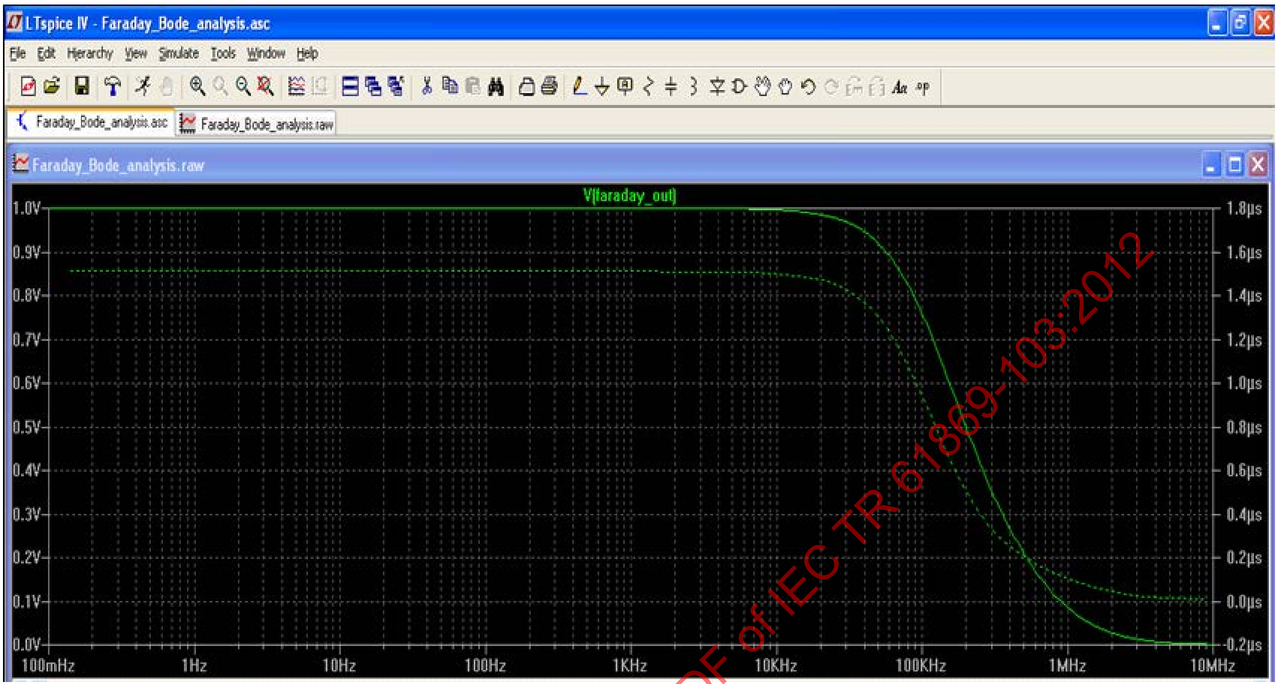


Figure 42 – Frequency response calculation for an optical CT (Courtesy of Alstom Grid)

6.4.4.1.3 Impact on the measurements of PQ parameters

Table 19 shows the impact on the measurements of PQ parameters of an optical current transformer.

Table 19 – Optical current transformer: Impact on the measurements of PQ parameters

Power Frequency	Not yet investigated. No effect is expected
Magnitude of the supply voltage	Not yet investigated. No effect is expected
Flicker	Not yet investigated. No effect is expected
Supply voltage dips and swells	Not yet investigated. No effect is expected
Supply voltage unbalance	Not yet investigated. No effect is expected
Harmonics and interharmonics	Not yet investigated. No effect is expected
Main signalling on the supply voltage	Not yet investigated. No effect is expected
Rapid voltage changes	Not yet investigated. No effect is expected
Voltage interruptions	Not yet investigated. No effect is expected
Transient voltages	Not yet investigated. No effect is expected

6.4.4.2 Low Power Current Transformers (LPCTs)

6.4.4.2.1 Architecture

The LPCTs represent a development of the classical inductive current transformer and they consist of the main components detailed in Table 20.

Table 20 – Main components of LPCTs

Primary winding	The LPCTs may have the primary winding as an essential part of the structure. If the primary winding is part of the structure the terminals are located at the top and/or sides of the LPCT. If the primary winding is external to the structure it may be an insulated conductor (i.e. MV bushing or MV cable) or it may be a not insulated conductor (i.e. busbar switchgear). In this case the MV insulation can be assured by the LPCT or by the distance between the conductor and the LPCT.
Secondary winding and magnetic core	The LPCT needs only one magnetic core and one secondary winding to measure accurate over an extended current range. Therefore one LPCT can be used for metering and protection purposes at the same time. The magnetic core is usually toroidal and uniformly covered by the secondary winding.
Shunt	A shunt which is connected at the ends of the secondary winding is designed in that way that the power consumption in the transformer is very low. The secondary output measurement at the terminals of the shunt (of the LPCT) is a voltage.
MV insulation	For MV indoor and outdoor applications synthetic resins are mainly used which provide MV insulation and mechanical strengths to the LPCTs. LPCTs are Current Transformers with a secondary interface designed to match the conditions of digital secondary technology. Due to the low power input requirements of digital secondary technology the LPCTs can be dimensioned for high input impedances. As long the input impedance of the secondary technology connected in parallel to the shunt is higher than 20 kΩ the accurate measurement of the LPCT is guaranteed. The very low power consumption of the LPCT enables a saturation free measurement of currents up to short circuit current with a high accuracy.

6.4.4.2.2 Frequency response behaviour

Due to distributed capacitances, the frequency response of a LPCT is limited to frequencies below 100 kHz. A typical frequency response measurement of a LPCT is shown in Figure 43.

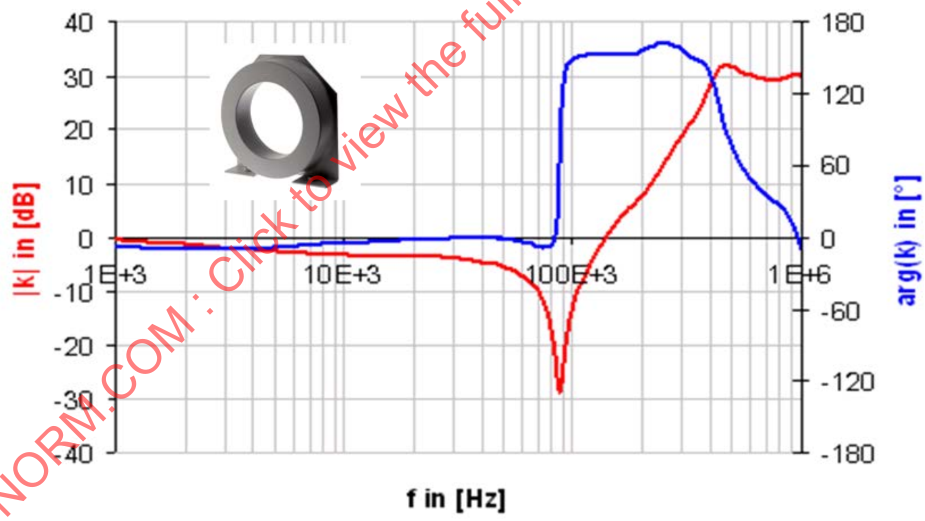


Figure 43 – Typical frequency response measurement of a LPCT (Courtesy of Trench Switzerland AG)

6.4.4.3 Rogowski current transformers

6.4.4.3.1 Architecture

The Rogowski coils are air core coils and, in some cases, they can be used like current clamps. Since they have not magnetic core, saturation problems are avoided for very high currents or in presence of DC components.

Rogowski coils have been well known in laboratories for decades, especially for the measurement of large high frequency current impulses. Basically, they can be considered as a special current transformer, and may be represented with the model shown in Figure 44.

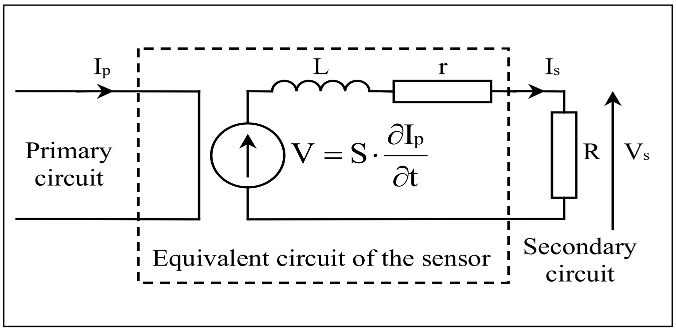


Figure 44 – Equivalent circuit for a Rogowski coils (Courtesy of Alstom Grid))

Where

I_p is the primary current to be measured

I_s is the secondary current

V is the electromotive force induced in the winding

S is the sensitivity of the sensor

L is the internal magnetizing inductance

r is the internal resistor

R is the secondary load

V_s is the secondary voltage

The sensitivity and the internal magnetizing inductance have a simple relationship:

$$S = \frac{N_p}{N_s} \times L$$

where N_p and N_s are respectively the number of turns of the primary and secondary windings.

The general equation related to the equivalent circuit shown in Figure 44 is:

$$V_s = S \times \frac{\partial I_p}{\partial t} \times \frac{R}{R+r} - \frac{L}{R} \times \frac{\partial V_s}{\partial t} \times \frac{R}{R+r}$$

At power frequency and assuming steady state condition, the secondary current I_s and the secondary voltage V_s are given by:

$$I_s = \frac{I_p}{N_s} \times \frac{j \times L \times \omega}{R + r + j \times L \times \omega}$$

$$V_s = R \times I_s$$

For a current transformer, the primary and secondary current I_p and I_s should respect the ideal relationship $I_s = I_p/N_s$.

Practically, the equation can be rewritten as:

$$I_s = \frac{I_p}{N_s} \times \frac{1}{1+\frac{R+r}{j \times L \times \omega}} = \frac{I_p}{N_s} \times \frac{1}{1+error}$$

Low values of the ratio $(R+r)/L \times \omega$ are requested in order to make this error negligible. When a high value of the loading resistor is imposed by the application, it is necessary to use a high permeability magnetic core and to increase the magnetizing inductance L. Values in the range of hundreds of Henry are commonly used.

Symmetrically, the output of a Rogowski coil delivers a secondary voltage V_s that should be linked to the primary current by the ideal relationship:

$$V_s = S \times \frac{R}{R+r} \frac{\partial Ip}{\partial t}$$

The voltage output of a Rogowski coil is proportional to the derivative of the primary current: this is the basic characteristic of a Rogowski coil.

At power frequency and in steady state conditions, the ideal relationship can be rewritten as:

$$V_s = j \times S \times \omega \times I_p \times \frac{R}{R+r}$$

Practically, a residual error remains, and the two last equations may be combined to obtain V_s, at power frequencies:

$$V_s = j \times S \times \omega \times I_p \times \frac{R}{R+r} \times \left[\frac{1}{1+j \times \frac{L \times \omega}{R+r}} \right]$$

The residual error is now equal to: $\frac{L \times \omega}{R+r}$

This error can be made negligible very easily, since Rogowski coils are usually loaded by electronic circuits. Consequently, the resistor "R" can be chosen freely. Moreover, the magnetizing inductor is usually extremely small; the ideal relationships given by equations can therefore be applied with extremely high accuracy for a wide range of frequencies.

From frequency behaviour point of view, the transfer function may be written as:

$$G(j\omega) = -\frac{S}{L} \frac{j\omega\tau + \omega^2\tau^2}{1+\omega^2\tau^2}$$ where $\tau = L/(R+r)$.

The equation above for $\omega\tau << 1$ can be written as:

$$G(j\omega) = -\frac{S}{L} j\omega\tau$$

obtaining this way a differentiating behaviour: by choosing a low inductance and a high resistance the frequency behaviour is improved.

For $\omega\tau >> 1$ the equation above can be written as:

$G(j\omega) = -\frac{S}{L}$,obtaining this time a self-integrating behaviour.

Table 21 gives the main components of Rogowski sensors and Figure 45 shows an electrical scheme and picture of a Rogowski current transformer.

Table 21 – Main components of Rogowski sensors

Primary winding	The air-core sensors may have or not the primary winding as an integral part of the structure. If the primary winding is a part of the structure, the terminals are located at the top and/or low sides of the device. If the primary winding is external to the structure it may be an insulated conductor (i.e. MV bushing or MV cable) or not insulated conductor (i.e. busbar switchgear) and, in this case, the MV insulation can be assured by the sensor or by the distance between the conductor and the sensor.
Secondary winding and non-magnetic former	Air-core sensors may have one or more secondary windings, each with its support. The formers can have different shape (i.e. toroidal, rectangular …)\ and the secondary windings can be uniformly distributed or localized on only one part of it.
MV insulation	For MV indoor and outdoor applications synthetic resins are mainly used which provide MV insulation and mechanical strength to the device

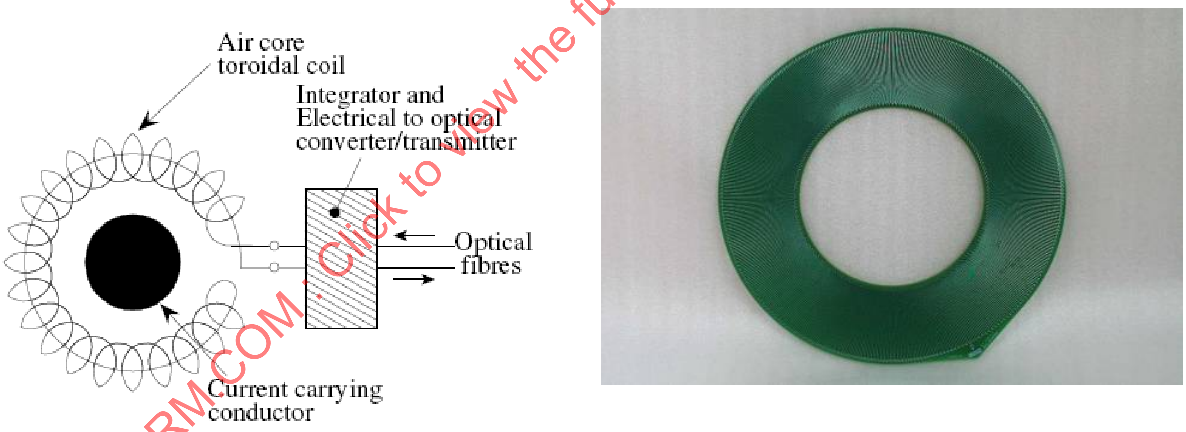


Figure 45 – Electrical scheme and picture of a Rogowski current transformer (Courtesy of Alstom Grid)

6.4.4.3.2 Frequency response behaviour

The Rogowski coil does not pass DC signals and the output signal is proportional to the derivative of the primary current. The coil signal must therefore be integrated by signal processing techniques, which limits the bandwidth on the DC side.

For high frequency the bandwidth can be very high (100 kHz (3dB)), as shown for optical transformers.

The system can be properly designed in order to avoid any resonance.

6.4.4.3.3 Impact on the measurements of PQ parameters

Table 22 shows the impact on the measurements of PQ parameters of a Rogowski current transformer.

Table 22 – Rogowski current transformer: Impact on the measurements of PQ parameters

Power Frequency	Not yet investigated. No effect is expected
Magnitude of the supply voltage	Not yet investigated. No effect is expected
Flicker	Not yet investigated. No effect is expected
Supply voltage dips and swells	Not yet investigated. No effect is expected
Supply voltage unbalance	Not yet investigated. No effect is expected
Harmonics and interharmonics	Not yet investigated. No effect is expected
Main signalling on the supply voltage	Not yet investigated. No effect is expected
Rapid voltage changes	Not yet investigated. No effect is expected
Voltage interruptions	Not yet investigated. No effect is expected
Transient voltages	Not yet investigated. No effect is expected

6.4.4.4 Shunts

6.4.4.4.1 Architecture

A shunt is a conductor having low, very accurate resistance value, generally built with a material called Manganin (a mixture of components: copper, nickel, manganese) which provide a good stability in temperature.

The shunt range of operation starts from low currents as 10 mA for laboratory applications up to very high current as 10 kA for industrial applications. The measurement of current is easily obtained by measuring the voltage output. The shunt is typically manufactured in order to give a 100 mV output for application at rated current.

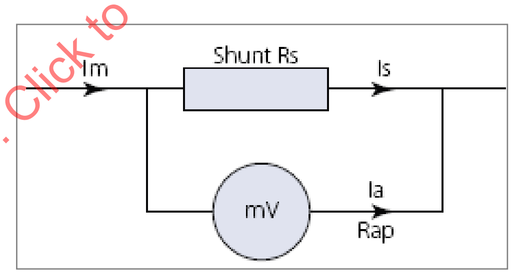


Figure 46 – Electrical scheme of a shunt current measurement (Courtesy of Alstom Grid)

The voltage is measured by voltmeter having a high input impedance in comparison of the shunt resistance, in order to make the current I_a negligible with respect to I_s (see Figure 46). For high voltage application, electronic equipment can be used in order to digitize this signal and transmit sample values by optical fibre.

For AC current application, shunts show some drifts with the frequency response, due to stray inductance and capacitance (see Figure 47).

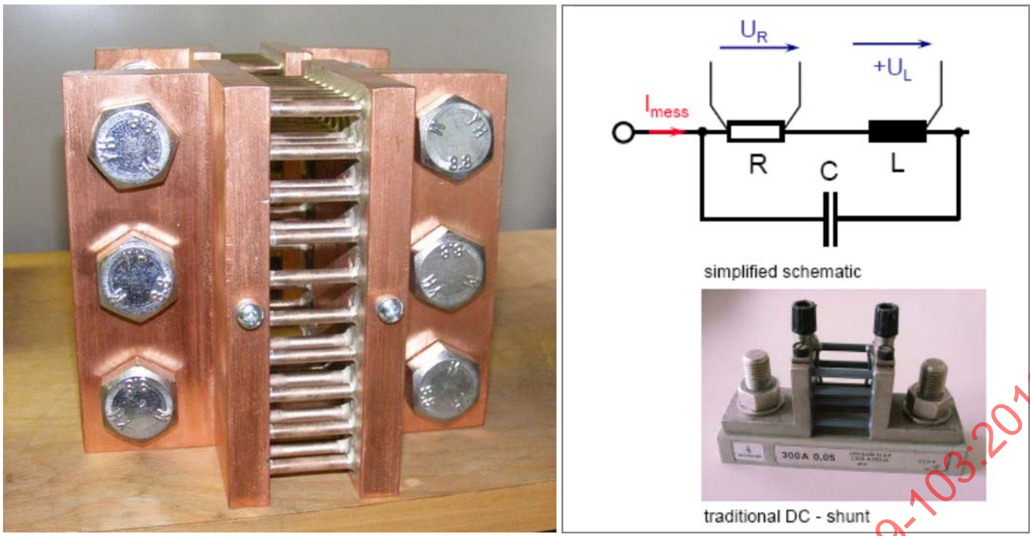


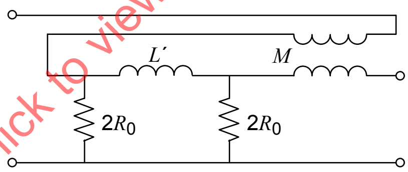
Figure 47 – Shunt for DC application (Courtesy of Alstom Grid)

For applications requiring a large bandwidth, a coaxial structure is commonly used, but in this case the current intensity range is limited.

6.4.4.4.2 Frequency Response Behaviour

High Current Shunts are not suitable for measurements over a high bandwidth. To measure currents having a high bandwidth (up to 100 kHz) only coaxial shunts may be used, available only for currents up to 400 A.

An equivalent circuit of a coaxial, compensated shunt is shown in Figure 48.



IEC 755/12

Figure 48 – Equivalent circuit for a compensated shunt

With reference to the circuit, a simplified transfer function for a coaxial shunt with inductive compensation may be written as:

$$G(j\omega) = \frac{R_0}{1 + j\omega T_1} + j\omega M \text{ , where } T_1 = L/4R_0 \text{ ;}$$

If $M/R_0 = T_1$ and $f_0 = 1/2\pi T_1$, the transfer function may be rewritten in the frequency domain as:

$$G(f) = R_0 \left(\frac{1}{1 + j\frac{f}{f_0}} + j\frac{f}{f_0} \right) \text{ and for } \frac{f}{f_0} << 1 \text{, as } G(f) = R_0$$

In any case, a perfect compensation cannot be obtained (see Figure 49).

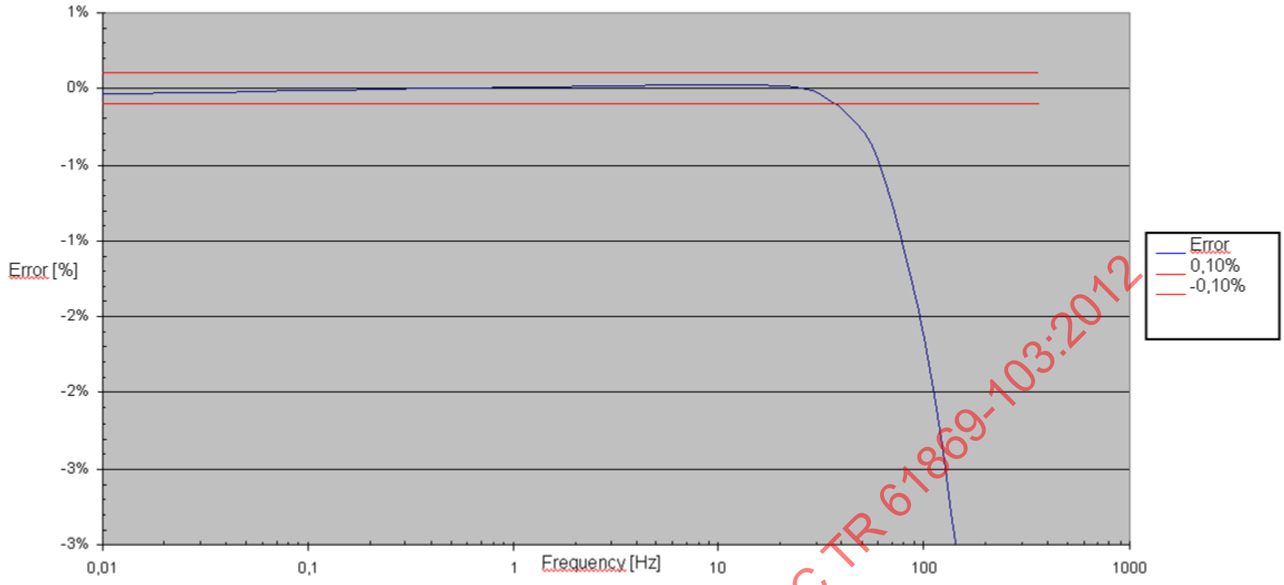


Figure 49 – Theoretic possible bandwidth of a shunt 5 kA /150 mV (Courtesy of Alstom Grid)

6.4.4.4.3 Impact on the measurements of PQ parameters

Table 23 gives the impact on the measurements of PQ parameters of a shunt.

Table 23 – Shunt: Impact on the measurements of PQ parameters

Power Frequency	Not yet investigated. No effect is expected
Magnitude of the supply voltage	Not yet investigated. No effect is expected
Flicker	Not yet investigated. No effect is expected
Supply voltage dips and swells	Not yet investigated. No effect is expected
Supply voltage unbalance	Not yet investigated. No effect is expected
Harmonics and interharmonics	Not yet investigated. No effect is expected
Main signalling on the supply voltage	Not yet investigated. No effect is expected
Rapid voltage changes	Not yet investigated. No effect is expected
Voltage interruptions	Not yet investigated. No effect is expected
Transient voltages	Not yet investigated. No effect is expected

6.4.4.5 Hall Effect Sensors

6.4.4.5.1 Architecture

Hall-effect sensors (see Figures 50, 51 and 52) are widely used for a large field of applications. For current measurement, the main issue is to guarantee stability vs. time for a long time period.

Hall phenomenon appears in a long semi-conductor plate with two larges electrodes to inject the current. All electrons have a constant speed of displacement, in the opposite direction of the current flow. When a magnetic field is applied perpendicularly to one large face of the plate, the electrons are deviated according to Lorentz forces:

$$\vec{F}_{\mathrm{m}} = -e \times \vec{v} \times \vec{B}$$

Where F_{m} is the Lorentz's force, $-e$ is the electron charge, v is its velocity and B is the magnetic induction. This induces an electric field to produce a force to compensate the previous one:

$$\vec{F}_e = -e \times \vec{E}_H$$

In these conditions, the electrons keep a uniform displacement and the "Hall Electric field" can be written:

$$\vec{E}_H = -\vec{v} \times \vec{B} = -\frac{\vec{B} \times \vec{j}}{n \times e}$$

Where:

n is the density of charges ($-e$)

j is the current density in the plate

d is the plate thickness

and the Hall voltage is:

$$V_H = \frac{I \times B}{n \times e \times d}$$

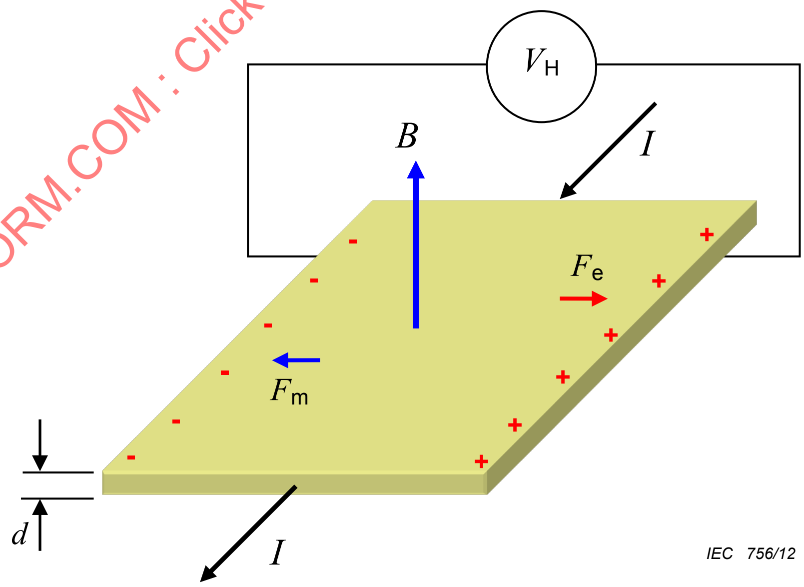


Figure 50 – Hall Effect Sensor

where F_{m} is the Lorentz's force on the negative charge carriers and F_{e} is the electric force that compensates the previous one.

A practical realisation to improve the sensitivity is to increase the magnetic flux by placing the sensitive plate in a magnetic core.

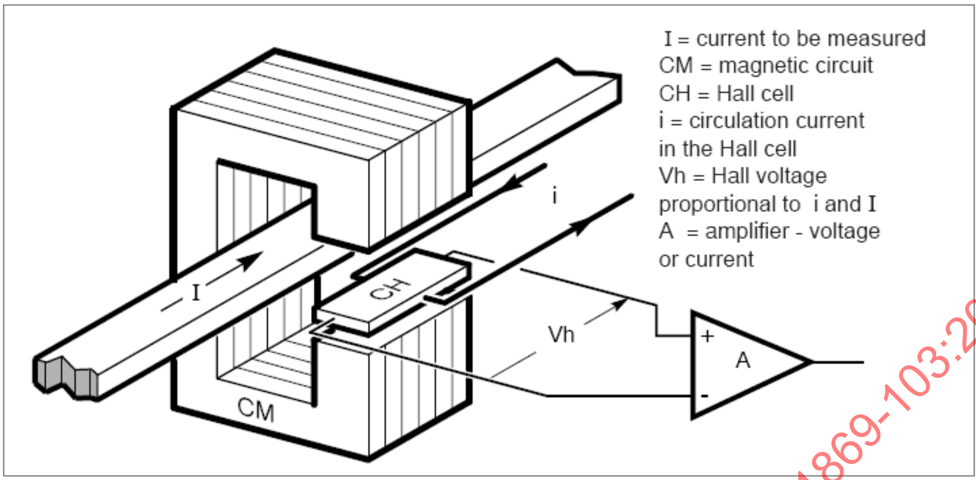


Figure 51 – Hall Effect Sensor (Courtesy of Schneider Electric – From II))

The current generation for the Hall cell and the signal processing are made with local electronics. This fact can be a limitation for high voltage applications.

A typical bandwidth range can be obtained from DC to 40 kHz.

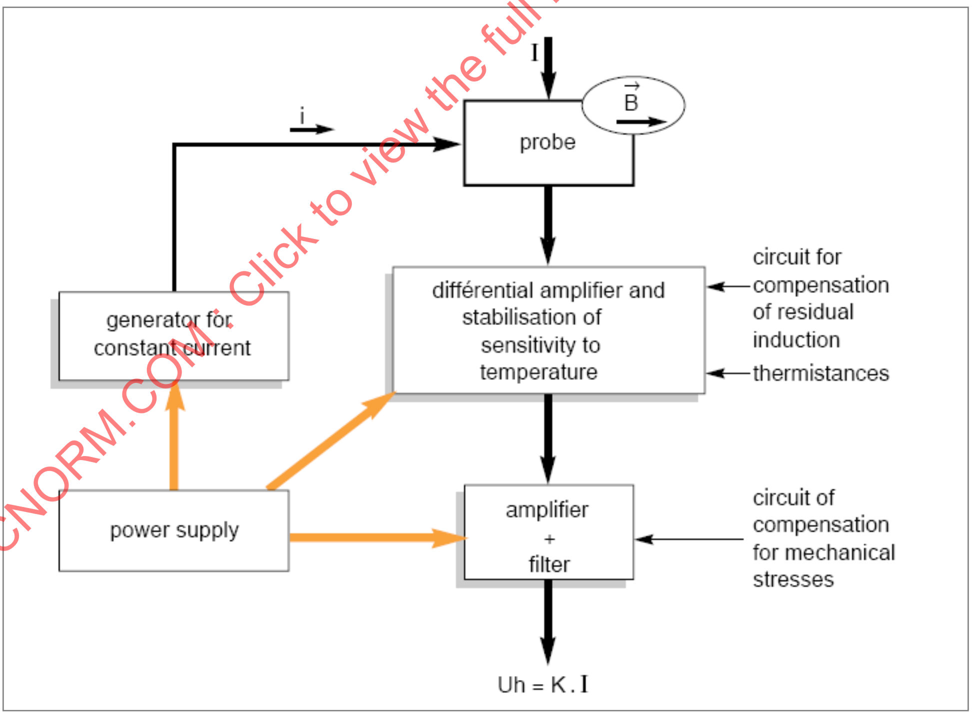


Figure 52 – Hall Effect Sensor (Courtesy of Schneider Electric – From II))

6.4.4.5.2 Frequency response behaviour

Hall effect sensors frequency response is better than the one provided by CTs (up to 100 kHz).

6.4.4.5.3 Impact on the measurements of PQ parameters

Table 24 gives the impact on the measurements of PQ parameters of a Hall effect sensor.

Table 24 – Hall effect sensor: Impact on the measurements of PQ parameters

Power Frequency	No effect is expected
Magnitude of the supply voltage	No effect is expected
Flicker	No effect is expected
Supply voltage dips and swells	No effect is expected
Supply voltage unbalance	No effect is expected
Harmonics and interharmonics	No effect is expected
Main signalling on the supply voltage	No effect is expected
Rapid voltage changes	No effect is expected
Voltage interruptions	No effect is expected
Transient voltages	No effect is expected

7 Tests for power quality

In order to verify HV instrument transformers accuracy, suitable standard transducers and testing procedures, including supply sources and reference measuring systems, are needed.

In calibration laboratories, reference transducers characterised for frequencies different from the power frequency are, in general, not readily available today. It is however possible to characterize reference measuring systems to achieve necessary traceability also for other frequencies. Inductive instrument transformers, commonly used for protection and measurement purpose, do not have a behaviour linear with frequency and amplitude. In order to correctly verify inductive instrument transformers frequency behaviour, it would be meaningful to evaluate their behaviour superposing PQ events and harmonics to the fundamental signal and the higher is the voltage or current level, the less easily this condition can be achieved. High current and voltage sources at high frequency are not commercially available, and are only found in a few national measurement laboratories.

The power quality tests for instrument transformers should be performed as special test for transformers that shall fulfil the PQ classes as given in Annex B.

The measurement of power quality parameters requires improved frequency response (magnitude and phase) as well as transient response on voltage and current transducers as summarised in Table 25:

Table 25 – Power quality parameters and requirements for CT and VT

Disturbance	CT	VT	Magnitude	Phase	Transients
Power frequency		x			
Magnitude of voltage supply		x	x	x	
Flicker		x	x	x	
Dips and swells		x	x	x	x
Voltage interruptions		x	x	x	
Voltage unbalance		x	x	x	
Current/Voltage harmonics	x	x	x	x	
Current/Voltage interharmonics	x	x	x		
Main signaling		x	x		
Rapid voltage changes		x	x		
U/O deviation parameters		x	x	x	

The tests to be performed for VTs are:

- Frequency response (magnitude and phase) in the frequency range 15 Hz to the 50th harmonic.
- Frequency response with respect to burden (if relevant).

7.1 Test procedure for VT frequency response

The test procedure for VT depends on the linearity characteristic. If the frequency response of the transducer can be proven to be not affected by the presence of the fundamental voltage and varying burden, the frequency response test can be performed at a voltage level lower than the rated by applying a single tone sine wave and varying the frequency. The input voltage level has to be chosen so that the output signal has a level suitable for measuring with adequate accuracy.

When the frequency response of the transducer is affected by the presence of the fundamental voltage the test should be performed by applying a voltage of fundamental frequency close to or equal to the nominal voltage with harmonics and sub-harmonics added. The level of harmonics should in this case be in the range of 0,2 % to 3 % amplitude compared to the fundamental for HV transformers and 2 % to 10 % for MV transformers. If relevant, the burden dependency of the frequency response of the transformer has to be established during the test.

7.2 Test set-up for VT frequency response test

The circuit for reduced voltage test can consist of a power amplifier and of a signal generator. The VT under test is connected to the output of the amplifier. A reference transducer is connected in parallel to the VT.

The output of the VT under test and the output of the reference transducer are compared by means of a suitable voltage comparator able to compare amplitude and phase of the reference and the device under test. A traditional voltage transformer set does not have a bandwidth useful for this comparison. The comparison can be performed by means of two high resolution sampling voltmeters synchronised by a computer. If the applied voltage is below the maximum input voltage of the reference sampling voltmeter used in the comparison, the voltage may be measured directly without the interposition of the reference transducer.

For high voltage VT the generation of a sine wave with an amplitude suitable for obtaining an output signal level well above the background noise may not be achieved by an amplifier. In this case, a suitable step up transformer can be inserted between the amplifier and the VT as shown in Figure 53.