Low Power Voltage and Current Transducers for Protecting and Measuring Medium and High Voltage Systems

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LOW POWER VOLTAGE AND CURRENT TRANSDUCERS FOR PROTECTING AND MEASURING MEDIUM AND HIGH VOLTAGE SYSTEMS

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ABSTRACT

This paper introduces a new generation of instrumentation transducer systems suitable for the substation environment. The concepts presented here are a first step away from individual component thinking to that view required for instrumenting an integrated system. As compared with traditional instrument transformers, these new sensors have comparable or reduced wiring costs, have reduced weight, consider the very low input burden of digital relays, and are immune to the electromagnetic interference in the substation. These new sensors also offer superior transient performance for diagnostic purposes and remove application restrictions imposed by past technologies.

COMPENSATED R- AND RC-DIVIDERS FOR VOLTAGE MEASUREMENT IN MEDIUM AND HIGH VOLTAGE SYSTEMS

Introduction

All new microprocessor-based protection and measuring systems impose very little burden upon the instrumentation transformers or sensors [1]. These low burdens may create accuracy problems for voltage transducers such as wound potential transformers.

The devices in these systems include an input circuit or module which reduces the instrument transformer output signal level to an electronic level suitable for reading by an analog-to-digital (A/D) converter. The typical input circuit resistance of each protection relay is between 1 MΩ and 10 MΩ. Assuming a maximum A/D voltage, Vs, equal to 5 V zero-to-peak, the relay input power requirement has a range of 15 μW to 25 μW. Note that this input power requirement is many orders of magnitude less than the rated output of traditional instrument transformers or potential devices.

For analysis, let us separate the main system into four subsystems (Figure 1). The input to this system is the primary voltage Vp(t) and the primary current Ip(t). The system (S1), is comprised of the voltage- and current-transducers/sensors. The function of these transducers is to convert Vp(t) and Ip(t) to a level suitable for input to the A/D [2], [3].

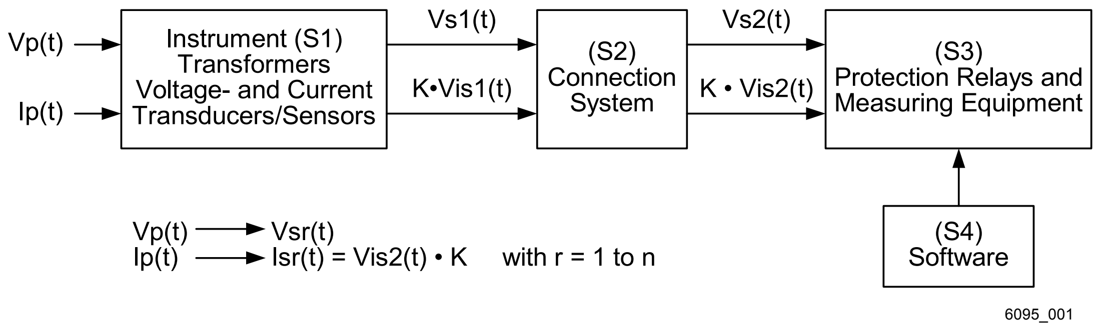


Figure 1: Main System for the Application of Voltage and Current Transducers

As Figure 1 illustrates, the relay system first reduces the input signals to a lower level. This step or process stems from the requirement of these devices to utilize the same input signal levels as their electromechanical and static predecessors. Given the quick acceptance of the microprocessor-based relay technology, we can now investigate instrument sensors whose output signal levels are directly compatible with the new relays. Later we show that removing the high level signal output gains significant performance and application advantages. Let us next investigate the progression of instrumentation sensors that led to the development of the new low power output technology.

The Haefely milestones for R, C and RC-divider technology are [4], [5], [6] :

1957: Start of the development. Application: Measurement of the acceleration voltage of ion- and electron-accelerators.

1960: RC-divider for the measurements of transients in ac-high voltage systems.

1965: Standard production of RC-divider with high stability for electron accelerators. Voltage level: 300 kV, 600 kV and 1000 kV.

1980: Application of RC-divider in high voltage dc-converter station for dc- and ac-voltage measurement.

1982: C-divider for GIS-installation. Disadvantage: the problem of “trapped charges” [7].

Compensated R-Divider for Medium Voltage Systems (MVS)

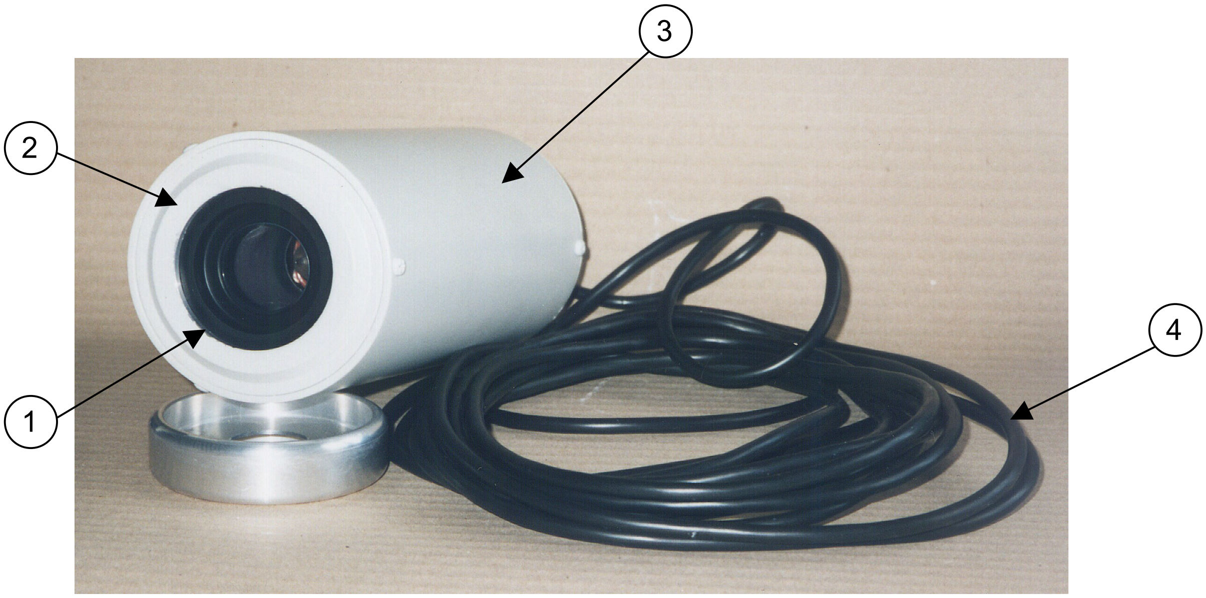
The ohmic or R-divider is the sensor for measuring the primary voltage Vp(t). It replaces the inductive or capacitor voltage transformer and is directly connected to the signal processing unit for protection and measuring purposes [8], [9].

Two compensated R-divider solutions are available for MVS:

1. An iron tube shielded R-divider for air insulated MV-switchgear (Type: LPVT; Figure 2).

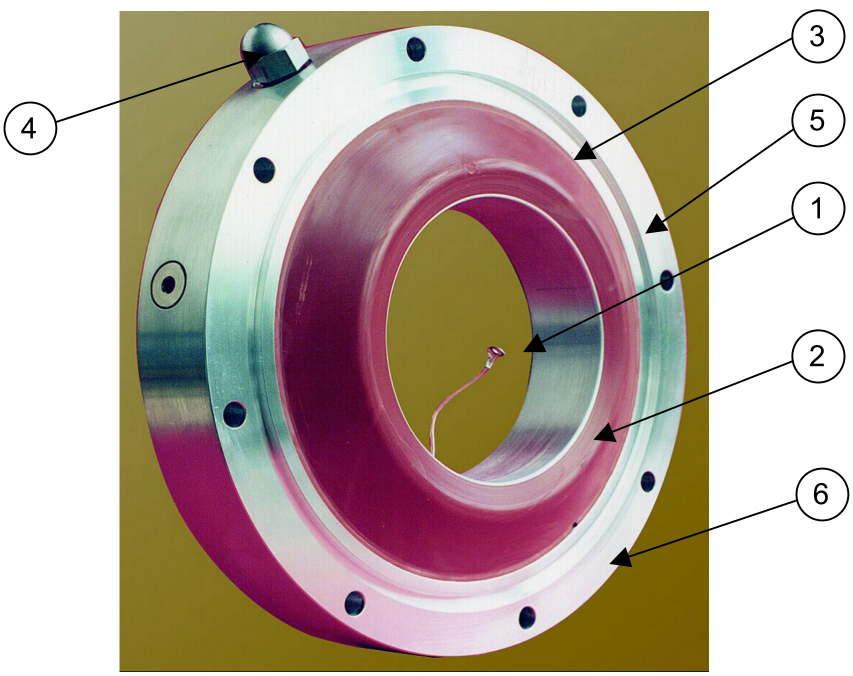
2. A coaxial flange shielded R-divider for gas insulated MV-switchgear (Type: LPVTG; Figure 3).

Both types are applicable for the full range of Vm (highest voltage for equipment) in accordance to IEC and ANSI standards.



1. High Voltage Terminal
2. Insulation Material: Cast Resin
3. Iron Tube
4. Double Shielded Cable for the Connection Voltage Sensor to the Signal Processing Unit

Figure 2: Shielded R-Divider for Air Insulated MV-Switchgear



1. High Voltage Terminal. Lead for Connection to the Busbar.
2. High Voltage Electrode
3. Insulation Material: Cast Resin
4. Grounding Screw with Multicontact Connection
5. O-ring Groove
6. Al-flange

Figure 3: Coaxial Flange Shielded R-Divider for Gas Insulated MV–Switchgear

Figure 2 shows the high voltage design circuit of the iron tube shielded R-divider. The subsystems S1, S2 and S3 of Figure 1 are also shown in Figure 4. The voltage sensor is a high impedance network shielded against electric fields by the iron tube. The primary and secondary resistors are thick film resistors specifically developed for this application. The thick film active part is well protected against the high electric field existing between the surfaces of the resistors and the inside of the tube wall that is at ground potential.

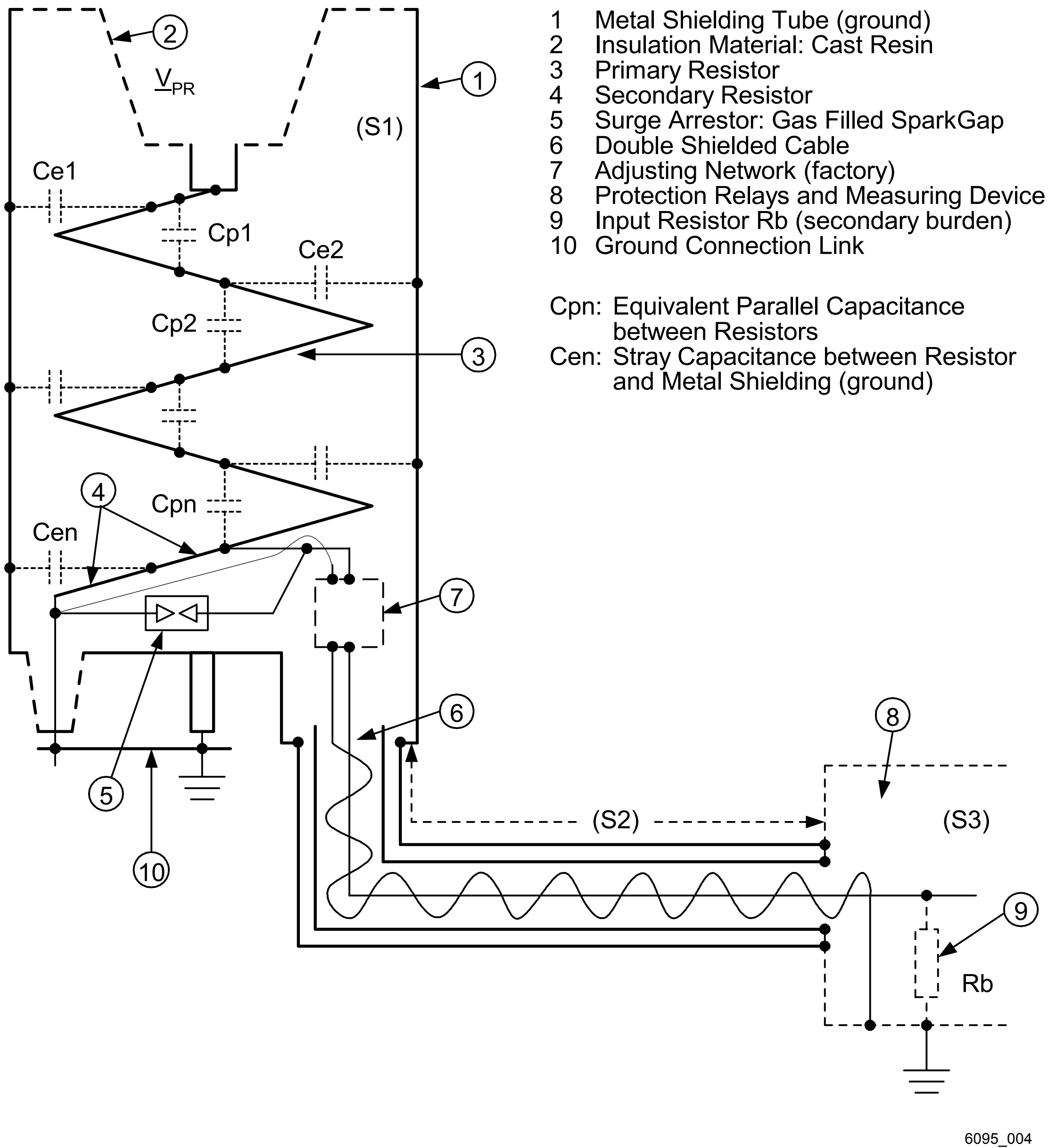


Figure 4: High Voltage Design Circuit

The other important requirement for MV sensors is the immunity against magnetic fields in the very compact switchgear environment. The sensors (S1) and the connection system (S2) are close to the busbars carrying the high magnitude fault and load currents. The internal design of the R-divider (shown in Figure 4) must avoid any loops or areas in which voltages can be induced. The two low voltage terminal wires are twisted pair. One low voltage wire, connected to ground in (S1), is closely situated to the secondary Resistor 4. Figure 5 shows the equivalent circuit of the shielded R-divider.

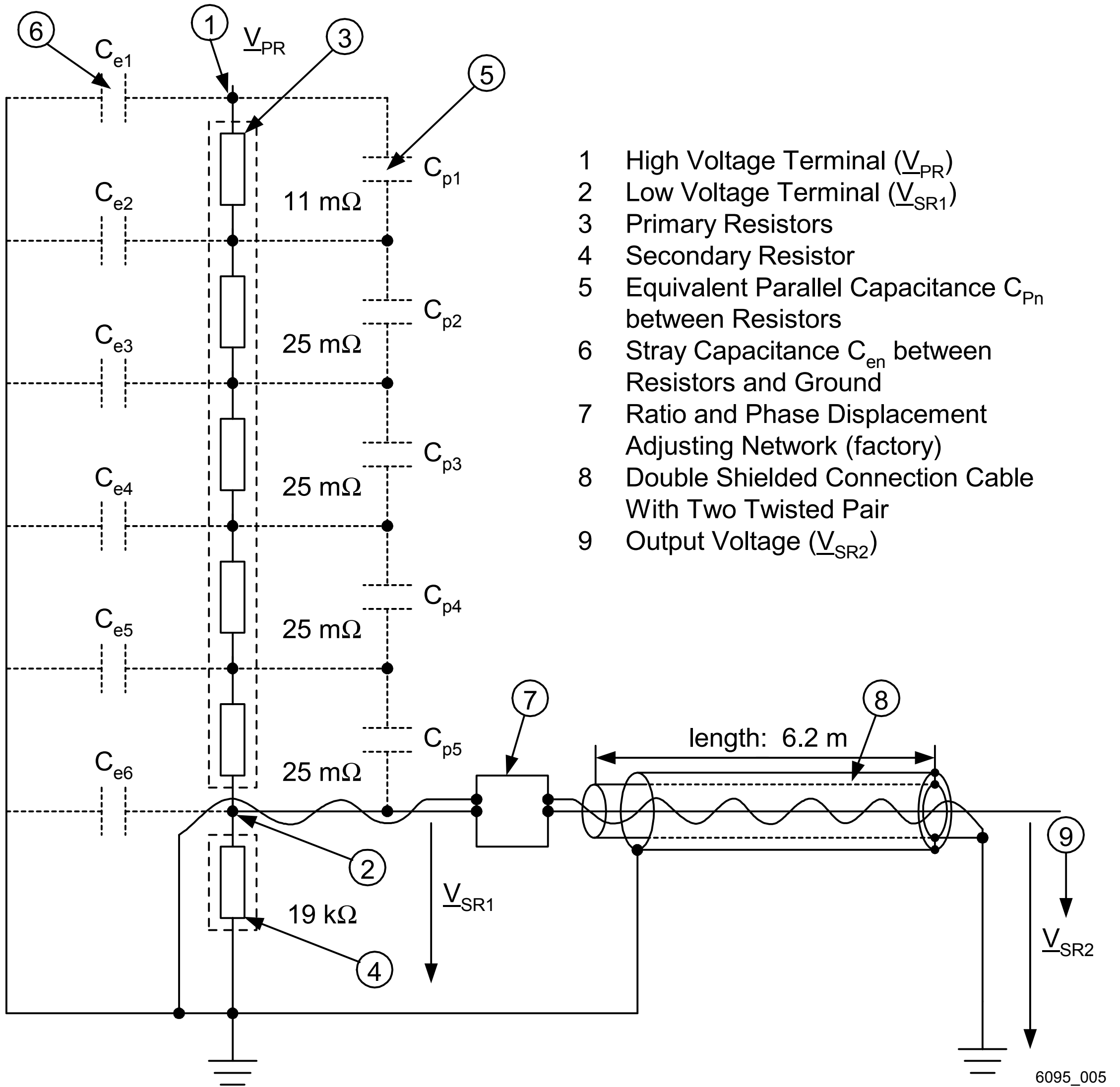


Figure 5: Voltage Sensor Equivalent Circuit of the R-Divider: Vm = 24 kV

Earlier we stated that the output power of these new sensors is much reduced as compared to the traditional instrumentation transformers. Table 1 shows the rated voltage and dissipated power requirements for the example 24 kV R-divider.

Table 1: Rated Voltages, Power, and Current Requirements for 24 kV R-Divider

	Rating Value	Notes
Primary Voltage: V_{PR}	11.6 kV	$V_{PR} \le \frac{24\ \text{kV}}{1.2 \cdot \sqrt{3}}$, Rated Frequency: 50 or 60 Hz
Secondary Voltage: V_{SR}	$\frac{3.25\ \text{V}}{\sqrt{3}}$	IEC standard 60044-7 Status: FDIS Accuracy: Class 0.5 or class 0.2
Dissipated Power and Current: **At Continuous Max. Voltage**	1.7 W	a. $P = \frac{(1.2 \cdot V_{PR})^2}{111 \cdot 10^6}$; AC test voltage 1 min: 50 kV rms
8 hr Operating Voltage with 1.9 Voltage Factor	4.3 W	b. $P = \frac{(1.9 \cdot V_{PR})^2}{111 \cdot 10^6}$ BIL (1.2/50 ms): 125 kV (peak)
R-Divider Current at Rated Voltage (V_{PR})	100 µA	c. $I = \frac{V_{PR}}{111 \cdot 10^6}$

Note that the secondary voltage output of the R-divider requires a nontraditional voltage input circuit to the protective relay or meter.

For the coaxial flange sensor (Figure 3), the high voltage circuit design (Figure 4) is based upon the same principle. The two R-divider types simply have different adjusting networks.

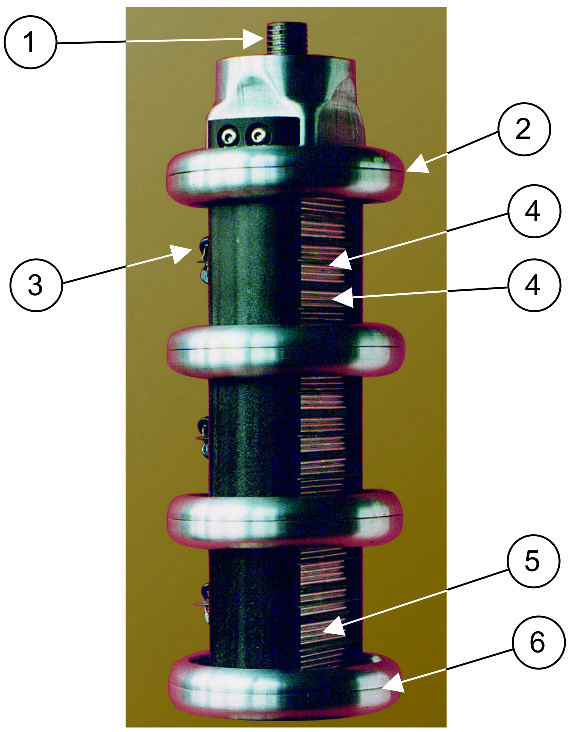
Table 2 shows weight and size of conventional VTs and LoPos.

The RC-Divider for High Voltage Systems

The RC-divider for open air installations has been in service for over 20 years [10], [11]. The main application is voltage measurement in dc converter stations. Amplifiers are used between the low voltage terminal (high impedance voltage source), the protection relays and measurement equipment. In recent years, the main system shown in Figure 1 was utilized without an impedance converter (power amplifier). For these systems, the low power, low voltage signals from the RC-dividers were converted into digital-optical signals and directly connected to the high input resistance of the processing units.

Table 2: Weight and Size of Conventional VTs and LoPo

Voltage Class		Cast Resin WPT	Compensated R-Divider Shielded Design	Compensated R-Divider Coaxial Flange
24 kV 36 kV	Weight	38 kg 65 kg	3.2 kg 5.0 kg	5.2 kg 5.2 kg
24 kV 36 kV	Height	300 mm 390 mm	230 mm 300 mm	64 mm 64 mm
24 kV 36 kV	Width	246 mm 370 mm	100 mm (diameter) 120 mm (diameter)	296 mm (outside diameter)



1. High Voltage Terminal
2. Ring Electrode
3. Resistor
4. Film Capacitor
5. Low Voltage Terminal
6. Ground

Figure 6: RC-Divider for Gas Insulated HV-Switchgear without the Pressure Vessel

A new application of the RC-divider is the voltage measurement in gas insulated systems. This voltage sensor is a low cost solution as compared with the inductive voltage transformer for the voltage range Vm ≥145 kV.

Figure 6 shows a 145 kV RC-divider without the SF_6 pressure vessel. The equivalent circuit for this divider is the same as that shown in Figure 5. The capacitance between resistors, Cpn, are film capacitors.

Table 3 shows the rated voltage and test standards for the example 145 kV RC-divider.

Table 3: Rated Voltages for a 145 kV RC-Divider

	Rating Value	Notes
Primary Voltage: V_{PR}	70 kV	$V_{PR} \le \frac{145\text{ kV}}{1.2 \cdot \sqrt{3}}$, Rated Frequency: 50 or 60 Hz
Secondary Voltage: V_{SR}	$\frac{3.25\text{ V}}{\sqrt{3}}, \frac{6.5\text{ V}}{\sqrt{3}}$	Accuracy: Class 0.5 or class 0.2, respectively
Continuous Max. Operating Voltage	84 kV	$\frac{145\text{ kV}}{\sqrt{3}}$, AC-test voltage 1 min: 275 kV rms
8 hr Operating Voltage	133 kV	$1.9 \cdot \frac{145\text{ kV}}{1.2 \cdot \sqrt{3}}$, BIL (1.2/50 μs) : 650 kV (peak)

Again, note that the secondary voltage output of the R-divider requires a nontraditional voltage input circuit to the protective relay or meter.

Figure 7 shows the outline drawing of the RC-divider for SF_6 insulated system with a pressure vessel.

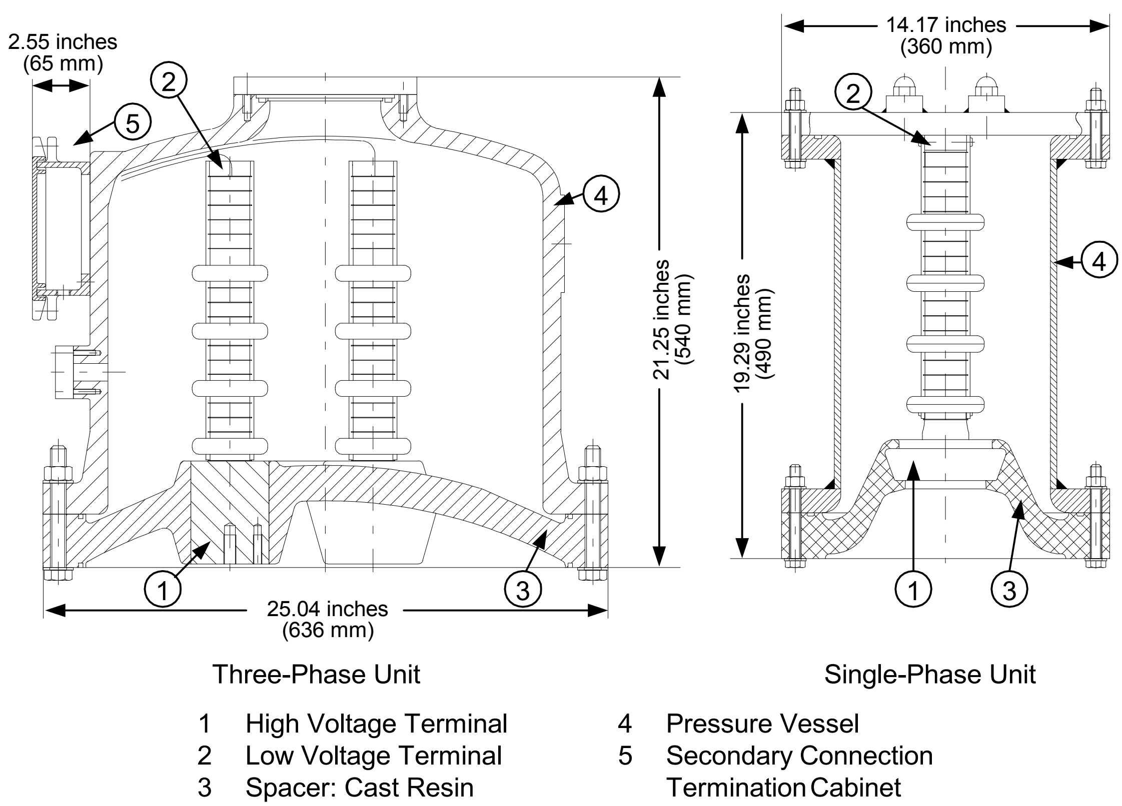
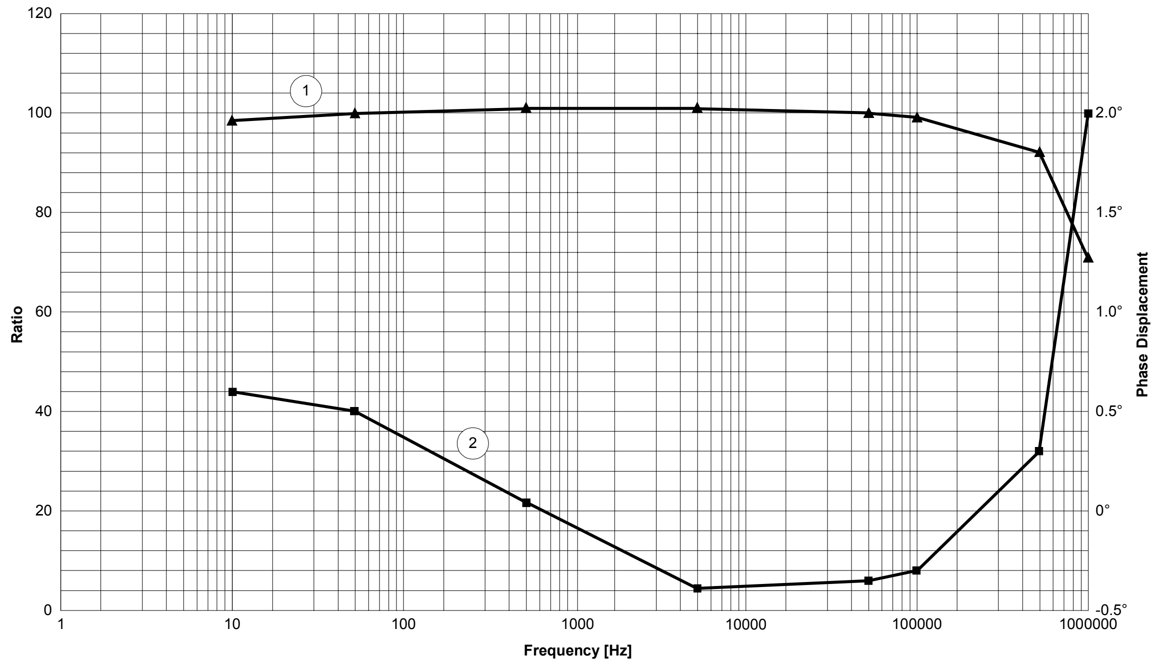


Figure 7: 145 kV SF6 Insulated RC-Divider

RC-Divider Transient Performance

Using an HP spectrum analyzer, we measured the frequency response of a RC-divider 145 kV without an adjusting network. This device was designed as a single-phase unit in a pressure vessel. The ratio $\frac{|\underline{V}a| \cdot n}{|\underline{V}e|} \cdot 100\%$ and phase shift $\Delta\varphi$ of the frequency response are plotted in Figure 8. The curves in Figure 8 indicate a wide frequency range of the RC-divider from 0 Hz (dc) to 1 MHz. With this characteristic the voltage sensor can be used for protection and metering. Additionally, these sensors are useful for diagnostic purposes such as partial discharge (PD) measurement in a gas-insulated substation (GIS).



Legend

1 Ratio: $\frac{|\underline{V}a| \cdot n}{|\underline{V}e|} \cdot 100\%$ (left hand vertical scale)

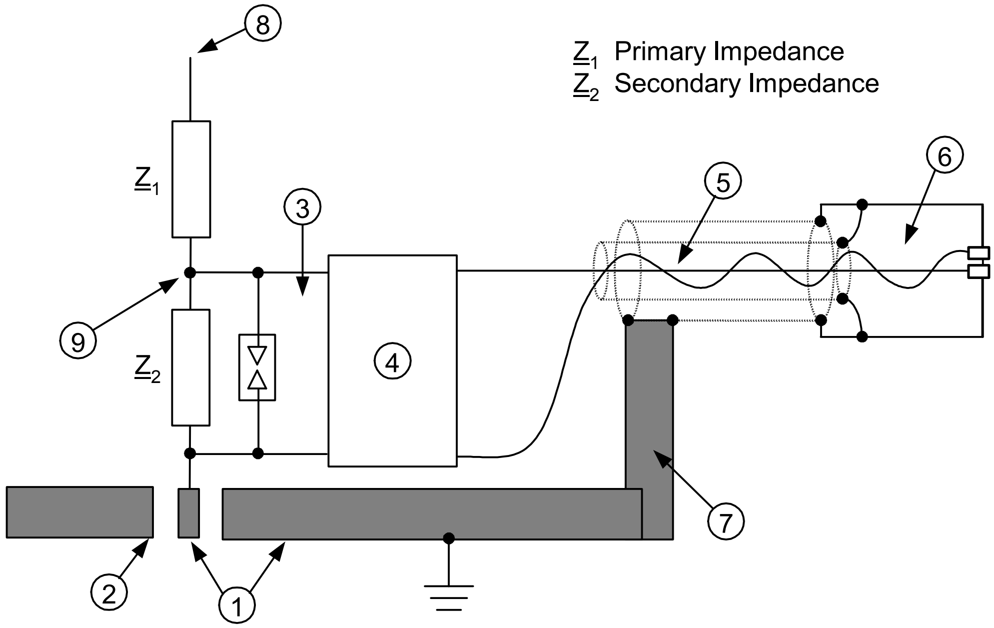
n ≡ Primary to secondary ratio

2 Phase displacement $\Delta\varphi$ in degrees [°]

Figure 8: Frequency Response of a RC-Divider Voltage Sensor (response range: f = 0 Hz to 1 MHz)

Dielectric Test of the Secondary Circuit

The secondary circuit is tested with an ac voltage of 3 kV_{rms} driven against ground (see Figure 9) to prove the electrical strength of the complete assembled secondary circuit. This secondary circuit consists of the secondary impedance Z_2, encapsulated gas-filled gap arrestor, adjusting network, double shielded cable and screened connector.



1 Test Voltage 3 kV rms
2 Ground Connection: Open
3 Gas-Filled Gap Arrestor; Break-Down Voltage = 90 V peak
4 Factory-Adjusted Network
5 Double-Shielded Cable With Two Twisted Pairs
6 Voltage-to-Relays and Metering
7 Flange or Iron Tube Housing
8 High-Voltage Terminal
9 Low-Voltage Terminal

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Figure 9: Secondary Circuit Dielectric Test Setup

Accuracy Test

The standard analog bridges for accuracy tests, protection and measuring cannot be used for the testing of low power R- or RC-dividers. The input resistance of the bridge is much too low for this application. The following two steps solved this accuracy validation problem.

a) Calibration of high precision RC-divider[1] using a Schering bridge in a high voltage laboratory[1]. This bridge may also be used as a standard RC-divider, and

b) Routine accuracy test in a bridge circuit with calibrated digital voltmeters, phase meter and the standard RC-divider.

Note 1: The development of the divider and the calibration was performed in the college HTA Burgdorf-CH.

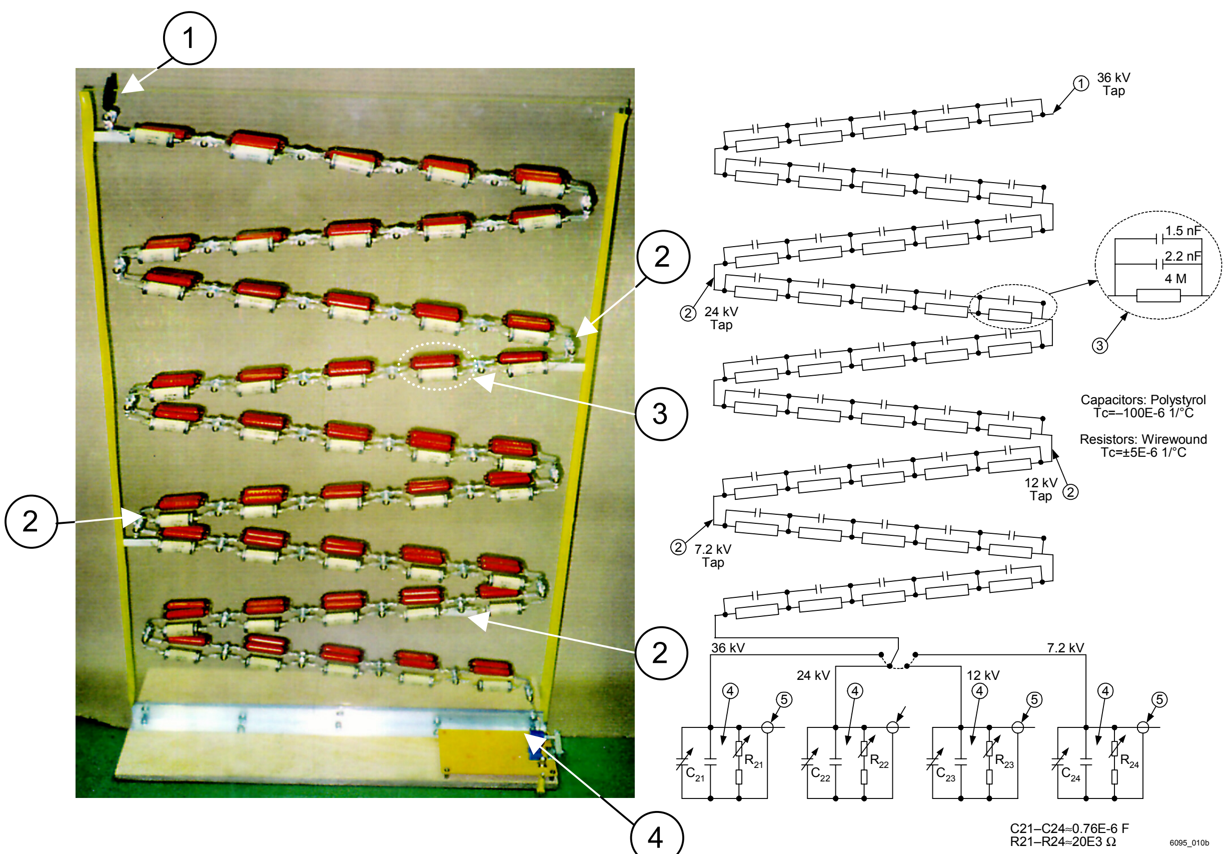
Figure 10 illustrates a precision RC-divider with a high voltage terminal rated for Vm = 36 kV and three taps for Vm = 7.2 kV, 12 kV and 24 kV. For high accuracy application purposes, every tap requires a separate secondary divider. Only one Vm voltage (36 kV) was calibrated for these tests. The calibration was performed using ac in the high voltage lab of the college HTA with a Schering bridge. Figure 11 shows a simplified drawing of this classic measuring circuit without a potential guard. The calibration requires experience with high voltage test technique, partial discharge (PD) measurement, electromagnetic compatibility (EMC) and a well shielded HV-lab.

The requirements are the same for routine accuracy tests. Metering class 0.2 is achieved with this calibration setup (see Table 4). The voltage error and phase displacement at rated frequency shall not exceed the values given in Table 4 at any voltage between 80% and 120% of the rated voltage.

Table 4: Limits of Voltage Error and Phase Displacement for Electronic Measuring Voltage Transformers

Accuracy Class	ε_u Percentage Voltage (Ratio) Error (±)	φ_{uv} Phase Displacement (±)		φ_{u0}
		Minutes	Centiradians	
0.1	0.1	5	0.15	φ_{un}
0.2	0.2	10	0.3	φ_{un}

Note : The normal value of φ_{un} should be zero. However, different values can be specified when the electronic voltage transformer must be used in combination with other electronic voltage transformers or electronic current transformers in order to have a common value.

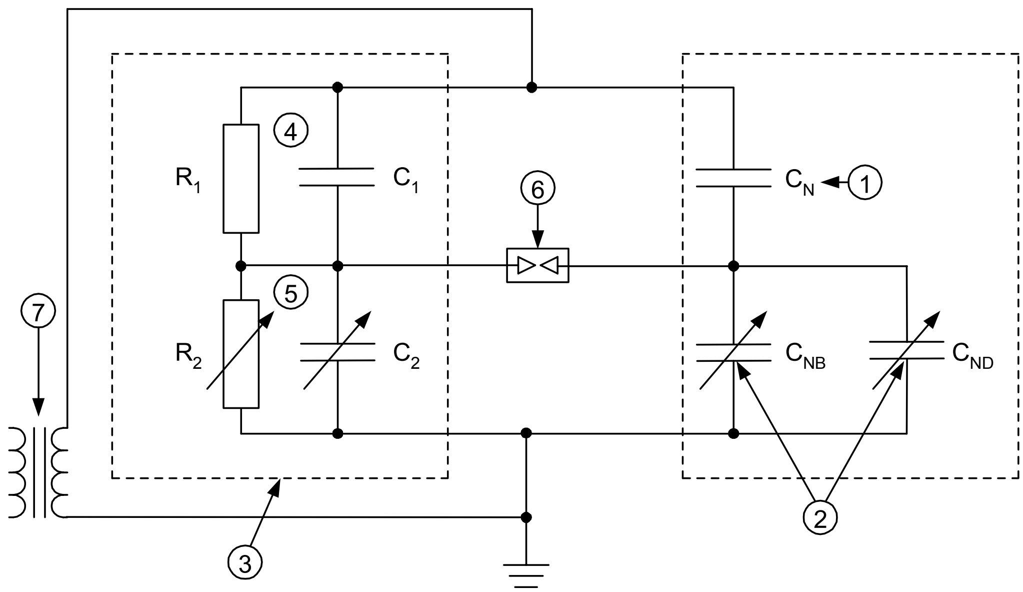


a. Divider

b. Precision RC-Divider Network

1 High Voltage Terminal
2 Voltage Taps
3 RC-Module
4 Secondary Divider for Vm = 36 kV
5 Low Voltage Terminal

Figure 10: Precision RC-Divider



1 Standard Capacitor (C_N)
2 Standard Adjusting Capacitors (C_{NB}, C_{ND})
3 Precision RC-Divider
4 High-Voltage Section
5 Low-Voltage Section
6 Electronic Zero Indicator (amplitude and phase displacement)
7 High-Voltage Transformer

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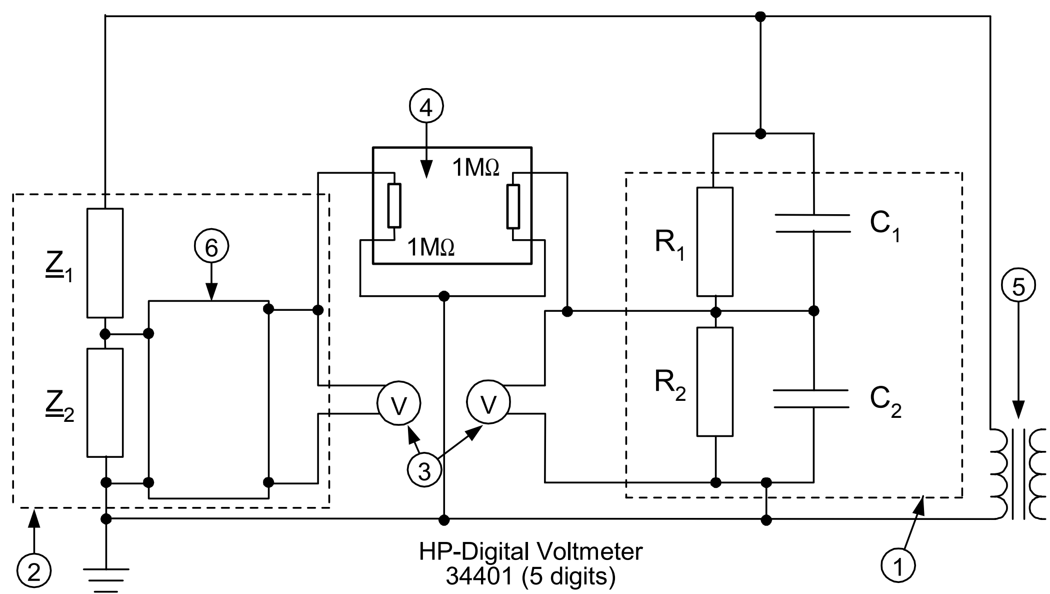
Figure 11: High Voltage Calibration Circuit. Schering Bridge



1 Precision RC-Divider
2 Divider Under Test
3 Digital Voltmeters
4 Phasemeter
5 High-Voltage Transformer
6 Adjusting Network for Amplitude and Phase Displacement (factory adjusted)

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Figure 12: Circuit for Routine Accuracy Tests

Dielectric Development Tests

Table 5: Voltage Measurement Technology Comparison

Technology	Wound PT	CVT	C-Divider	Compensated R- or RC-Divider
Steady State Accuracy	(+ +) Excellent	(+) Good	(+) Good	(+ +) Excellent
High Voltage Line Discharge	(+ +) yes	(- -) Problem dissipating trapped charge	(- -) Problem dissipating trapped charge	(+ +) yes
Ferro-resonance with System or Itself	(- -) Yes	(- -) Yes	(+) No	(+ +) No Not sensitive to ferroresonance
Transient Performance	(+) Sufficient for slower protection functions	(- -) Requires additional damping or relay correction	(+) Sufficient for traditional protection functions	(+ +) Excellent
Short Circuit Secondary	(- -) Requires fuses to prevent damage	(- -) Requires fuses to prevent damage	(+)	(+ +) Can be shorted for extended periods without damage
Dielectric Performance Against Surge	(+) Requires high skill level to design layer winding	(+) Accuracy changes if one capacitor short circuits	(+) Accuracy changes if one capacitor short circuits	(+ +) Cast resin insulation is completely insensitive to surges
Wide Burden Range	(+) Burden must fall within spec. range	(-) Ferro. damping increases with burden	(-) Ratio changes with burden	(-) Only the ratio changes

Grading Legend: (- -) unsatisfactory, (-) poor, (+) satisfactory, (+ +) excellent

The College HTA performed the following tests on thick film resistor and film capacitors [12], [13] during the last five years:

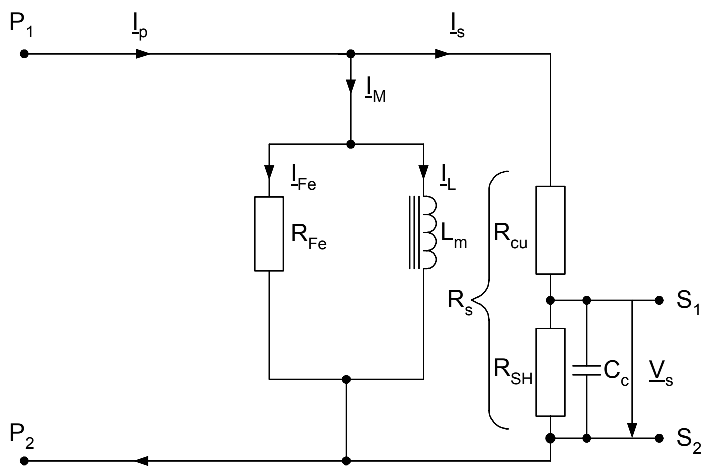
1. AC-life test.
2. Test with lightning impulse voltage (1.2/50 μs).
3. Bipolar and unipolar lightning impulses with a fast rise wavefront ($\frac{dV(t)}{dt}$ = 5 ns to 8 ns).
4. Stability test of a coaxial GIS R-divider against re-striking during switching operation using a vacuum circuit breaker.

Papers showing the results of these tests are scheduled. Table 5 summarizes the benefits of each technology for voltage measurement.

Low Power Current Transducer (LPCT)

The Iron Core Type Current Sensor

The LPCT current sensor consists of an inductive current transformer having a primary winding, a small core and a minimized-loss secondary winding. The shunt resistor R_{sh} is an integral part of the secondary winding and converts the traditional current output to a voltage.



P_1, P_2	Primary Terminals	N_S	Secondary Winding
S_1, S_2	Secondary Terminals	R_{SH}	Shunt Resistor (converter from current to voltage)
K_R	Rated Transformation Ratio		
$\underline{I}_p(t)$	Primary Current	R_{Fe}	Equivalent Iron Core Loss Resistor
$\underline{I}_s(t)$	Secondary Current	L_m	Equivalent Magnetizing Inductance
$\underline{I}_L$	Magnetizing Inductance Current	R_{cu}	Total Resistance of Secondary Winding/Wiring
$\underline{I}_M$	Magnetizing Impedance Current		
$\underline{I}_{Fe}$	Magnetizing Resistance Current	R_s	Total Secondary Resistance
$\underline{V}_s(t)$	Secondary Voltage	C_c	Equivalent Capacitance of the Cable
N_P	Primary Winding		

The output voltage, $\underline{V}_s$, of a LPCT equals $\underline{V}_s = R_{SH} \cdot \frac{N_p}{N_s} \cdot \underline{I}_p = \frac{1}{K_R} \cdot \underline{I}_p$

with $K_R = \frac{1}{R_{SH}} \cdot \frac{N_s}{N_p} \rightarrow \underline{I}_p = K_R \cdot V_s$

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Figure 13: Equivalent Circuit of the Iron Core Current Transducer With Voltage Output

Equation 1 lists the output voltage V_{SR} of a LPCT as a function of primary current I_P.

$$\underline{V}_{SR} = R_{sh} \cdot \underline{I}_S = R_{sh} \cdot \frac{N_P}{N_S} \cdot \underline{I}_P = \frac{1}{K_R} \cdot \underline{I}_P \qquad (1)$$

Where:

$$K_R = \frac{1}{R_{sh}} \cdot \frac{N_s}{N_p} \quad \left[\frac{A}{V}\right]$$

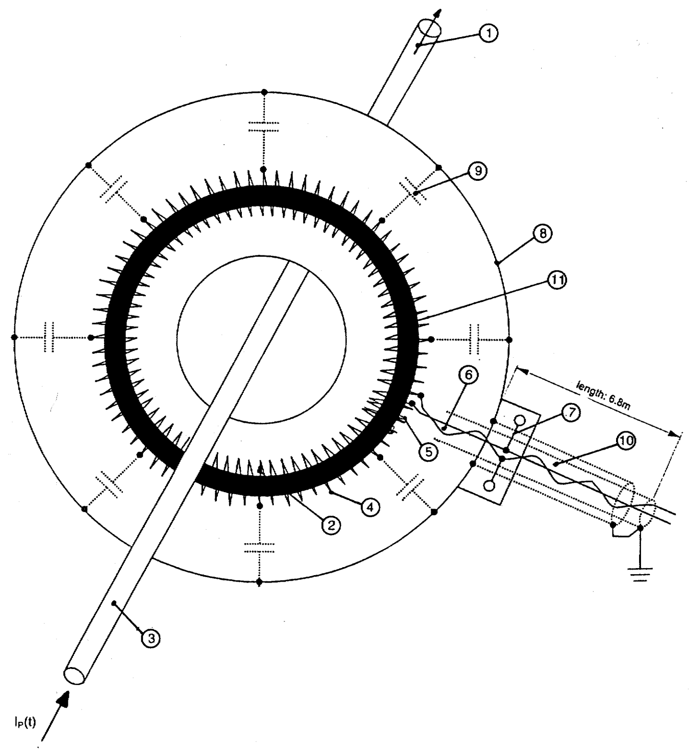
R_{sh} = Secondary resistance
$\underline{I}_P$ = Primary current [A]
$\underline{I}_S$ = Secondary current [A]
N_S = Number of secondary windings
N_P = Number of primary windings

Substituting K_R into Equation 1 yields

$$\underline{I}_P = K_R \cdot \underline{V}_{SR} \qquad (2)$$

The Design of the LPCT with an Iron Core

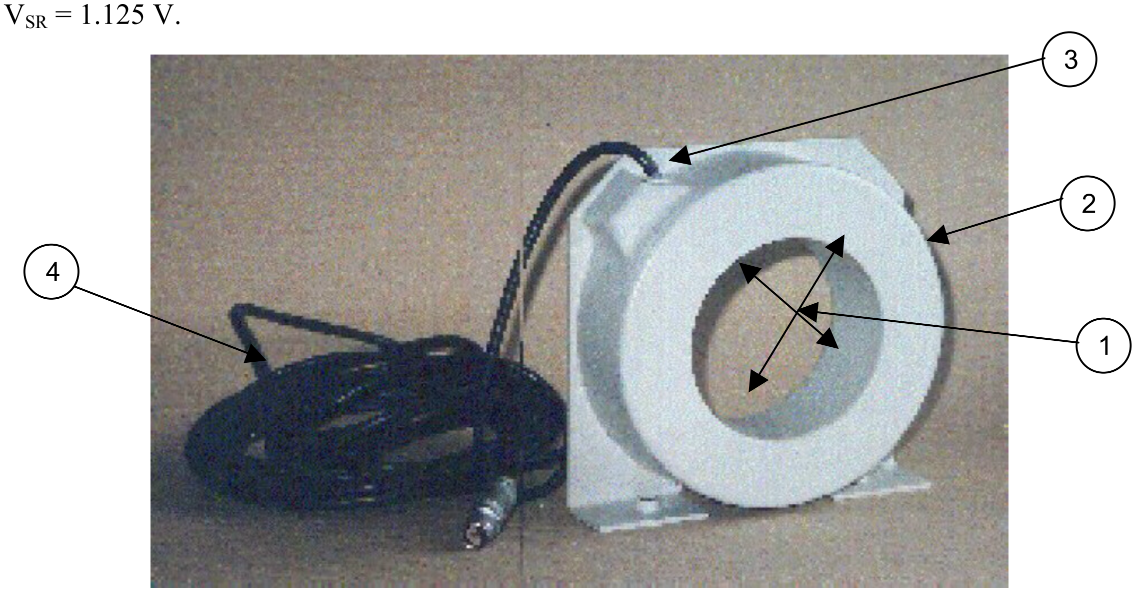
An important requirement for MV current sensors with a voltage output is a high immunity against electric and magnetic fields. A metallic housing shields the internal circuitry of the LPCT against the influence of electric fields. For the immunity against magnetic fields, the LPCT design avoids any loops and areas in which voltages can be induced. The two wires connected to the shunt resistor are twisted and protected against external electric fields with a double screen (Figure 14).



1 $I_P(t)$ Primary Current
2 $I_S(t)$ Secondary Current
3 N_P Primary Winding
4 N_S Secondary Winding
5 R_{SH} Shunt Resistor
6 Twisted Pair Secondary Wires
7 Connection: Shunt Wires–Cable Wires
8 Metallic Housing
9 Equivalent Stray Capacitor C_{EN} Against Ground
10 Double Shielded Cable
11 Iron Core

Figure 14: LPCT Design Circuit

Figure 15 shows an LPCT with a rated primary current I_{PR} = 2500 A and a secondary voltage V_{SR} = 1.125 V.



1. Space for Primary Conductor
2. Metallic Housing with Core, Secondary Winding, and Shunt Resistor
3. Connection: Shunt Wires-Cables Wires
4. Double Shielded Cable with Twisted Wires

Figure 15: Low Power Iron Core Current Transducer for MV-Switchgear

Table 6: Primary Current to Secondary Voltage Transformations[4,5,6]

Primary Current: I_{PR}	Secondary Voltage: V_{SR}
50 A[2]	22.5 mV[3]
500 A[2]	225 mV[3]
2500 A	1.125 V
25,000 A	11.25 V

Note 2: Preferred standard values for rated primary currents I_{PR}.

Note 3: Standard values for rated secondary voltage VSR at rated primary currents I_{PR}.

Note 4: Example: (Base: IEC draft 60044-8; status CDV).

Note 5: Current range: 50 A to 2500 A.

Note 6: Ratio: K_R = 2222.2 A / V.

The Dynamic Test of the Iron Core LPCT

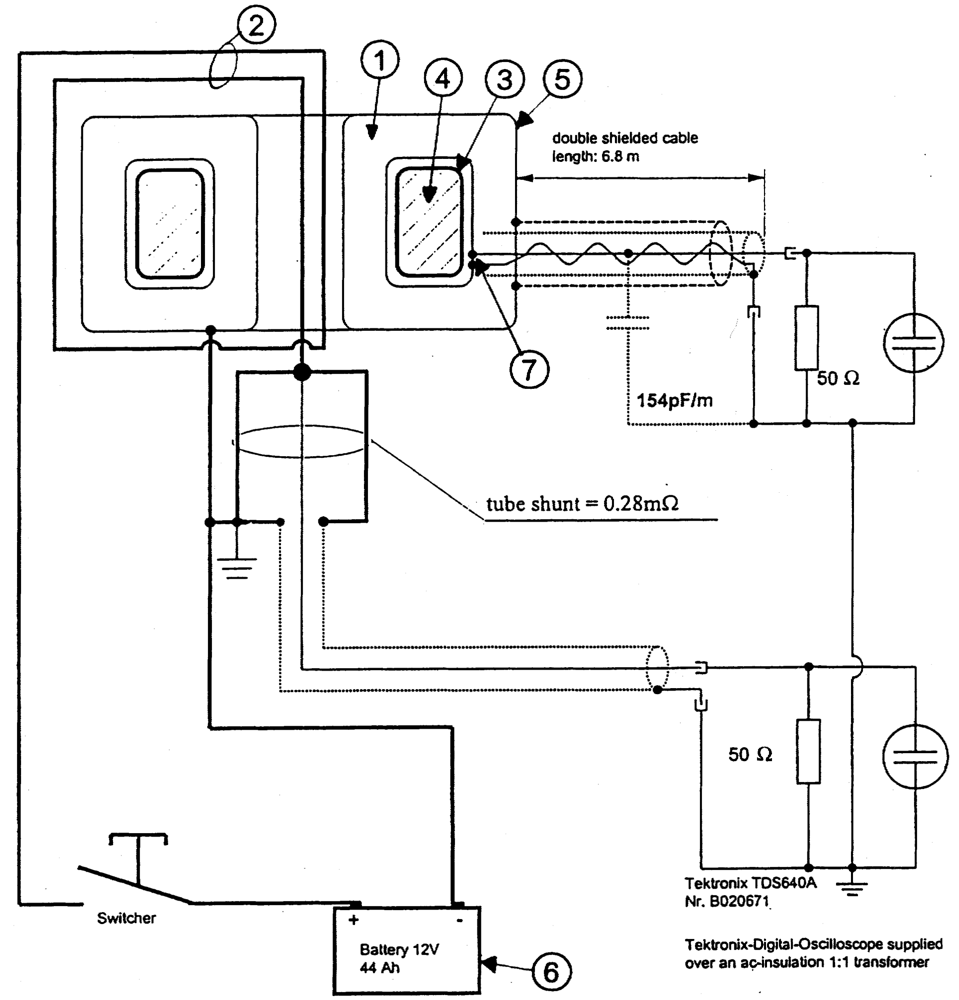
A primary step function current is one test to prove the dynamic performance of the LPCT (Figure 16). A high frequency tube shunt measured the step input current. The value of the input current was (Figure 17):

$$I_P = \frac{V_{CH1}}{0.28 \cdot 10^{-3}} = \frac{50 \cdot 10^{-3} \cdot 3.4}{0.28 \cdot 10^{-3}} = 607 \text{ A} \qquad (3)$$

From Figure 17, we measured the secondary output voltage V_{SR} to 170 mV. The calculated primary current I_P was:

$$I_P = \frac{V_S}{R_{SH}} \cdot \frac{N_S}{N_P} = \frac{170 \cdot 10^{-3} \cdot 5000}{0.708 \cdot 2} = 600 \text{ A} \qquad (4)$$

The time constant $T = \frac{L}{R}$ = 0.6 ms of the step input current Ip(t) was determined by the inductance and resistance of the loop.



The dynamic test was performed with a primary step function current.

1 Current Sensor
2 Primary Windings: $N_P = 2$
3 Secondary Windings: $N_S = 5000$
4 Iron Core
5 Metallic Housing
6 Current Supply Source
7 Shunt Resistor Value: 0.708 Ω (part of secondary winding)

Figure 16: Dynamic Test Circuit

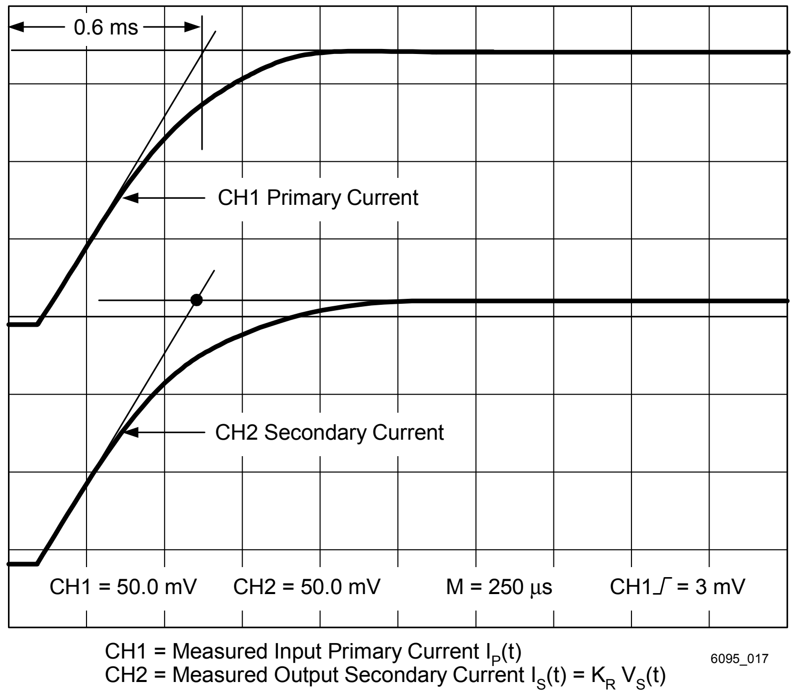


Figure 17: Measured Input (CH1) and
Output (CH2) Current of the LPCT During the Time t = 0 to 2 ms

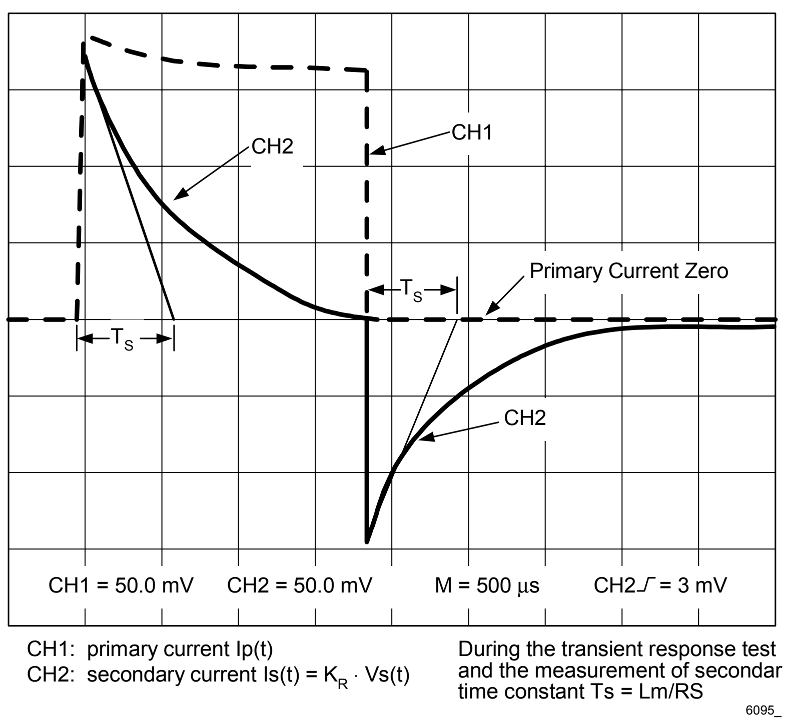
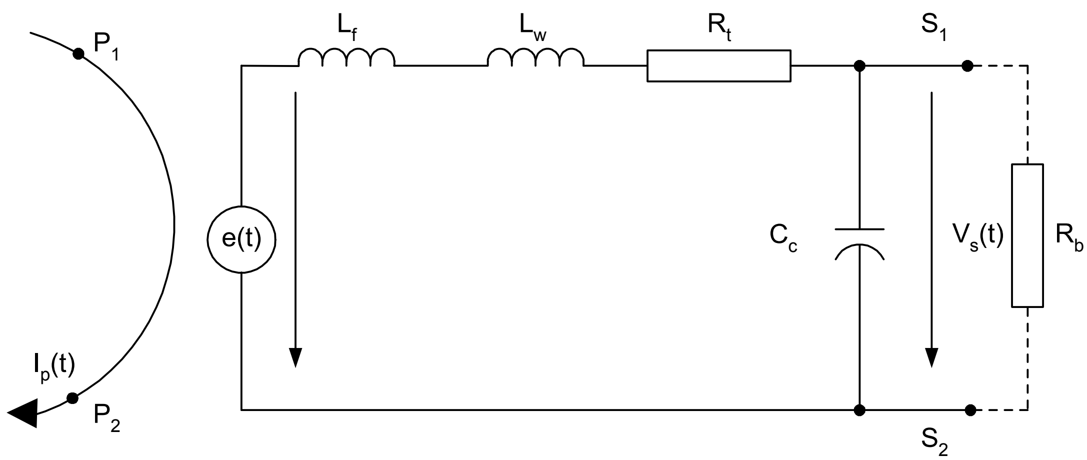


Figure 18: Input (CH1) and Output (CH2) Current
During Switching On and Off the Primary Input Current (CH1)

The Stand Alone Air Core Coil Sensor[7]

In high voltage networks, air core coils are increasingly used for protection and measuring where the connected burden is fixed and known. In an air core coil, the secondary windings are wound on nonmagnetic core material. These sensors have no saturation and no hysteresis. This design principle provides a good transient response and good steady-state behavior.

Figure 19 shows the equivalent circuit of a stand-alone air core current transducer with a voltage output.



$I_p(t)$	Primary Current	Rt	Total Resistance of Secondary Winding/Wiring
e(t)	Induced Voltage	$V_s(t)$	Secondary Output Voltage
L_f	Leakage Inductance of Secondary Winding	C_c	Equivalent Capacitance of the Cable
L_w	Wiring Inductance	R_b	Load Impedance, Power Factor = 1
L	$L_f + L_w$	P_1,P_2	Primary Terminals
		S_1,S_2	Secondary Terminals

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Figure 19: Equivalent Circuit of an Air Core Current Transducer

Note 7: By definition a stand alone air core coil (IEC draft 60044-8; status: CDV) is an air core coil without an integrator. These coils are also commonly referred to as Rogowski coils.

From the circuit shown in Figure 19, we can derive the following equations to see the influence that the value of the connected burden has on the output of the air core sensor (we excluded the cable capacitance, Cc, to simplify the calculations).

$$e(t) = M \cdot \frac{\partial i_P\ (t)}{\partial\, t} \tag{5}$$

where: M = the mutual inductance between the primary and secondary circuit.

For sinusoidal steady-state current conditions:

$$\underline{E} = M \cdot\ j\, \omega \cdot \underline{I_P} \tag{6}$$

Using the equations for E and e, we can now calculate the secondary voltage.

$$\underline{V}_S = \frac{R_b}{R_t + R_b + j\omega L} \cdot \underline{E} = \frac{R_b}{R_t + R_b + j\omega L} \cdot M \cdot j\omega \underline{I}_P \tag{7}$$

For $R_b \rightarrow \infty$,

$$\frac{\underline{V}_S}{\omega M} = \frac{\underline{E}}{\omega M} = j\underline{I}_P \tag{8}$$

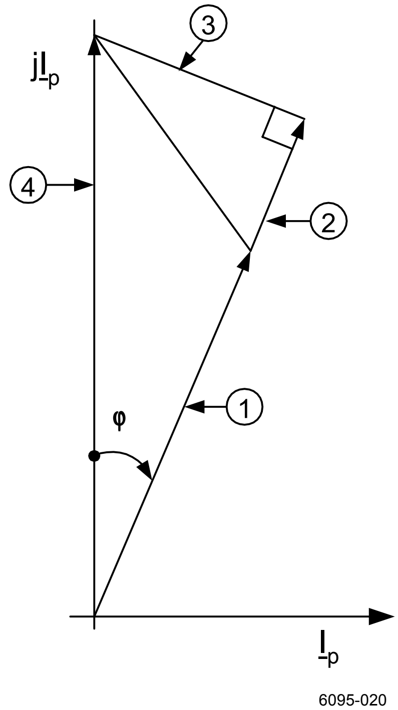
The phasor diagram in Figure 20 follows from Equation 7 with

$$\frac{\underline{V}_s}{M\omega} + \frac{R_t}{R_b} \cdot \frac{\underline{V}_s}{M\omega} + \frac{j\omega L}{R_b} \cdot \frac{\underline{V}_s}{M\omega} = j\underline{I}_P \tag{9}$$

From Figure 20 with $\frac{\Delta M}{\Delta t} = 0$:

a) Phase-error: $$\varphi = -\arctan \frac{\omega L}{R_b + R_t} \approx -\arctan \frac{\omega L}{R_b} \tag{10}$$

b) Amplitude-error: $$\underline{\varepsilon} = -\frac{R_t + j\omega L}{R_b + R_t + j\omega L}, \quad |\underline{\varepsilon}| \approx -\frac{R_t}{R_b} \tag{11}$$



$$\underbrace{\frac{\underline{V}_S}{M\omega}}_{1} + \underbrace{\frac{R_t}{R_b} \cdot \frac{\underline{V}_S}{M\omega}}_{2} + \underbrace{\frac{j\omega L}{R_b} \cdot \frac{\underline{V}_s}{M\omega}}_{3} = \underbrace{j\underline{I}_P}_{4}$$

Figure 20: Phasor Diagram of a Stand Alone Air Core Coil

CONSIDERATIONS ABOUT THE IRON CORE AND AIR CORE LPCT TECHNOLOGIES

The iron core LPCT with a voltage output on the secondary side is based on today's well known current transformer technology. The internal shunt resistor is a new element but the knowledge of resistor material for shunt application is very well developed and understood. For air core LPCT the output voltage $\underline{E} = M\ j\omega\, \underline{I}_P = \underline{V}_S\big|_{R_b \to \infty}$ depends upon a stable and constant mutual inductance M to deliver accurate and repeatable results. This means that the material selected for this type of current sensor must be stable across a wide temperature range.

For protection applications not requiring high fault sensitivity, the influence of M is of minor importance. However, for multipurpose LPCTs used for protection and requiring a metering accuracy class of 0.1, there is little experience with air core coils.

The influence of the load impedance R_b, having a unity power factor, on the accuracy of both LPCTs is completely different. For iron core LPCTs the manufacturer must specify only a minimum value of burden resistance: $R_b \geq R_X$. For example, $R_b \geq 20$ kΩ. The value is a function of the guaranteed accuracy class.

For air core LPCTs the value of R_b must take into account the ratio and phase adjustment. The values of the internal shunt resistor of the iron core LPCTs are in the range between 1 Ω to 50 Ω. The values depend upon the application of the LPCT. As a result of the low values of R_b, the immunity against external disturbances is very high.

For air core coil sensors the loop resistance is in the order of 2 MΩ. With this high loop impedance the shielding of the measuring circuit becomes very important.

Table 7 lists the benefits of each type of current transducer technology discussed.

Table 7: Benefits of Various Current Transducer Technologies

Technologies for Electrical CT	Open Ckt Secondary Produces High V_{SEC}	Multipurpose for Metering and Protection	Burden Range	Phase Shift
Iron Core: 1 or 5 A	(- -) Dangerous	(- -) Requires separate cores for highest accuracy classes with rated burden	(+) Within spec. up to the specified burden	(+) Approximately 5 to 50 MOA (minutes of angle)
Air Core with Voltage Output	(+ +) Secondary can be open	(- +) Acceptable for certain range of metering (error for low |I|)	(- -) Calibrated for each burden	(- -) Introduces –90° phase shift
Iron Core with Voltage Output	(+ +) Secondary can be open	(+ +) 50 A to 25 kA for metering and protection without saturation	(+ +) Rs ≥ 10 kΩ Rb ≥ 20 kΩ	(+ +) <10 MOA

Grading Legend: (- -) unsatisfactory, (-) poor, (+) satisfactory, (+ +) excellent

TESTS OF 24 KV MV SYSTEM WITH MICROPROCESSOR RELAY AND LOW POWER VOLTAGE AND CURRENT TRANSDUCERS

An important part of the development of low power voltage and current transducers was the testing of a complete MVS: circuit breaker, relays, voltage sensors and current sensors.

During university graduate work in the college HTA-Burgdorf-CH, such a test circuit was installed. The electric diagram of the installation is shown in Figure 21 [14].

While equipped for three-phase, only one phase of the MVS energized at the system voltage 13.8 kV_{L-N} (24 kV_{L-L}). Thus, two phase currents were zero during the test. The function of the distance relay was simulated first with the software program Lab View™ for control purposes and as a means of validating the results.

The resistance of the relay input network was 10 MΩ to ground. The relay input circuits were well protected with semiconductor devices and capacitor networks. This same input circuit was developed earlier for integrating with the output of a fiber-optic voltage and current transducer application. No isolator transformer after the voltage or current terminals separated the different dynamic potential ground points during switching operations with the MV-vacuum breaker.

The input protection network of the relay was very effective against surge voltage at the beginning of the tests. The selected grounding of the double-shielded cable with twisted wire between the current sensor and the relay was not optimal and during the "close to open" operation of the HV-circuit breaker, high surge voltages were measured on the I_A input terminal of the relay. Induced surge voltages were eliminated in the circuit shown in Figure 22.

In all fault tests, the relay performed well. A secondary result of this testing is that the manufacturer is making input circuit modifications to comply with the IEC meter class accuracy requirements outlined by class 0.1 (see Table 8).

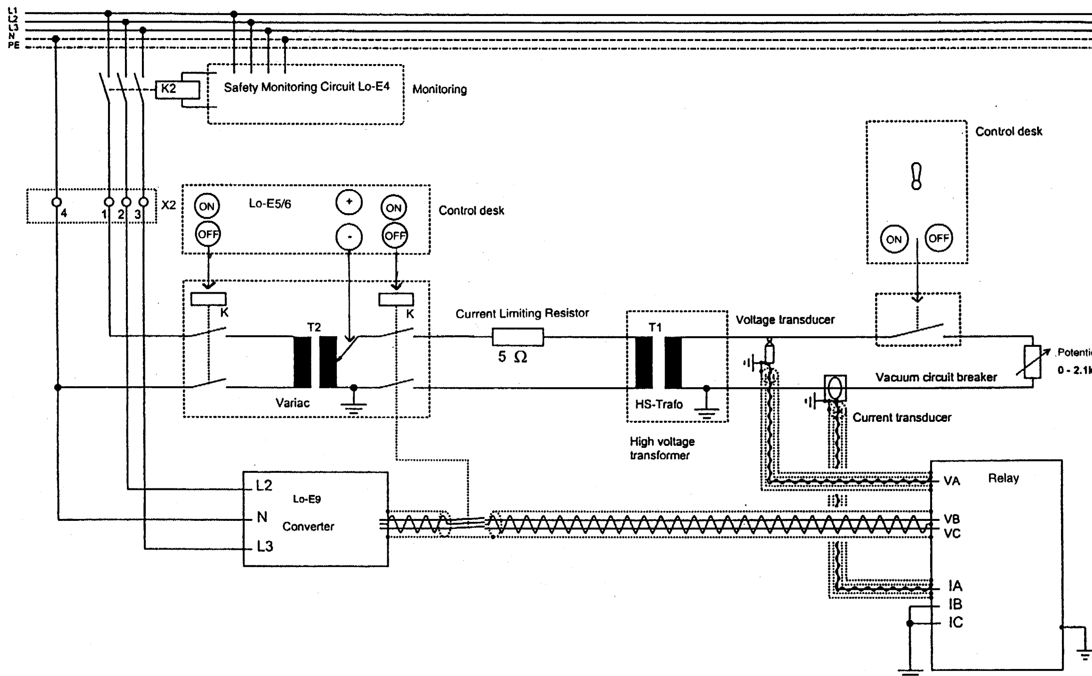


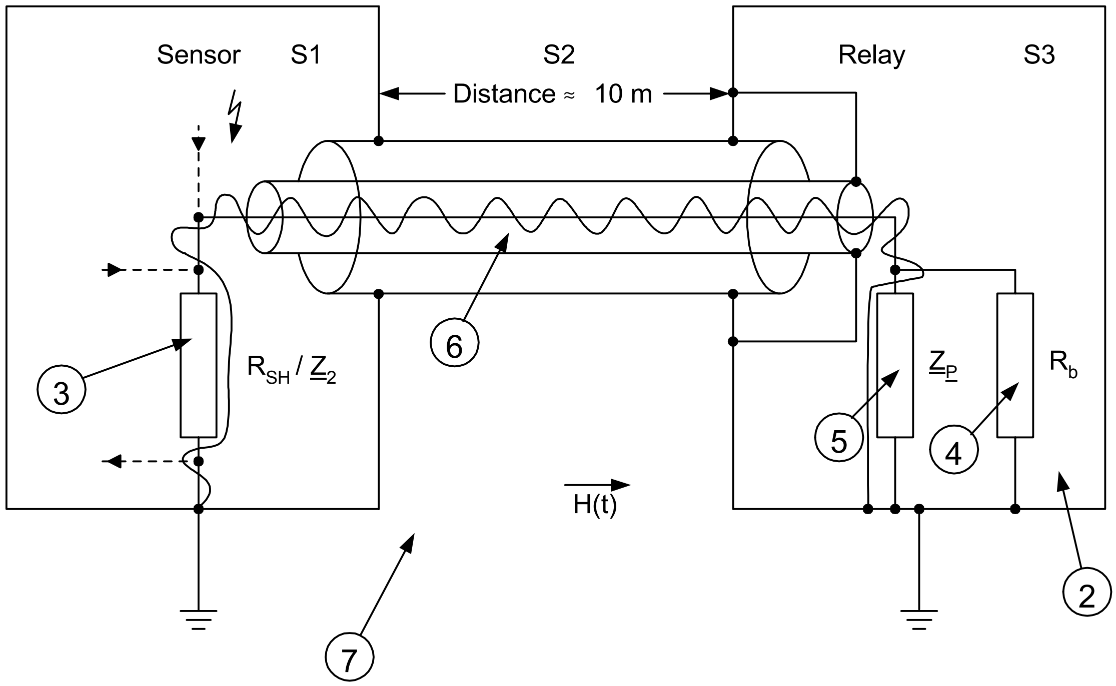
Figure 21: Test Circuit of a MVS, Vm = 24 kV System

Table 8: Limits of Error

Accuracy Class	± Percentage Current (Ratio) Error at Percentage of Rated Current Shown Below				± Phase Error at Percentage of Rated Current Show Below							
					Minutes				Centiradians			
	5	20	100	120	5	20	100	120	5	20	100	120
0.1	0.4	0.2	0.1	0.1	15	8	5	5	0.45	0.24	0.15	0.15
0.2	0.75	0.35	0.2	0.2	30	15	10	10	0.9	0.45	0.3	0.3

The microprocessor relay was used for both voltage and current sensing functions [15].

The connection system (S2) between the sensors (S1) and the protection relays (S3) becomes a sensitive part of the new technology. This is a result of the low power and output voltage signals of the transducers, the high input impedance of the protection relays and measuring equipment. This sensitivity is controlled using double-shielded, twisted pair connections.



1 Voltage- or Current Transducer
2 Relays/Measuring Device
3 Secondary Impedance $\underline{Z}_2$ of the R- or RC-Divider or Shunt Resistor R_{SH}
4 Input Impedance of the Relays and Measuring Device
5 Protecting Network $\underline{Z}_P$
6 Double Shielded Cable with Two Twisted Pair
7 Loop for Inducing Interference Voltages

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Figure 22: Connection System: Sensor to Relays

CONCLUSIONS

1. The connection system S2 is an important component for the interference free measurement.
2. It is easy to measure signals from 10 µV and higher.
3. The power factor of the high impedance input network of system S3 must be taken into account for the calibration of the voltage transducer.
4. The phase shift from the input network of a relay together with the high impedance output source of the voltage sensor was approximately 6°. Reducing the input circuit capacitance can reduce this phase shift to <0.01°.
5. The protecting network on the input terminals can be easily modified to suit the need for safe operation.
6. The protecting input network for metering must be very stable and must be specified for high accuracy adjustment of the R-divider.

7. The iron core LPCT with a low impedance voltage output source can easily be introduced for measuring and protection purposes in MV- and HV-switchgear.

8. The air core current transducer needs more application technique than the iron core transducer.

9. The reliability of the new voltage sensor is equal to a magnetic voltage measuring transformer but the new system is free from ferroresonance oscillations and has a high electric strength against surge voltages.

10. The high transient response performance of the R/RC-divider voltage sensor and of the LPCT opens new opportunities for diagnostic purposes.

11. The iron core LPCT does not require external shorting switches for safety.

12. The weight of the new sensors is very low compared with cast resin vts and cts.

13. The cost reduction for simplified assembly and the smaller size are advantages of this new technology for use in switchgear.

STATUS OF THE INTERNATIONAL STANDARDS FOR VOLTAGE AND CURRENT TRANSDUCER

The IEC standard 60044-7 “Electronic Voltage Transformer” is now a FDIS (Final Draft International Standard) and an excellent base for low power voltage transducers with analog voltage output. Only the standard values of rated output are too high for the application. This will be modified in a future amendment to 60044-7. In annex B4 of this standard, the transient conditions and the trapped charges phenomena of C-divider are described; this is a subject of discussions in IEC working groups.

The IEC standard 60044-8 “Electronic Current Transformer” will now be a CDV (Committee Draft for int. Voting). The working group WG 27 hopes to finish the CDV this year. In this standard are both:

- output with analog voltage signals, and
- output with digital signals.

For analog output signals two technologies are described:

- iron core LPCT, and
- air core LPCT.

The iron core current transducer is developed in accordance to this standard.

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BIOGRAPHIES

Dr. -Ing. Ruthard Minkner

Dr. Ruthard Minkner earned his Dr.-Ing. degree from the Technical University of Berlin-Charlottenburg, West Berlin, Germany in 1966. From 1957 until 1966, Minkner worked as a development engineer for Emil Haefely AG in Basel, Switzerland, where he specialized in ion-accelerators; electron-accelerators; high-precision, high-voltage measuring dividers; and closed loop voltage regulation circuits.

From 1967 until 1971, Dr. Minkner served as manager of new product development at Regel and Messtechnik in Kassel, Germany. In 1972 he returned to Emil Haefely AG and served there until 1988 as director for high-voltage components.

From 1989 to 1998, Dr. Minkner taught at the college Burgdorf Switzerland the subjects high-voltage engineering and servo-mechanisms.

He now works at the college on projects for various industries and is a consultant for Trench Switzerland AG. Dr. Minkner serves as chairman of the national Swiss Technical Committee for instrument transformers and is convenor of working groups and taskforces for new IEC standards.

He has presented several special lectures and has published many papers, including three in 1999 on coaxial flange voltage sensors in gas-insulated medium-voltage switchgear, resistor technology for high-voltage sensors, and a flexible fiber optic current-measuring system. He has also been a visiting power professor at Washington State University in Pullman, Washington USA.

Edmund O. Schweitzer, III, Ph.D.

Dr. Schweitzer was born in Evanston, Illinois, USA, in 1947. He received his Bachelor's degree and his Master's in electrical engineering from Purdue University. He received his Ph.D. degree from Washington State University, upon completion of his dissertation on digital protective relaying.

Dr. Schweitzer continued his research in digital protective relaying while serving on the electrical engineering faculties of Ohio University and Washington State University. The research covered both theoretical and practical aspects, and demonstrated the feasibility and practicality of digital techniques for protecting electric power apparatus and systems.

He also taught courses in electric power system analysis, electrical energy conversion, power system protection, electronics, and communications theory.

In 1982, Dr. Schweitzer founded Schweitzer Engineering Laboratories, in Pullman, Washington, to develop and manufacture digital protective relays and related products and services. Today, SEL is an employee-owned company, which serves the electric power industry worldwide, and is certified to the international quality standard ISO-9001. SEL equipment is in service at voltages from 5 kV through 765 kV, to protect feeders, motors, transformers, capacitor banks, transmission lines, and other power apparatus.

Dr. Schweitzer is recognized as a pioneer in digital protection, and holds the grade of Fellow of the Institute of Electrical and Electronic Engineers (IEEE), a title bestowed on less than one percent of IEEE members.

He has written dozens of technical papers in the areas of distance relay design, filtering for protective relays, protective relay reliability and testing, fault locating on overhead lines, induction motor protection, directional element design, dynamics of overcurrent elements, and the sensitivity of protective relays.

Dr. Schweitzer holds more than twenty patents pertaining to electric power system protection, metering, monitoring, and control.

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