Tutorial PCIC 2026-5

Protection and Control in Distribution Switchgear using Current and Voltage Sensors

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Philadelphia, PA

Tutorial Presenters

Dr. Harsh Karandikar

- Product Line Manager
- ABB Inc., Mebane, NC
- Dr. Harsh Karandikar has over 35 years of experience in the engineering and product management of industrial products and services and with a focus in the last decade on technologies for medium voltage electrical power distribution. He is currently the Product Line Manager for ANSI MV switchgear for ABB & leads the digital initiatives for ANSI LV & MV switchgear. He is a Senior Member of IEEE and a Fellow of the ASME. He holds a Ph.D. from the University of Houston.

Dr. Lukas Cesky

- Global Product Manager
- ABB s.r.o., Brno, Czech Republic
- Lukas holds a doctorate in Power Engineering from the Slovak University of Technology. Lukas is a member of the PES and the member of IEC, IEEE working groups, which focus on MV instrument transformers and sensors. Lukas has 10+ years of experience in Power Engineering and is the author of many articles connected with this topic. He continues to lecture within the industry including at universities and international conferences.

Tutorial Presenters

Terry Neighbours

- Global Product Manager
- ABB Inc., Lake Mary, FL
- Terry Neighbours has over 40 years of experience in the medium voltage switchgear and motor control businesses. Terry is a Senior IEEE Switchgear Committee member, a member of the IEEE – SA organization and a member of several IEEE working groups. He holds a BS degree in Organizational Management and has an extensive background in electrical engineering, applications, manufacturing and testing of medium voltage switchgear.

Agenda

Opening Remarks	1:00 – 1:15 pm
Current practice for current & voltage measurement in Distribution	1:15 – 1:45 pm
Overview and history of sensor technologies & the relevant standards	1:45 – 2:15 pm
Low Power Passive Current Transformers	2:15 – 2:30 pm
Low Power Passive Voltage Transformers	2:30 – 2:45 pm
Sensor features & applications	2:45 – 3:00 pm
Testing of Sensors – Type tests, Routine tests, FAT, On site tests	3:00 – 3:15 pm
Break	3:15 – 3:30 pm
A Sensor Application: Digital Switchgear	3:30 – 4:30 pm
Closing remarks and Q&A session	4:30 – 4:45 pm

Current practice for current & voltage measurement in Distribution

The General Equation – Faraday's Law

$$e = -N\int d\phi/dt$$

where;

e is the electromotive force (emf) generated or induced in average volts

N are the turns in the winding

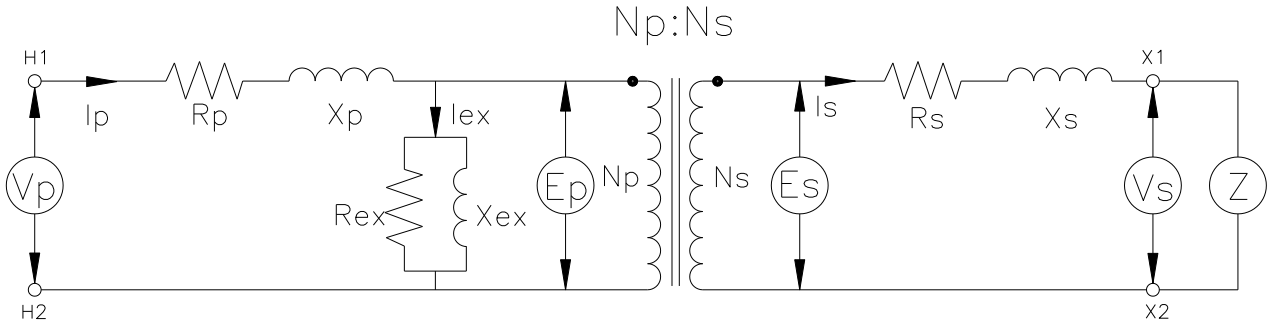
$d\phi/dt$ is the magnetic flux that varies by time

In order to induce a voltage, flux must vary in time.

If there is no change in flux, then there is no voltage.

Equivalent Circuit

In the “real” world, transformation comes at a cost due to the magnetic core. When the primary energizes or excites the core, some of the energy is consumed in the core, and what is left is transferred to the secondary circuit.



$$V_P I_P - V_{ex} I_{ex} = V_S I_S$$

For VTs, it’s VA balance

$$I_P N_P - I_{ex} N_P = I_S N_S$$

For CTs, it’s Ampere-Turn balance

The equivalent circuit above is valid for any wound-type instrument transformer

Instrument Transformers (ITs)

Magnetically coupled devices that isolate the Primary circuit from the Secondary circuit and are separated into 2 major types:

Current Transformers (CT)

- Measures currents as high as 50,000 A
- Reduces primary current to 5A nom, as well as 2.5A and 1A
- Are connected in series with the load
- Operating flux varies by load

Voltage Transformers (VT)

- Measures voltages as high as 765,000 V
- Reduces primary voltage to 120/115V or 69.3/66 V
- Are connected in parallel to the load
- Operating flux is constant

What You Must Know to Apply ITs

- Indoor or Outdoor use
- System Voltage & BIL
- Metering Class and Rated Burden
- Protection/Relay Class
- Frequency (if other than 60 Hz)
- Operating ambient temperature (if other than 30^{O}C)
- Mounting orientation

Additional information the *user* may need to know

- Any dimensional/physical constraints
- Utility specifications, special customer requirements, and standard (if other than IEEE)

What You Must Know (contd.)

… specifically for CTs

- Primary Current, taps if applicable
- Secondary Current, taps if applicable
- Window, Bar, or Wound Primary Type
- Gapped core, Remanence control

- Continuous Current Rating Factor (RF)
- Short-Time Thermal & Mechanical Ratings

… specifically for PTs

- Primary Voltage, taps if applicable
- Secondary Voltage, taps if applicable
- L-L or L-G connected
- Primary fuses

- Thermal Capacity – VA (for light power use)
- Over-Voltage ratings, continuous and short-time duty, IEEE Group class

Examples of CTs

Bushing Current Transformers (BCTs)

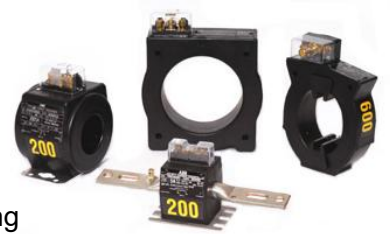
- No BIL (Internal BCTs)
- BIL – 10 kV BIL (External/Outdoor BCTs)
- Retrofit and Replacement
- Used in Power Transformers & Circuit Breakers
- May be customized w/special mounting features
- Available in a wide variety of sizes
- Utility & Commercial users

LV Protection & Control CTs

- BIL – 10 kV
- Plastic case / indoor rated
- Specific mounting footprints
- Used in MCC/MV switchgear & outdoor breakers
- Utility & Commercial users

LV Metering CTs

- BIL – 10 kV
- Indoor/Outdoor
- Window & Bar-type
- Secondary Revenue Metering
- Utility & Commercial users



Examples of PTs (also called VTs)

LV Indoor/Outdoor

- BIL – 10 kV
- Utility & Commercial users
- Secondary Revenue Metering

MV Outdoor class

- BIL – 60 kV to 250 kV BIL
- Single & Two bushing
- Primary Revenue Metering
- Substation metering & protection
- Light duty station service power

MV Indoor class

- BIL – 60 kV – 200 kV
- Single & Two bushing
- Fused and unfused
- Metering & Control
- Used in MV switchgear
- Utility & Commercial users

Sensors

- 30+ year old technology
- Solid state components, passive technology, analogue device with +30 years life-time
- No magnetic core → linear characteristic covering the whole application with one design only
- Numerous form factors, indoor & outdoor applications (voltage, current, combination)
- Low power output signal with safe level from mV to few Volts

What You Must Know to Apply Sensors

- Indoor or Outdoor use
- System Voltage & BIL
- Type of IED (Intelligent Electronic Device, e.g., a Protection & Control Relay)

Additional information the *user* may need to know

- Any dimensional/physical constraints
- Utility specifications, special customer requirements, and standard (if other than defined by standards)

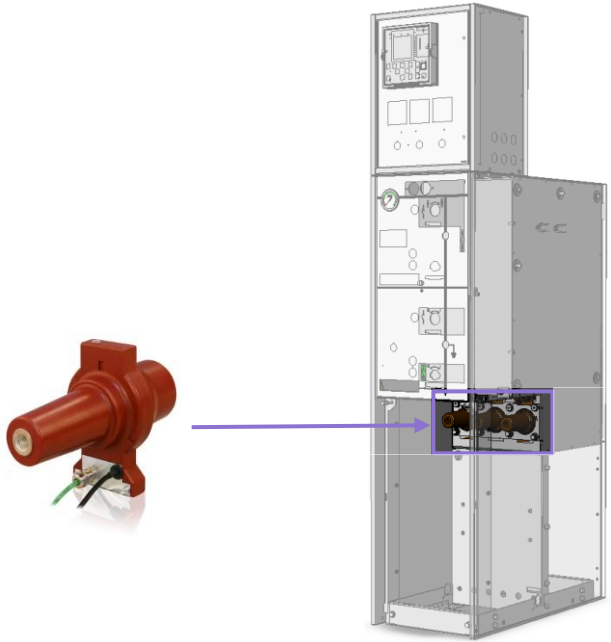
Examples of Current sensors for Air Insulated Switchgear (AIS)

- Example ring type sensor for AIS applications
- Suitable for new installations as well
- Rated primary current of application based on size constraints, typically up to 4000A
- Typical current accuracy classes 0.5 and 5P

Examples of Voltage sensors for AIS

- Resistive and capacitive based voltage sensing
- Suitable for new and retrofit installations
- Typical voltages up to 36 kV (IEEE 38kV class)
- Typical accuracy classes
  up to 0.5 measurement, 3P protection
- May double as insulator in compartment

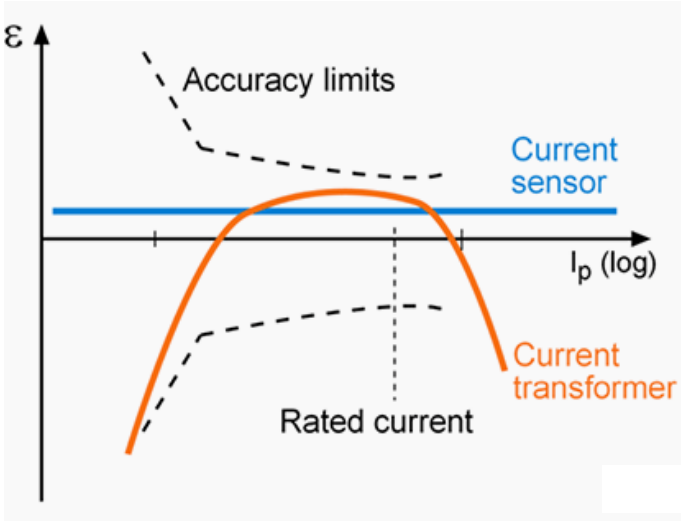
Example of Combined sensors for Gas Insulated Switchgear (GIS)



- Current and voltage measurments together with voltage indication in one compact frame
- Typical primary current of application up to 630 A
- Typical current accuracy class up to 0.5/5P
- Typical voltage accuracy class up to 0.5/3P

Accuracy Comparison – Rogowski Coil vs. Traditional CT

Current sensor accuracy for pure Rogowski coil



Summary of Sensor vs. Traditional IT Comparison

Feature	CT/VT	Sensors
Signal (output)	1/5 A / 110-240 V	150-180 mV / 2-10V / 120V
Secondary cables	To be added	Included and tested
Linearity	No	Yes
Saturation	Yes	No
Ferro-resonance	Yes (VT)	No
Temperature coefficient	No	Incl. in accuracy
Short-circuited secondary	Destructive (VT)	Safe
Open secondary	Destructive (CT)	Safe
Weight (typical MV)	40-60 kg (CT+VT)	2-25 kg (combined)
Standardization possible	Limited	Wider possibilities

Benefits of Sensors vs. Traditional ITs

Safety

One of the most important benefits

- Low voltage, low energy output signals
- No need to use PT fuses
- No need for personnel to access the switchgear for fuse replacements or maintenance of PT drawouts
- CT secondary can be left open or short-circuited
- Increased safety for personnel during testing & operation
- Plug – and – play solution directly connected to the IED
- Easy and reliable connection to protection relays

TRADITIONAL ITs

WARNING!!! The secondary circuit of CTs should never be opened or left open when current is flowing in the primary. If the secondary circuit is open, the primary current will drive the core to saturation, inducing abnormally high and possibly lethal PEAK voltages.

Benefits of Sensors vs. Traditional ITs

Installation

- Upgrade of switchgear parameters without additional costs
- Indoor sensors can often be retrofitted in existing structures with new relays
- Less weight, smaller size, e.g., switchgear PT drawout trays may be avoided
- Simplified installations – less wiring, smaller footprint, lighter weight

Benefits of Sensors vs. Traditional ITs

Linearity

- Flexibility toward varying load flow – linear response, extensive dynamic range
- More linear response, esp. when harmonics present
- Simplified installations – less wiring, smaller footprint, lighter weight
- Standardization – one sensor covers full voltage or current range of traditional IT family

Benefits of Sensors vs. Traditional ITs

Sustainability

- Environmental friendliness
  - less raw material needed
  - less energy consumption due to reduced losses

Challenges in using current & voltage sensors

- Cabling - sensors impedance matched
- Lack of power transfer to secondary to power devices
  - cannot run secondary devices on Sensor circuits in series. One set of sensors needed per relay/meter.
- Lack of standardization - standards limited in the ANSI/IEEE markets (UL certification available)
- Limited selection today of meters compatible with sensors

Overview and history of sensor technologies & industry standards

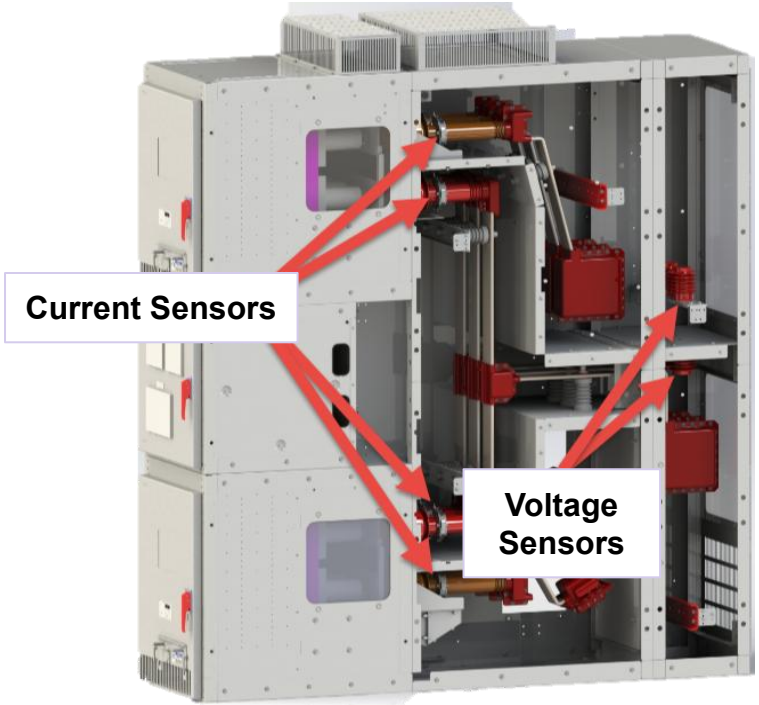
- History of sensor technology
- Industry standards related to sensor technology

Introduction

- Current & voltage sensors for MV applications available on the market 30+ years
- Large global installed base
- Growing demand around the world due to new grid applications

Role of Sensors in Switchgear

MV Switchgears and three key components



Brain

Intelligent electronic device (protection & control relay)

Muscle

Circuit breaker

Senses

Instrument transformer or Sensor

Evolution of Key Components

Historical development

Inteligent electronic devices

Electromechanical relays

Static (Solid State) relays

Digital (Microprocessor) relays

Circuit breakers

Air and magnetic principle

Oil principle

Vacuum principle

Instrument transformers

Oil insulation

Epoxy resin insulation

Epoxy resin insulation

Sensors

Market Drivers Contributing to Sensors' Need

Distribution systems improvement

- Fault Detection, Isolation & Restoration
- Power quality management
- Sub-station automation
- Remote grid control
- Safety

New applications

- Integrating renewables (solar, wind, etc.)
- Volt/VAR Optimization (VVO) – management of reactive power
- EV charging and consequent grid upgrade

Improving existing systems

- Safety
- Grid balancing and power flow modeling
- Improved asset management, optimizing use
- Flexible Retrofit solutions
- Data centers

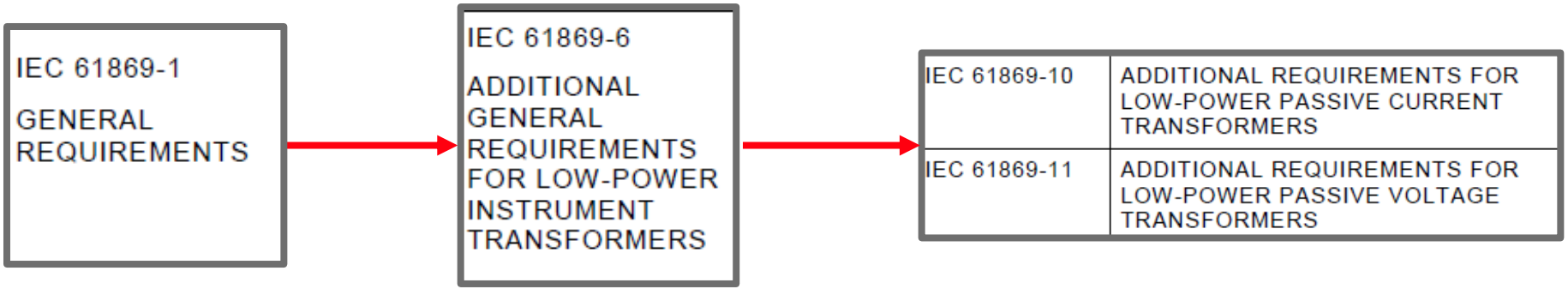
Legislative influence

- Penalties to non-delivered energy and system outages
- Incentives to digitalization
- CO2 zero emission policies

Evolution of Standards

1999	IEC 60044-7 Instrument transformers – Part 7: Electronic voltage transformers
2002	IEC 60044-8 Instrument transformers – Part 8: Electronic current transformers
2007	IEC 61869-1 Instrument transformers – Part 1: General requirements
2016	IEC 61869-6 Instrument transformers – Part 6: Additional general requirements for low-power instrument transformers
2017 December	**IEC 61869-10 Instrument transformers – Part 10: Additional requirements for low-power passive current transformers** **IEC 61869-11 Instrument transformers – Part 11: Additional requirements for low-power passive voltage transformers**
???	**IEEE device standard for sensors**

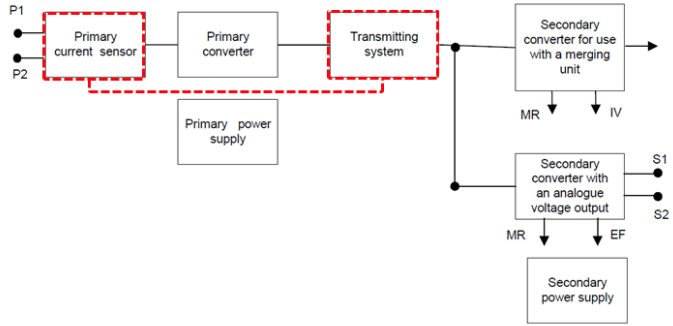
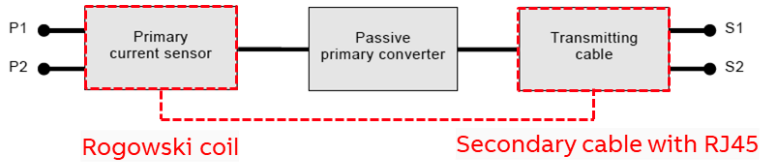
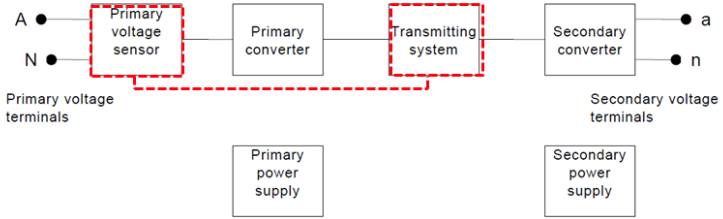
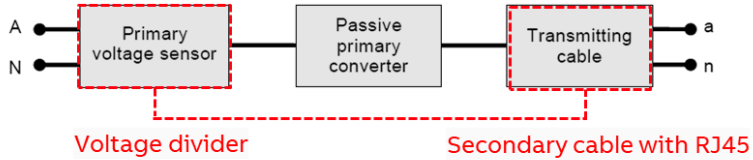
IEC 61869 standard family



IEC standardization

- IEC 60044-7 (1999) - Electronic voltage transformers
- IEC 60044-8 (2002) - Electronic current transformers
- **IEC 61869-10 (2017)** - Additional requirements for low-power passive current transformers
- **IEC 61869-11 (2017)** - Additional requirements for low-power passive voltage transformers

Sensor definitions according to IEC standards

	Old definition according to IEC 60044-7 and IEC 60044-8	New definition according to IEC 61869-10 and IEC 61869-11
Current sensor		
Voltage sensor		

Why comply with the latest standards?

Value of standardization

- **IEC 61869 sensor standards:**
  - Represent the consensus on requirements in industry.
  - Prepared by various experts from designers, producers, consultants and users.
  - Define all requirements on sensors based on the latest needs in applications.

Performance and Quality

- All requirements are defined by IEC standards (dielectric, temperature, short-time, power frequency, transient, etc.).
- Long-term compatibility with different IEDs
- Standardized connectors with defined pinout
- Accuracy performance defined for the measurement, frequency and temperature ranges.

Safety and Reliability

- Standards specify basic requirements on material, design and construction.
- Sensor designs are type tested, preferably in accredited laboratory.
- Sensors are tested together with cable connectors.
- Every piece is routine tested before dispatch.
- UL certifications are always made to the latest standards.

IEEE/ANSI Standards for current & voltage sensors

- **IEEE C37.235-2021** - Guide for the Application of Rogowski Coils used for Protective Relaying Purposes
- **IEEE Std C37.92™-2023** Standard for Low-Energy Analog Interfaces between Protective Relays and Power System Signal Sources
- **IEEE PSIM Sensor Subcommittee**:

  IEEE Paper: MV Smart Grid Sensor and Sensor Systems: Measurement Accuracy and Uncertainty Considerations

  Working Group: Guide for MV Smart Grid Sensor Accuracy Testing

  Task Force: Sensors Application Guide Paper

  Sensors Device Standard PAR Task Force

Standards for current & voltage sensors – ANSI markets

Role of standardization:

1. Defines all requirements on sensors based on the latest needs in applications
2. Standardizes parameters and requirements
3. Ensures the long-term performance and reliability in operation
4. Helps to manage the compatibility with connected devices
5. Standards establish the baseline or minimum requirements for performance

Comparison of sensor technologies

Advantage of passive sensors

- 30+ years of the product life cycle → same as switchgear and conventional instrument transformers
- Maintenance free product for all life cycle
- Power supply is not needed
- Latest sensors standards investigating performance in the application available
- Common, reliable and proven solution with 30+ years in medium voltage networks

Low-power passive current transformers

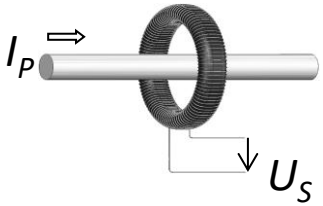
- Principles and functionality
- Performance

Performance with sensors

Current Sensor Options

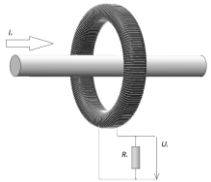
Rogowski coil

- Rated secondary output 180 mV for 60 Hz
- High linearity and wide dynamic range
- Metering accuracy up to 0.2S class
- Protection accuracy up to STC level (85 kA)
- Primary current of application up to 5 kA
- Analog device
- Passive element



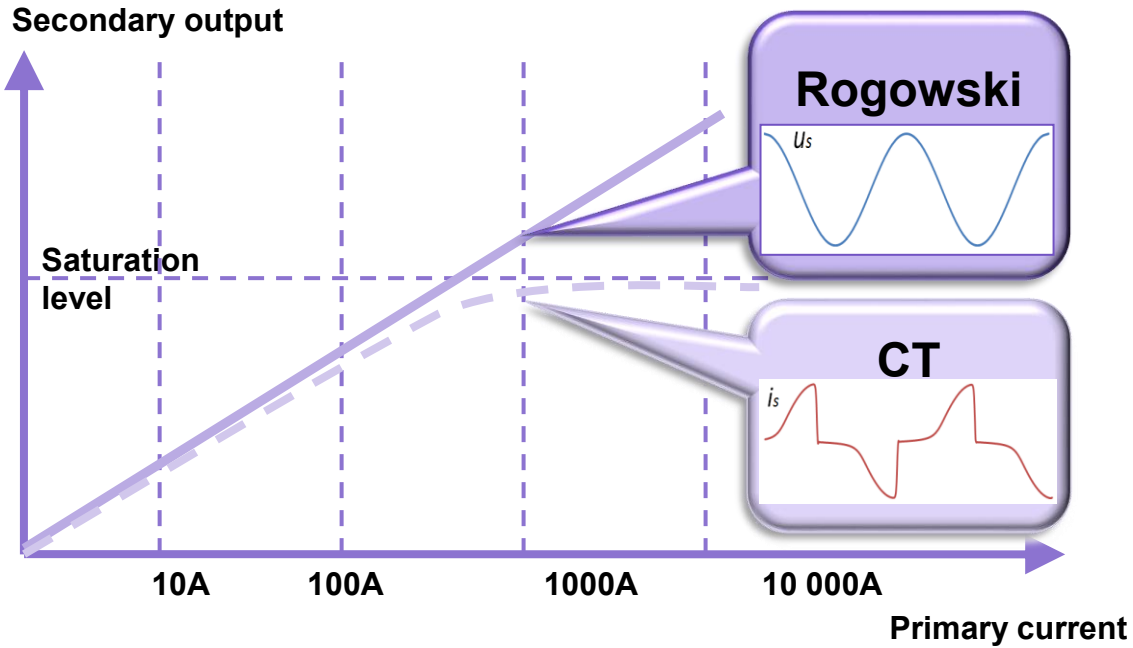
Low-power Current transformer

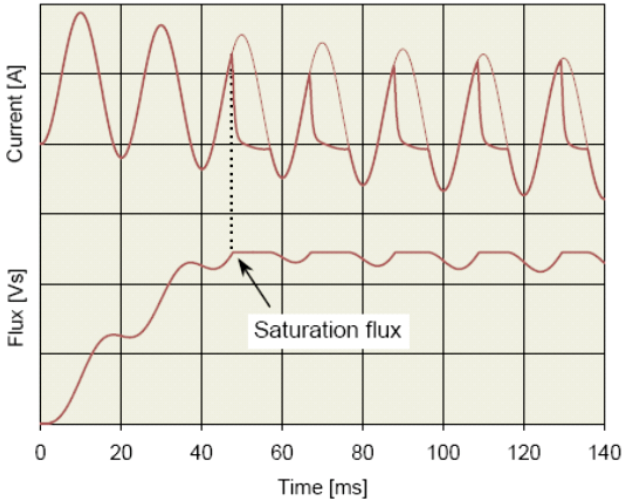
- Rated secondary output 225 mV or 22.5 mV
- Limited linearity and dynamic range
- Metering accuracy up to 0.2S class
- Protection accuracy limited (e.g., up to 6 kA)
- Primary current of application usually limited (e.g., up to 800 A)
- Analog device
- Passive element



Rogowski coil current sensor

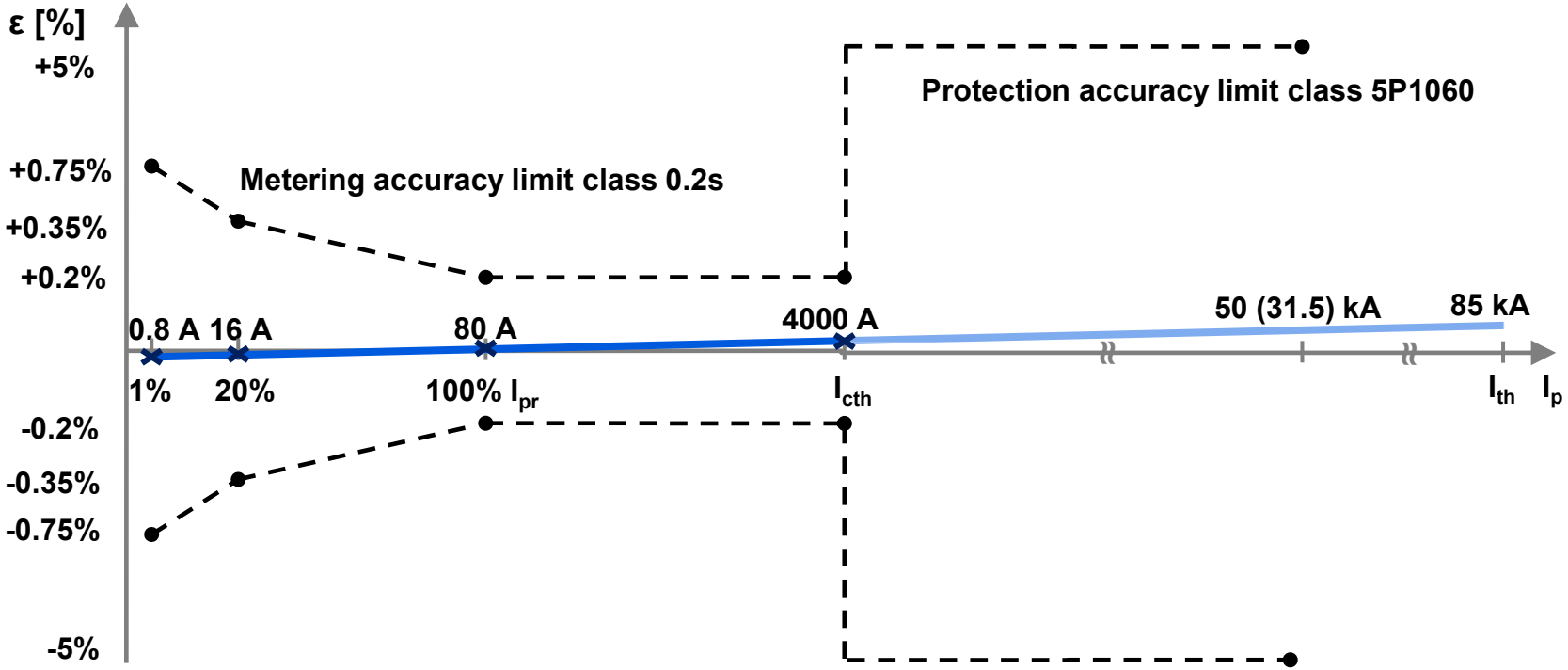
Sensors' linearity = no saturation = no distortion of secondary signal





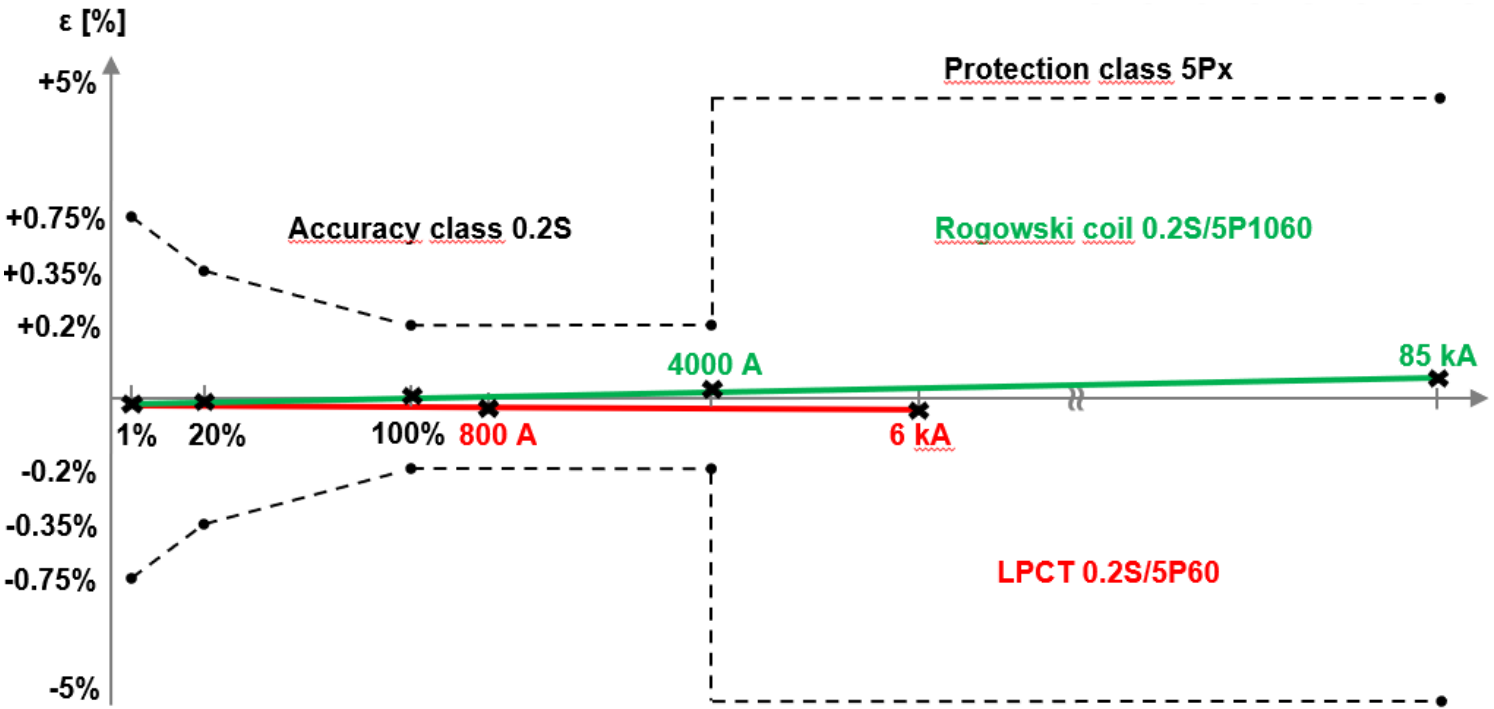
Rogowski coil current sensor

Combined current accuracy class 0.2s/5P1060



Comparison of Rogowski coil & LPCT

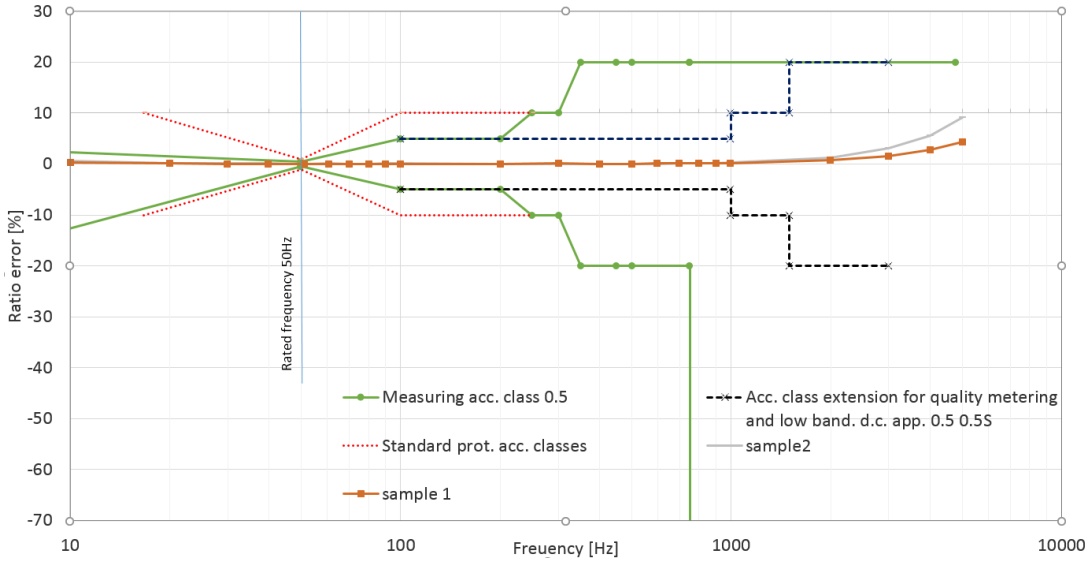
Accuracy performance



Rogowski coil current sensor

Frequency response

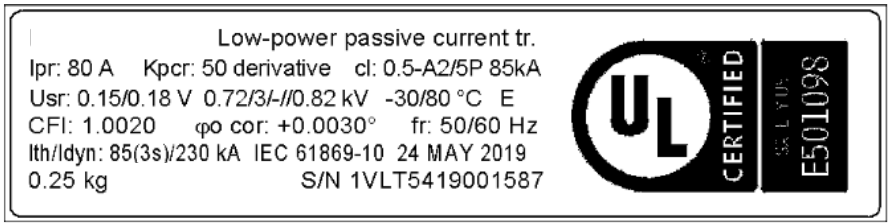
- IEC 61869 defines accuracy requirements for harmonics and low frequencies
- Rogowski coil fulfil IEC 61869 requirements for measuring accuracy class 0.5 and accuracy class extension for quality metering (3 kHz)



Frequency response for two samples of Rogowski coils

Ratings

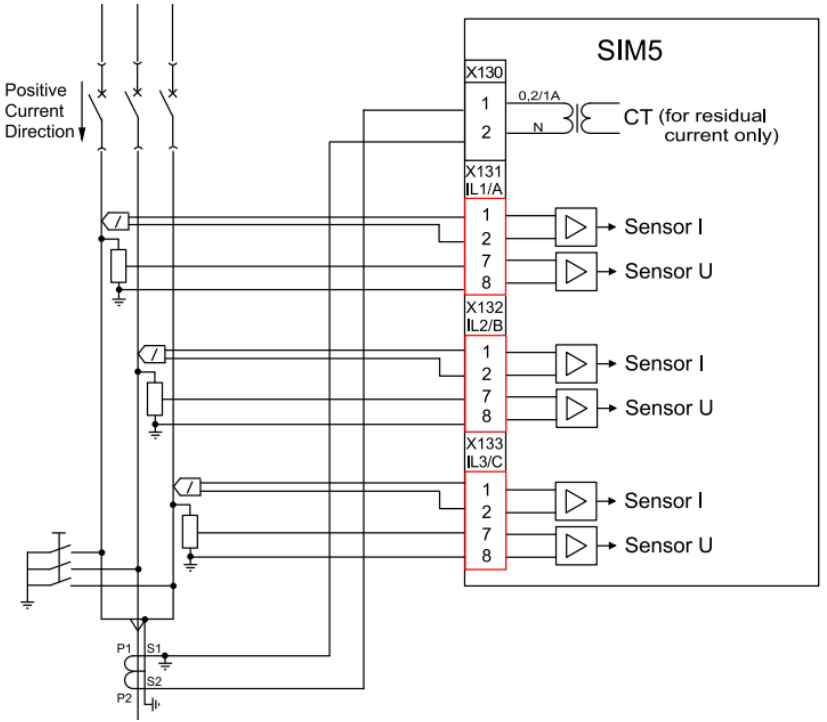
Examples of current sensor rating labels



Ipr	Rated primary current
Usr	Rated secondary output
cl	Accuracy class
Kpcr	Rated extended primary current factor
Cfs	Correction factors used for current sensor
al	amplitude correction factor
pl	phase error correction factor
fr	Rated frequency
Ith	Rated short-time thermal current
Idyn	Rated dynamic current
E	Insulation class

Application of Sensors for Ground CTs

- Only limited applications today
- Existing relays with LEA inputs have added separate input for Ground CTs

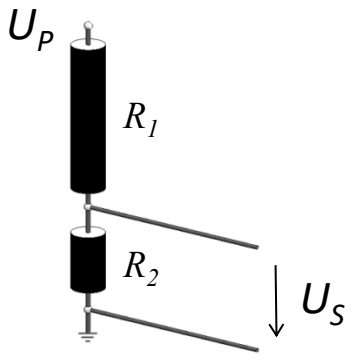


Low-power passive voltage transformers

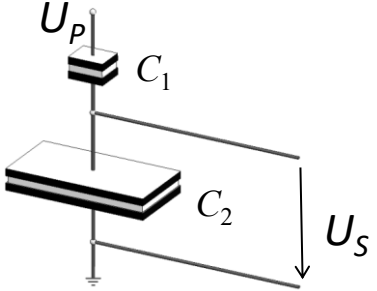
- Principles and functionality
- Performance

Voltage sensors – resistive & capacitive dividers

- Resistive voltage dividers used typically in MV sensors for voltage measurement
  - Failure mode is an open circuit
- Capacitive dividers used on both measurement and for voltage indication
- Light based sensors evolving but typically more expensive than resistive dividers
- Example ratios include 10,000:1
- Typical accuracy up to class 0.2
- Passive elements
- Applicable standards IEC 60044-7, IEC 61869-11



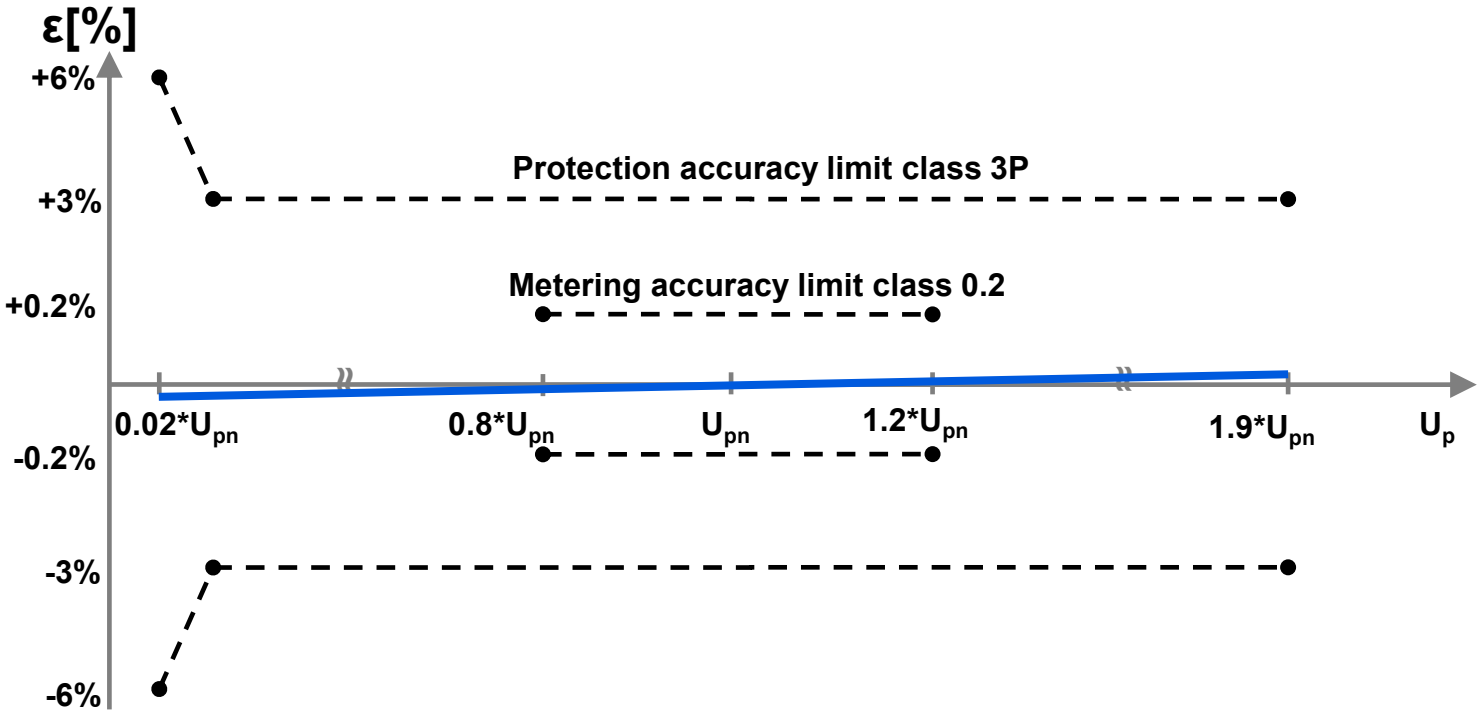
$$U_S = \frac{R_2}{R_1 + R_2} U_P$$



$$U_s = \frac{C_1}{C_1 + C_2} U_P$$

Resistive voltage divider sensor

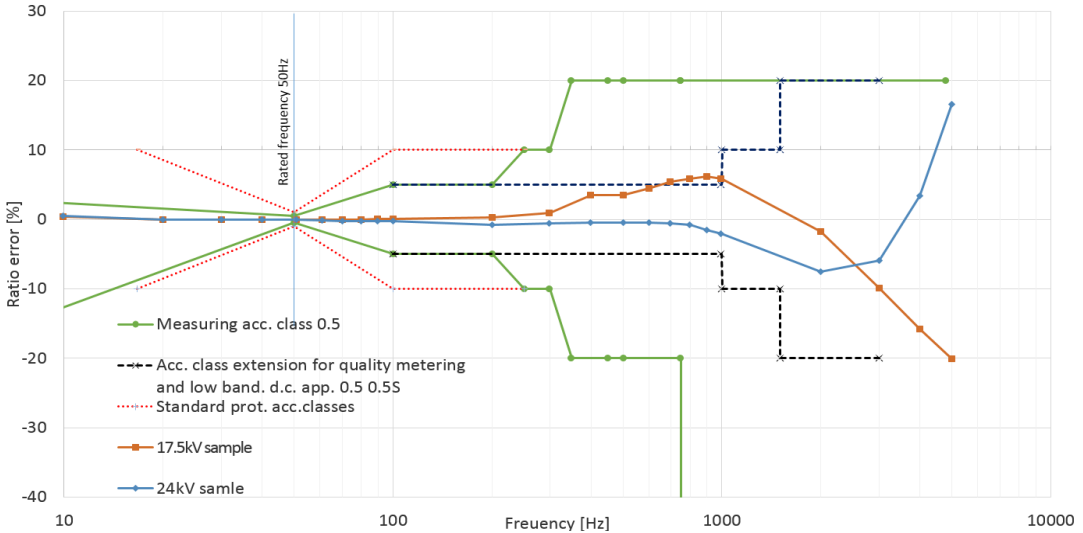
Combined voltage accuracy class 0.2/3P



Voltage sensor

Frequency response

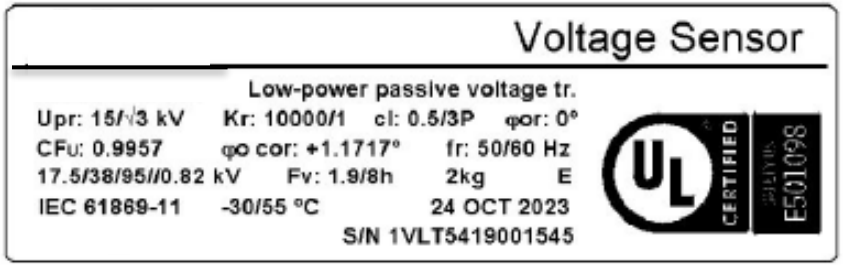
- IEC 61869 defines accuracy requirements for harmonics and low frequencies
- 24kV resistive voltage divider fulfil IEC 61869 requirements for measuring accuracy class 0.5 and accuracy class extension for quality metering (3 kHz)



Frequency response for 17.5 kV and 24 kV RVDs

Ratings

Examples of voltage sensor rating labels



Upn	Rated primary voltage
Kn	Divider ratio
cl	Accuracy class
ku	Rated voltage factor
Cfs	Correction factors used for voltage sensor. Correction factors are measured and calculated separately for each sensor.
aU	Amplitude correction factor
pU	Phase error correction factor in degrees
fr	Rated frequency in Hz
E	Insulation class

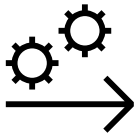
Sensor features and applications

- Benefits
- Compatible devices
- Application examples
- Segments of use

Benefits and features

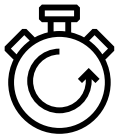
Fast and easy design process allows quick delivery time

Optimized design process



- Standardized products
- Wide range of parameters with one design
- Zero engineering
- Faster and simplified project documentation
- Flexible for last-minute changes

Supply chain point of view



- Products can be built to stock
- Quick dispatch
- No clarification delays due to feasibility verification as with conventional Instrument transformers

Benefits and features

Space saving and sustainable solution

Space saving solution

- Reduce the overall footprint of the switchgear room
- Saving of the transportation costs
- Savings of interconnection between switchgear frames, up to 90%

Sustainable solution

- Decrease of energy consumption during the production processes
- Reduction of the CO2 emission thanks to the material savings
- Self-energy consumption during the operation reduced by 99%

Benefits and features

Increased flexibility together with improved safety and reliability

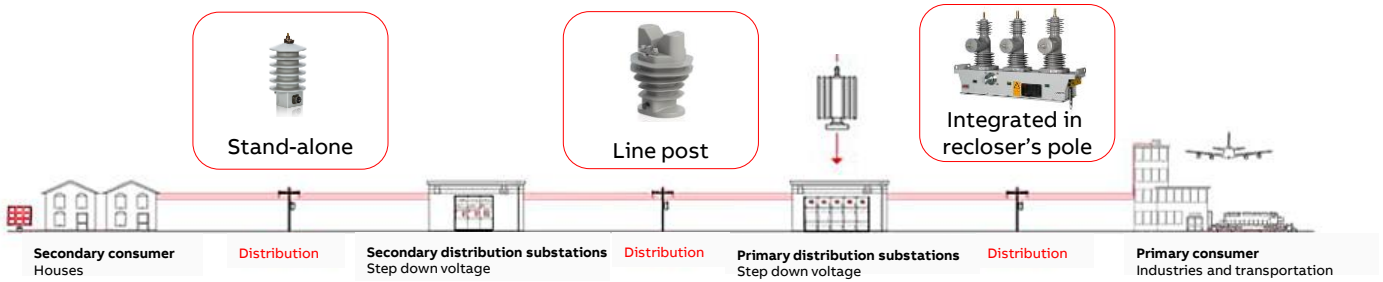
Flexibility

- Flexibility towards varying load flows
- Possibility to connect different equipment/load
- Upgrade of switchgear parameters without additional costs

Safety & reliability

- Ferroresonance free (no inductance to couple with line capacitance)
- Low voltage signals
- No need to use VT fuses (less violent failure mode)
- Secondary can be left open or short-circuited
- Easy and reliable connection to protection relays
- Increased safety for personnel during testing/ operation

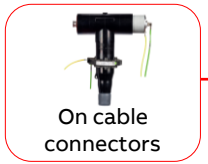
Sensors in Use Today

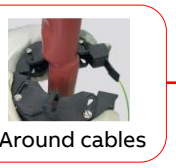


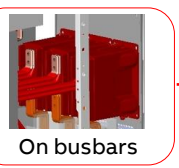
Secondary distribution

Example of installations

Primary distribution







And many others…

Sensors in Use Today

Examples of designs

Current sensors

Voltage sensors

Combined sensors

Sensors in Use Today

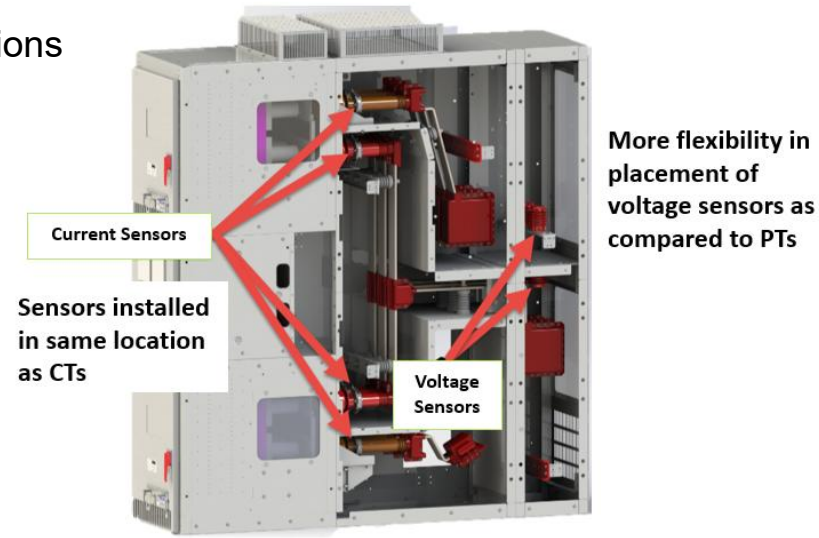
Current and Voltage sensor for Air-insulated Switchgear

Current sensor

- Ring type sensor for AIS applications
- Suitable for new installations
- Rated primary current of application up to 4000 A

Voltage sensor

- Post insulator type voltage sensors
- Suitable for retrofit purposes as well as new installations

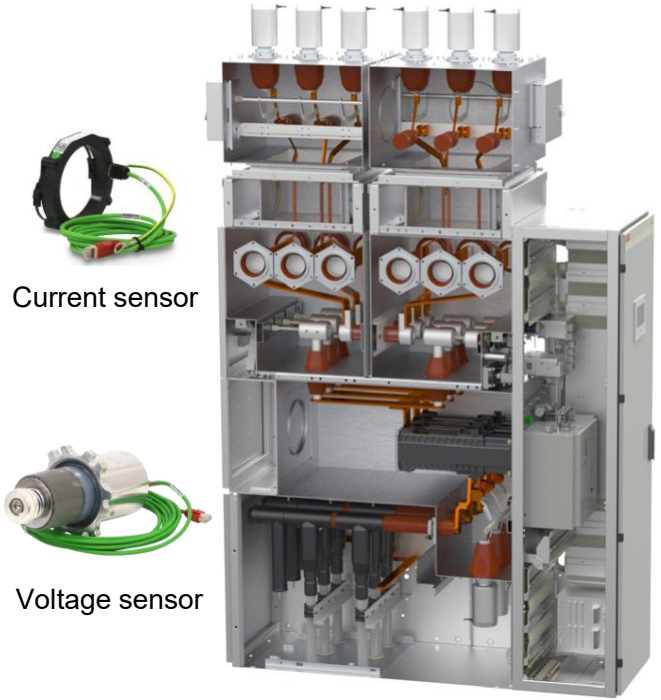


Sensors in Use Today

Current and voltage sensors for Gas-insulated Switchgear

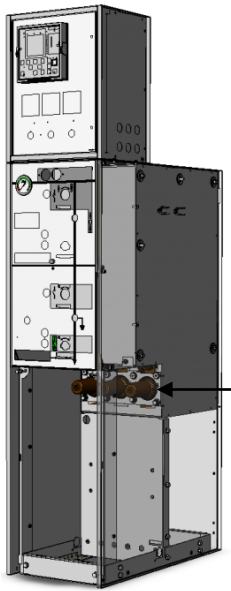
Current and voltage sensors

- Ring-type sensors for GIS applications
- Rated primary current of application: up to 4000 A
- Plug-type sensors for busbar or cable termination compartment
- Plug size 2 primary connection (CBN35-PT-2)
- Suitable for retrofit purposes as well as new installations
- Rated primary voltage of application: up to 40.5 kV



Sensors in Use Today

Sensor solutions for Gas-insulated Switchgear → bushing sensor integrated in Switchgear



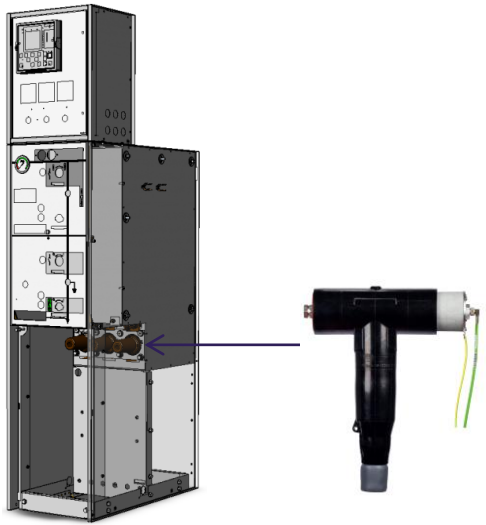
Bushing type combined sensor
- Suitable for new installations up to 40.5 kV
- Current and voltage measurements together with voltage indication in one compact frame

Sensors in Use Today

Voltage sensor for Gas-insulated Switchgear

Plug-type voltage sensors

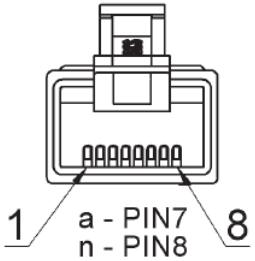
- Plug type sensors
- Suitable for retrofit purposes as well as new installations
- Rated primary voltage of application: up to 36 kV (40.5 kV)



Compatibility

Standardization helps to manage the compatibility

- Sensor rated burden = IED input impedance → 2 MΩ / 50 pF
- Connector type RJ45 with defined pinout
- Correction factors for Ratio and Phase angle



1	2	3	4	5	6	7	8
S 1	S 2					a	n

How to ensure the compatibility?

- Full compliance with the standards on both sides – Sensors and IEDs
- Compatibility test on representatives of portfolio
  - Basic accuracy range
  - High harmonics
  - Solution shall be proved by primary injection testing in full scale of parameters in certified high voltage laboratory

Compatibility

Intelligent Electronic Devices with LEA inputs

Protection relays

Fault passage indicators

Compatibility

Intelligent Electronic Devices with LEA inputs

Remote terminal unit

Controlled switching device

Compatibility

Intelligent Electronic Devices with LEA inputs

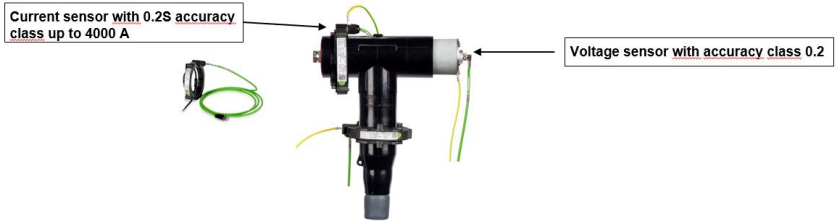
Arc detection relay

Compatibility

Intelligent Electronic Devices with LEA inputs

Energy and Power Quality meters

Revenue metering



Compatibility

Amplifier for voltage sensors

Pros

- Possibility to connect with IEDs without LEA input
- Possibility to connect multiple devices from one amplifier – max. 0.5 VA
- From voltage sensor point of view, utilizing most of benefits comparing with VTs – ferroresonance free, more compact, sustainable, etc.

Cons

- Increase the overall error of the chain
- Active device decreasing overall lifecycle of the solution
- Additional costs comparing direct connection of sensors to the IED

Testing of Sensors

- Type tests
- Routine tests
- Tests in Switchgear - Factory Acceptance Test
- Tests on site - commissioning

Current sensors

Tests defined by IEC standards

Type tests

7.2.1.1 Information for identification of specimen
7.2.6.602.1 Basic accuracy tests for measuring LPIT
7.2.6.602.2 Basic accuracy test for protective LPIT
7.2.6.603 **Temperature cycle accuracy test**
7.2.6.604 **Test for accuracy versus frequency**
7.2.6.606 Additional accuracy tests for protective LPIT
7.2.6.606.1001 Test for composite error

7.2.6.606.1002 Test for transient performance
7.2.6.1001 **Test for accuracy in respect of the positioning of the primary conductor**
7.2.6.1002 **Test for impact of magnetic field from other phases**
7.2.1001 Short-time current test
7.2.601.3 Power-frequency voltage withstand test
7.2.601.4 Impulse-voltage withstand test

Routine tests (Part of type tests)

7.3.4 Power-frequency voltage withstand tests on secondary terminals
7.3.5 Test for accuracy
7.3.6 Verification of markings
7.3.601 Power-frequency voltage withstand test for low-voltage component

Voltage sensors

Tests defined by IEC standards

Type tests

7.2.1.1 Information for identification of specimen
7.2.2 Temperature-rise test
7.2.3 Impulse voltage withstand test on primary terminals
7.2.6.602 Basic accuracy tests LPVT
7.2.6.603 **Temperature cycle accuracy test**
7.2.6.604 **Test for accuracy versus frequency**

7.2.6.1101 **Test for impact of electric field from other phases**
7.2.601 Low-voltage component voltage withstand test
7.4.1 Chopped impulse voltage withstand test on primary terminals

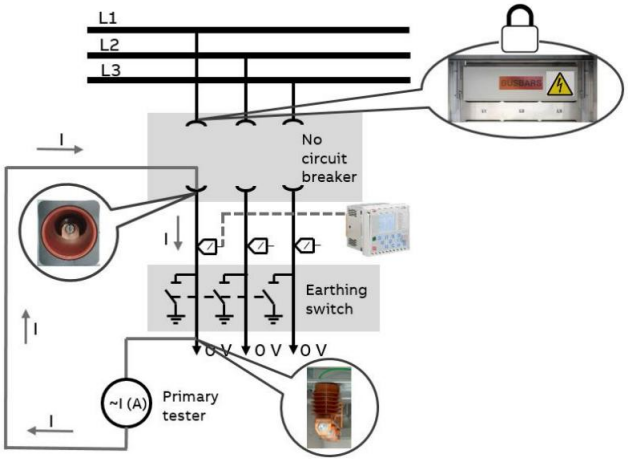
Routine tests (Part of type tests)

7.3.1 Power-frequency voltage withstand tests on primary terminals
7.3.2 Partial discharge measurement
7.3.5 Test for accuracy
7.3.6 Verification of markings

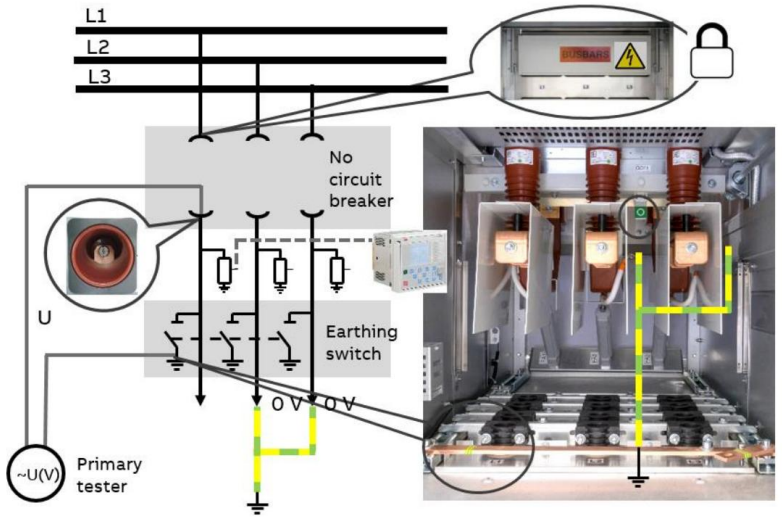
Example of testing in switchgear during FAT

Testing schemes

Current sensors testing



Voltage sensors testing



Commissioning of Current & Voltage sensor

Primary injection testing procedure

Recommended on site tests

- Primary test should be done to verify whole chain of measurement, including sensors, secondary cable connection and Protection relay.

- Primary injection test for current sensor
- Primary injection test for voltage sensor

- All safety instructions must be followed!
- Injection to be done with respect to real possibilities

Break – 15 mins.

Please be back on time

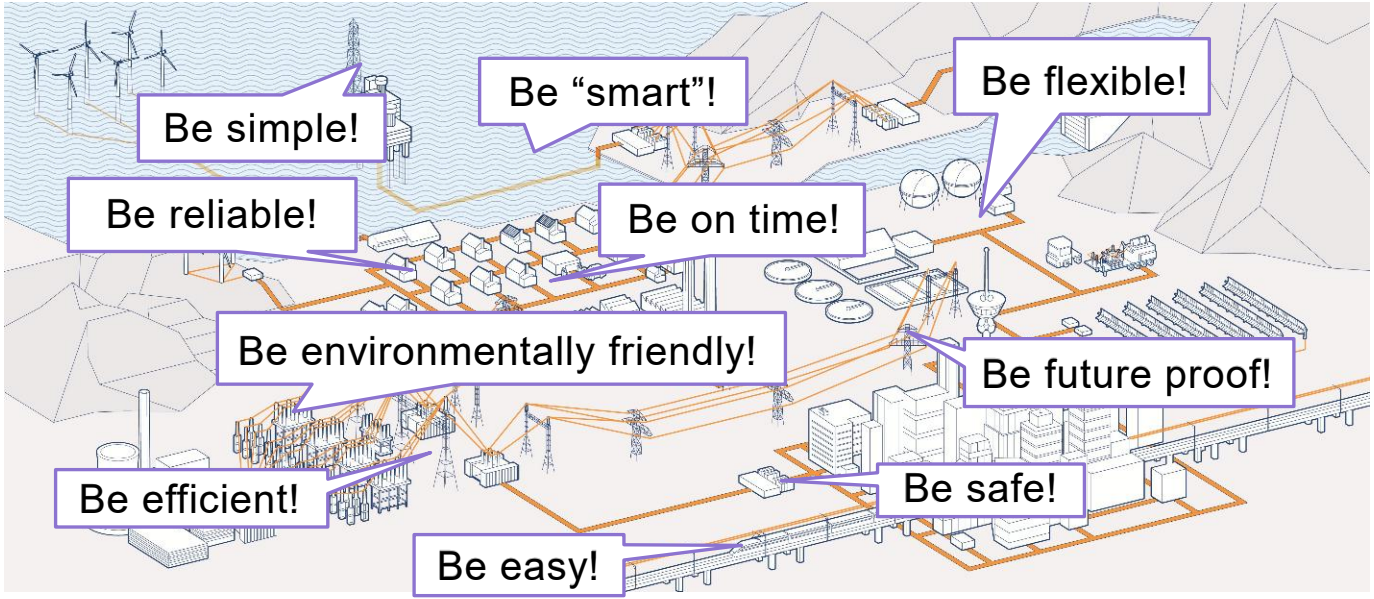
Sensors and Digital switchgear

- Why digital switchgear?
- What is digital switchgear?
- Key digital switchgear components:
- Value proposition

ANSI switchgear

What do customers want?

- Distribution networks have evolved and become more complex.
- Switchgear, as part of the grid, has a more important role than before.



Digital Switchgear defined

Applicable to any voltage class

Switchgear where device status information, current and voltage measurements and commands are reliably transferred on a common communication bus. When equipped, the condition monitoring and diagnostic information of the switchgear and its devices is also digitally available for advanced analysis.

ANSI medium voltage digital switchgear

Next phase in the evolution of switchgear

Digital Switchgear is primarily a new concept in protection, control and automation.

SAFETY & SIMPLICITY are the most significant benefits, but there are many more.

Both current & voltage sensors and common communication bus are essential to realize the full benefits of digital switchgear.

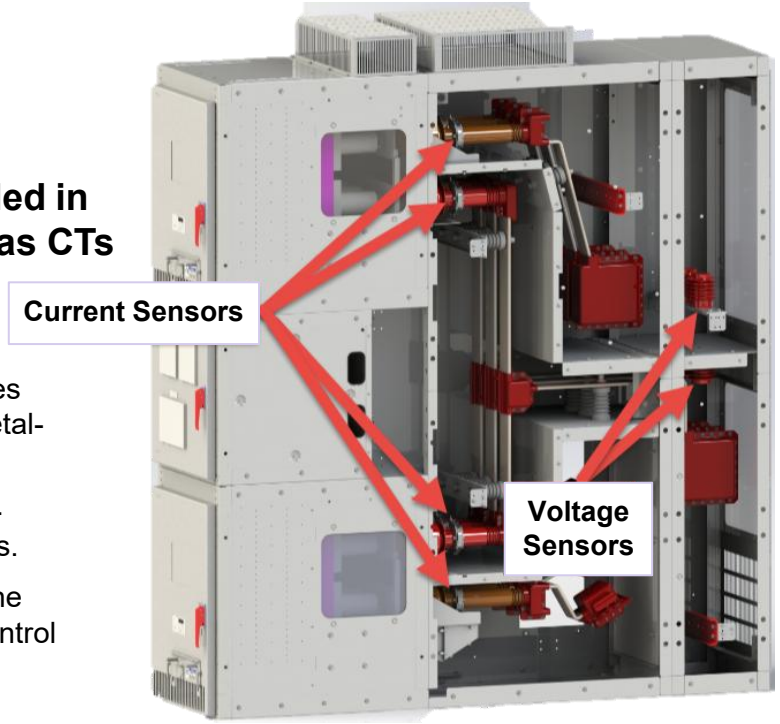
IEEE Switchgear Standards & Use of Sensors

- IEEE C37.20.2-2022 metal-clad switchgear standard addresses the use of current sensors in Section 5.9. Voltage sensors covered in Annex D.
- IEEE C37.20.3-2023 (metal-enclosed switchgear) in Section 5.8 & Annex C
- IEEE C37.20.9-2019 (GIS) in Section 5.12.5 & Annex D
- UL347 7th Ed. (Nov. 2020) for MV Motor Control Centers address the use of voltage sensors in Annex E (language needs updating)
  - No IEEE standards for current & voltage sensors, only IEC.
  - IEEE Switchgear standards refer to IEC standards when addressing sensors
  - UL certifies the sensors to the IEC standards

Is Digital Switchgear constructed differently?

Form factor permits switchgear space savings

Sensors installed in same location as CTs



- IEEE C37.20.2-2022 addresses the use of sensors in ANSI metal-clad switchgear (Annex D).
- Same considerations in metal-enclosed switchgear standards.
- UL347 6th & 7th Edition does the same in Annex E for Motor Control Centers.

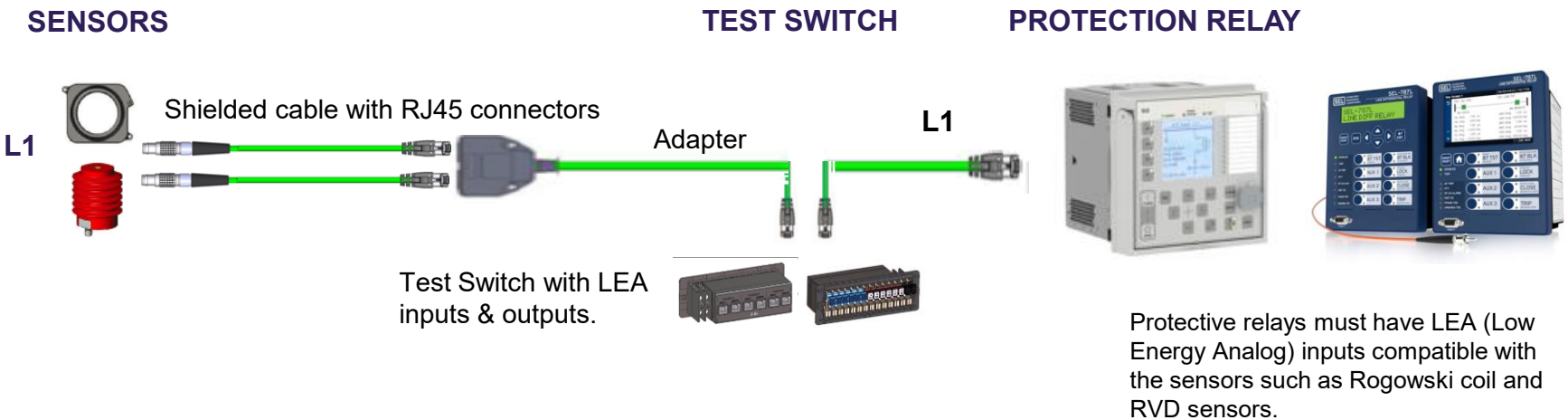
- **More flexibility in placement of voltage sensors as compared to PTs**
- Additional space savings possible if we use them as bus supports
- Located in bus/cable compartment to remove the necessity for a dedicated drawer

Sensors – ideal for critical applications

Impact of sensors

- Increased safety
- Reduced footprint
- Faster engineering phase
- Reduced energy use
- Simplified installations – less wiring, smaller footprint, lighter weight

Example of Current & Voltage sensor connections to IED in switchgear



Point-to-point wiring eliminated with Ethernet Cables

Almost no analog wiring in the switchgear – increases reliability

Relays for digital switchgear

Future proof solution based on IEC 61850

Minimum requirements

- Native IEC 61850 support
  - MMS vertical communication
  - GOOSE horizontal communication
  - SV process bus communication
- LEA (Low Energy Analog) inputs

MMS = Manufacturing Message Specification

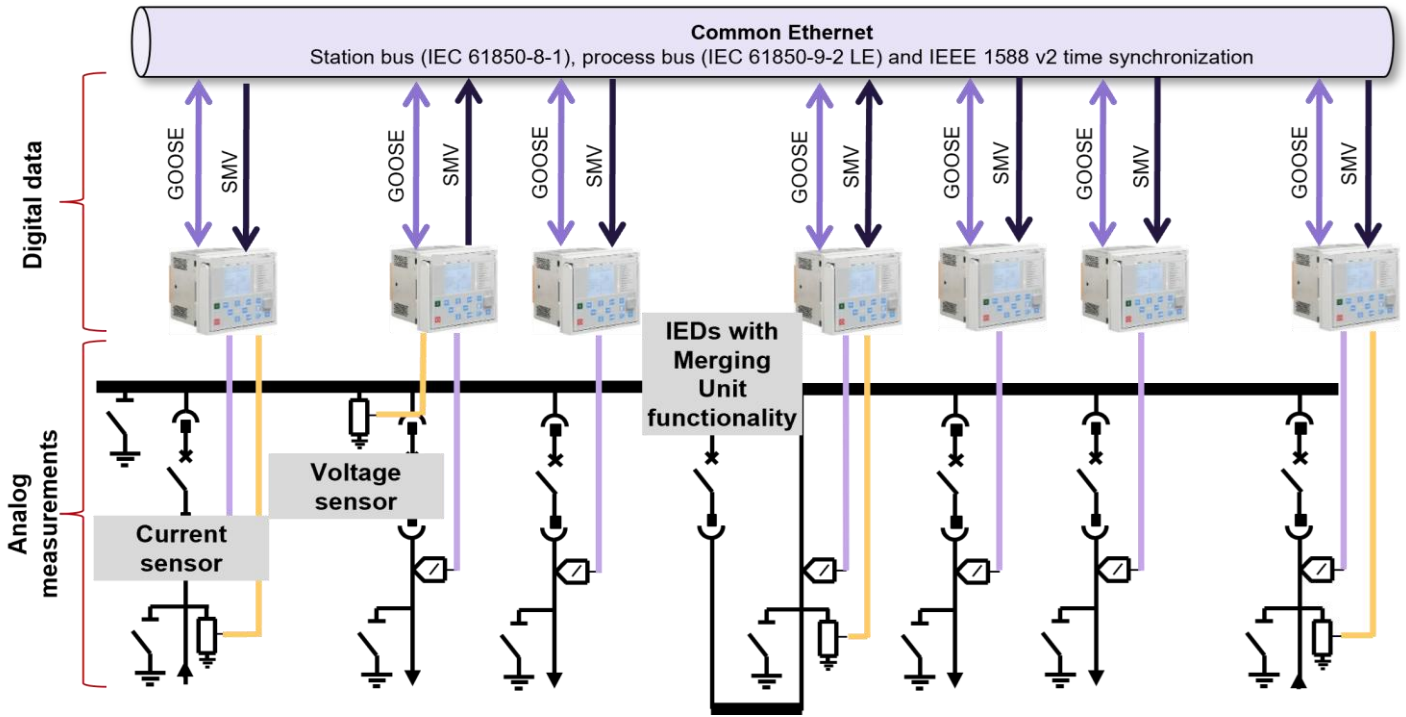
GOOSE = Generic Object Oriented Substation Event

SV = Sampled Value

IEC 61850

Protection & Control with Sensors

Switchgear application

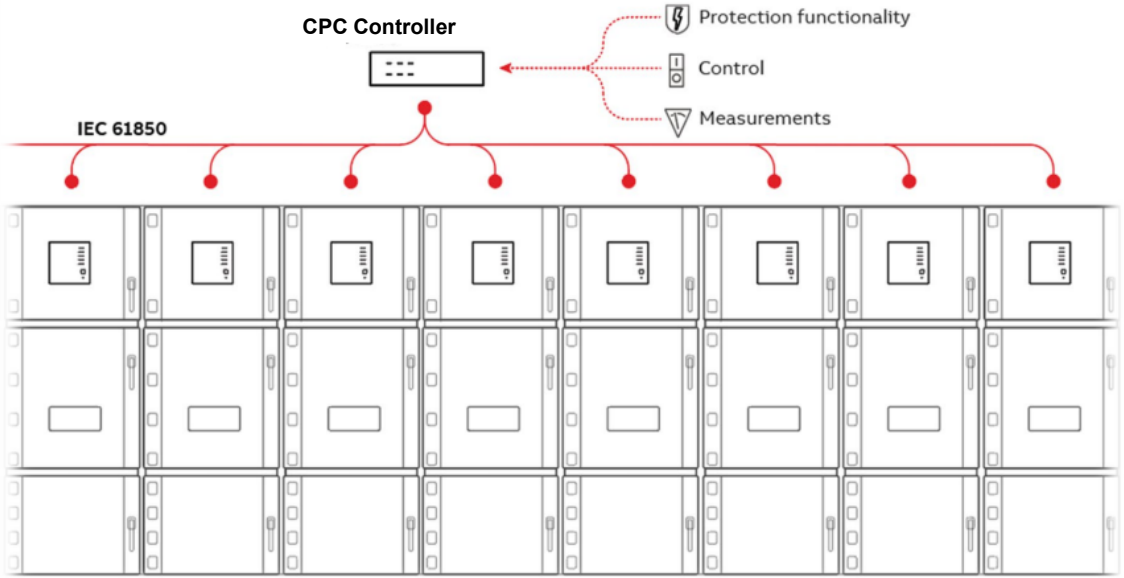


Smart IED functionality:

- Protection & Control
- Publishes & subscribes GOOSE / SMV
- Supports MMS & redundant communication

Protection & Control with Sensors

Centralized Protection & Control Relay

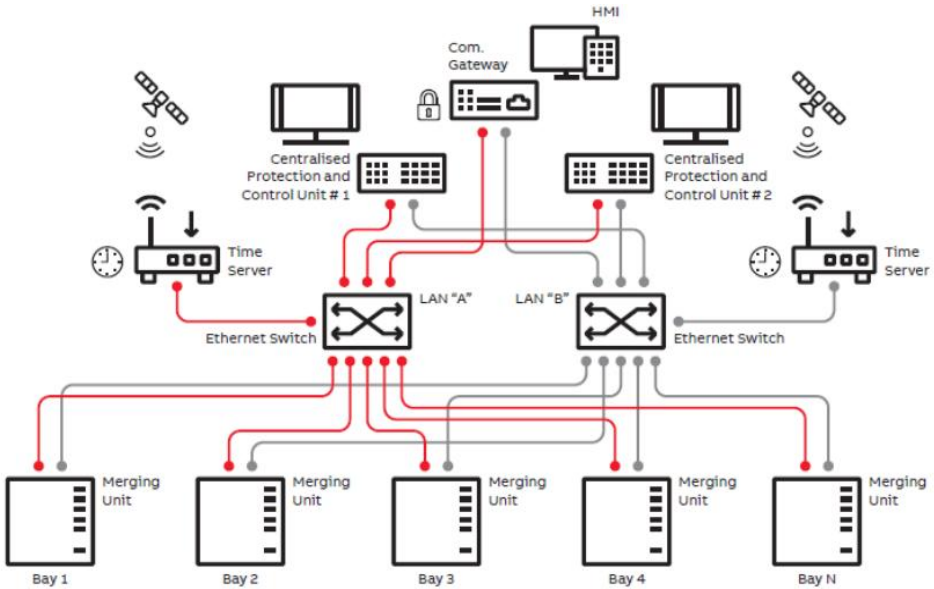


IEEE Guide C37.300-2024

centralized protection and control (CPC): The provision of functions such as protection, automation, control, monitoring, communication, and asset management performed by a centralized system rather than by a collection of discrete IEDs.

CPC system: A computing platform capable of providing protection, automation, control, monitoring, communication, and asset management functions.

Centralized Protection Redundant Architecture



Redundant Centralized Protection Relay Architecture

Alternately,
A dedicated digital relay per feeder with built-in MU functionality can provide back up protection with a single CPC relay architecture

Bus Protection Schemes

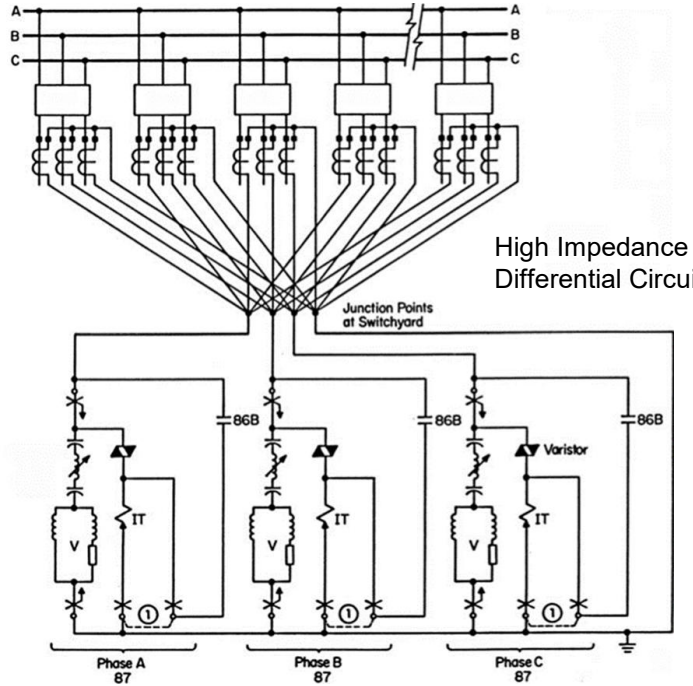
A Reference

- C. Modak, J. Xavier, V. Duong and H. Karandikar, "Bus Protection Schemes in Digital Switchgear: Alternative Approaches, Pros, and Cons," in IEEE Industry Applications Magazine, vol. 32, no. 4, pp. 21-31, July-Aug. 2026, doi: 10.1109/MIAS.2026.3682224.

Bus Protection Schemes in Conventional Switchgear

Commonly used hardwired schemes using CTs:

- Low impedance bus differential scheme
- Fast bus protection using directional comparison blocking (DCB) scheme.
- Partial bus differential scheme using overcurrent relays.
- High impedance bus differential scheme (need dedicated CTs and dedicated relay per bus section)



High Impedance Bus Differential Circuit

Bus Protection in a Digital Switchgear

Differences in construction:

- Current and voltage sensors in place of CTs and PTs
- Analog and digitals signal via communication bus instead of hard wiring
- Analog signals are converted to digitized sampled values
- Distributed or centralized protection relay architecture

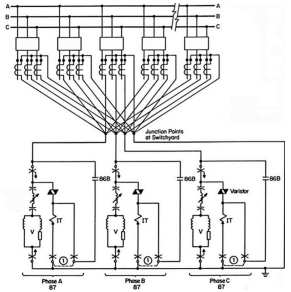
Advantages:

- Flexibility in configuration / changes due to ‘soft wiring’
- Enhanced safety with Low Energy Analog (LEA) input to the IEDs
- Better maintainability with lesser variants within the switchgear

High Impedance Bus Protection Scheme (1/2)

Implementation Challenges in Digital Switchgear

Characteristic	CT Scheme	Rogowski Coil Scheme
Operating Quantity	The relay measures voltage developed across a high-impedance stabilizing resistor. This voltage is high during internal faults and low during external faults.	The coil produces a voltage signal proportional to the *rate of change* of the current (the time derivative), not the current itself. The signal is then integrated to obtain the actual current waveform.
CT Saturation	This scheme relies on the behavior of standard iron-core CTs during external faults. When a CT is saturated, its impedance drops significantly, shunting the fault current away from the high-impedance relay. This provides stability during external faults.	Rogowski coils are air-core and do not saturate, regardless of the primary current. They cannot replicate the impedance-collapsing behavior of a saturated CT that is central to the high-impedance method's stability.



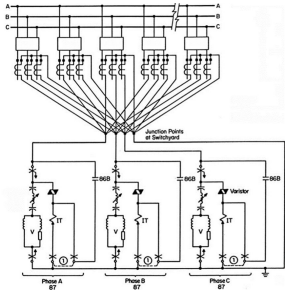
High Impedance Bus Differential Circuit

Rogowski Coil Current Sensor

High Impedance Bus Protection Scheme (2/2)

Implementation Challenges in Digital Switchgear

Characteristic	CT Scheme	Rogowski Coil Scheme
Fault Stability	Stability during external faults is achieved by forcing the differential current caused by a saturated CT to flow through the low-impedance path of the saturated CT, effectively bypassing the high-impedance relay.	Since Rogowski coils do not saturate, a different method would be required for stability against external faults. A scheme would need to digitally calculate the total bus current and compare it against a restrained value, which is the definition of a *low-impedance* differential scheme.
Device Configuration	All CT secondaries for a phase are connected in parallel to a single, high-impedance relay circuit. This reduces the number of relay inputs required.	A Rogowski coil differential scheme typically requires a digital relay with multiple, dedicated inputs for each coil. The summation and processing happen digitally inside the relay, classifying it as a low-impedance or digital scheme.



High Impedance Bus Differential Circuit

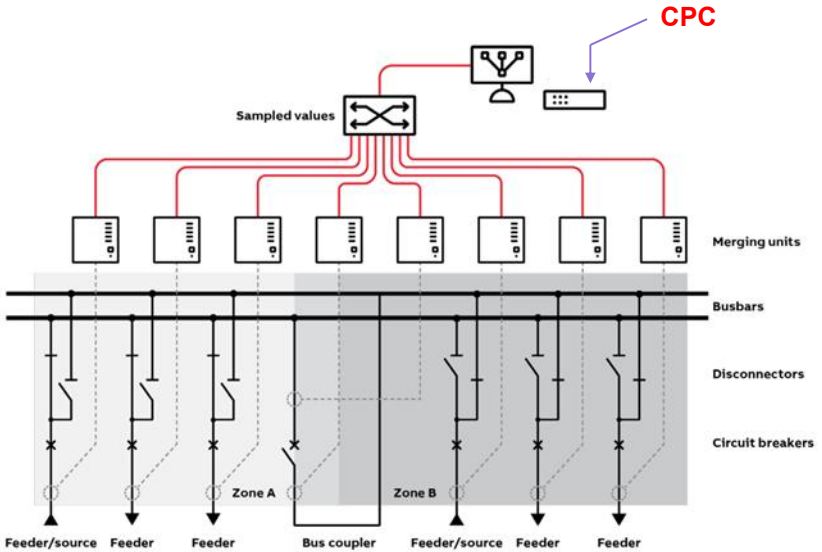
Rogowski Coil Current Sensor

Low Impedance Bus Differential Protection in Digital Switchgear

- Using digital relays & IEC 61850 (SMV, GOOSE) architecture
- The central relay runs the bus differential protection algorithm

Benefits

- No additional current sensors needed
- Design flexibility, no additional wiring required
- Better sensitivity and security
- Faster operation, by half cycle
- Stability testing by digital current injection



Low impedance bus diff protection using CPC

Bus Protection in Digital Switchgear – Best Value

Low impedance bus differential scheme

+

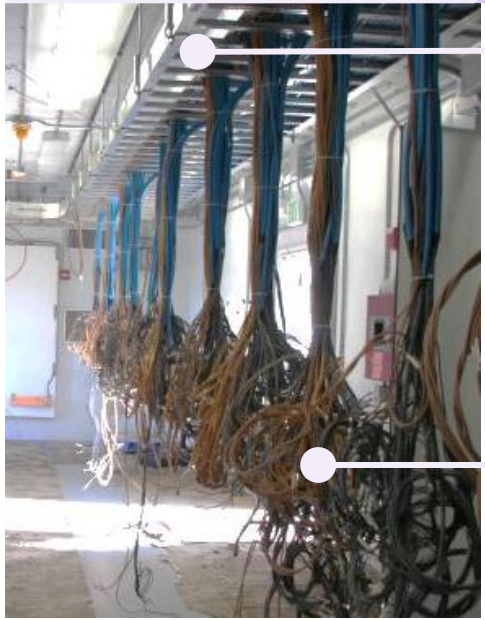
Backup arc flash detection scheme

61850-9-2LE Process Bus & GOOSE messaging in Digital Switchgear

Replacing copper with Ethernet

Digital substation reduces wiring complexity and resulting risks for operations & maintenance personnel.

Before



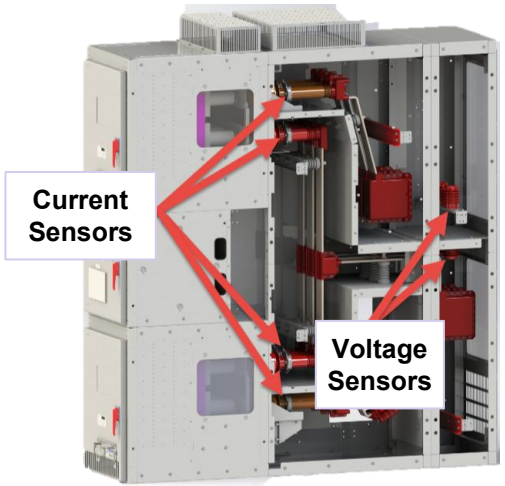
After

No cable tray

Single conduit to carry fibers

Digital Switchgear Value Proposition

The Five Ss



Safety

- Low energy analog output eliminates hazard associated with open CT secondary
- Fewer wires to install makes switchgear easier to maintain
- Solution is continuously self-supervising with maximized error detection

Savings

- Form factor of voltage sensors = switchgear space savings
- Size of current & voltage sensors = weight reduction
- Broad application range of the sensors = inventory savings
- Significant energy savings during operation
- Savings on total cost of ownership

Simplicity

- Fewer wires to install, commission & maintain
- Fewer parts to fail leads to increased reliability

Speed

- Concept allows for compression of time from order to delivery
- Late customization possible

Sustainability

- Universal standards (IEC 61850) enable future system expansion
- Handle future load changes without mechanical reconfiguration of system
- Lower lifetime environmental impact

Digital switchgear benefits – Safety

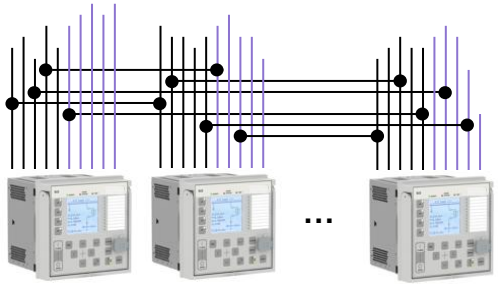
Substation availability and personnel safety

- Solution has increased safety for personnel during testing/operation
  - No dangerous CT secondary signals that could be touched
- Solution has less live parts and is flexible towards grid disturbances
  - Ferro-resonance free solution without conventional PTs
- Solution is continuously self-supervising with maximized error detection
- Solutions with less use of material, thus with less aging stress and reduced chance of failure
- Meets latest cybersecurity and communication performance standards
  - Manufacturer independent communication standard

Digital switchgear benefits – Simplicity

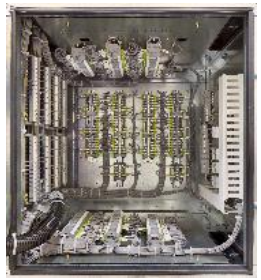
Simplicity of construction & component choices

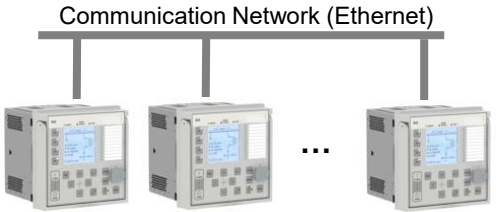
- You can do away with the PT compartment & save frames (reduces frame count)
  - Greater flexibility in configurations
- Greatly reduced wiring
- Sensors cover a wide application range & very few styles needed



- Conventional approach
  - Wiring between devices must be done individually per signal

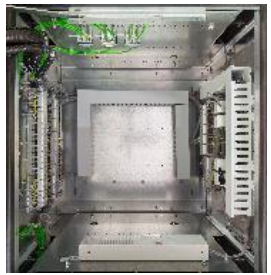
Conventional





- Horizontal GOOSE communication
  - Number of interconnections is equal to number of devices

Digital



Digital switchgear benefits – Speed

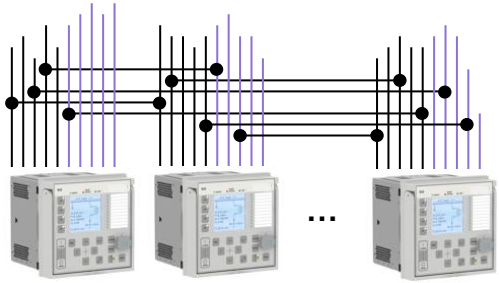
Flexibility for varying applications, late customization possible

- Changing loads does not require changes in hardware like instrument transformers
  - Saves time and money during planning and execution
- Set-up is flexible towards last-minute changes
  - The determination of wiring philosophy at an early project stage is not required
  - The determination of instrument transformer values at an early project stage is not required
- Most changes are simply realizable within the IED's logic, only minor changes in wiring and schematics (if any)

Digital switchgear benefits – Savings

Space saving solution / reduced weight up to 15%

- Solution has reduced weight
  - You can do away with the PT compartment!
    - Save frames (reduces frame count)
    - Greater flexibility in configurations.
- Solution does not require extra frames for instrumentation.
- Greatly reduced wiring



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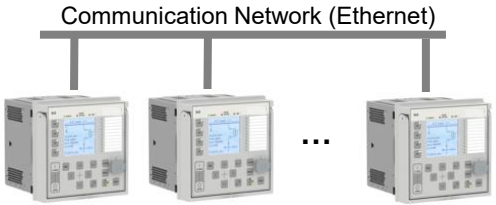
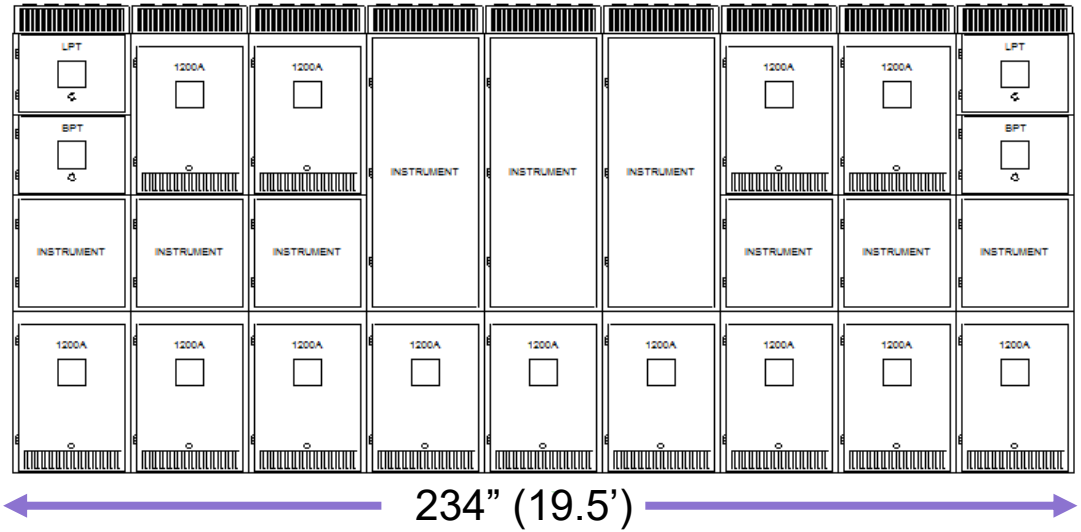


- Horizontal GOOSE communication
  - Number of interconnections is equal to number of devices

Space and weight reduction – Example

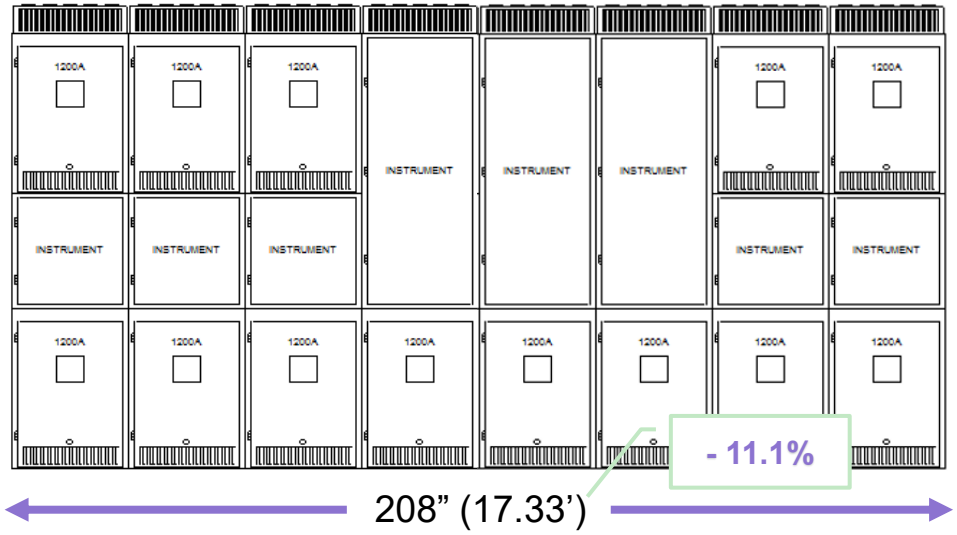
Conventional 15kV metal-clad digital switchgear



Estimated Weight (lbs.)	29100
CT and PT Wiring (ft.)	2500
CT and PT # of Wire Terminations	910
A/W/T Hours	135
Number of Shipping Splits	3

Space and weight reduction – Example

15kV metal-clad digital switchgear with same functionality

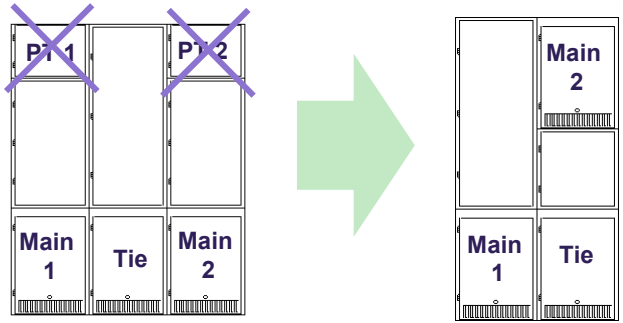


Estimated Weight (lbs.)	25182	- 13.5%
Sensor Wiring (ft.)	289	- 88.4%
Sensor # of Wire Terminations	76	- 91.6%
A/W/T Hours	24	- 82.2%
Number of Shipping Splits	2	- 33.3%

Digital switchgear benefits

Reference project: Typical MTM arrangement

- Typical applications involving Main-Tie-Main arrangements require transfer schemes which can only be achieved by having both current and voltage measurements.
- Frames need to house breakers, PTs/CTs, and bus tie transition. Therefore, 3 frame M-T-M configuration has become very common.
- PT compartments take up crucial space. When replaced by a voltage sensor this space becomes available.



Digital switchgear benefits

Reference project: Typical MTM arrangement

The use of non-conventional instrument transformers (NCITs) like sensors in place of current and voltage transformers will allow for a reduction from 3 to 2 frames for M-T-M arrangements.

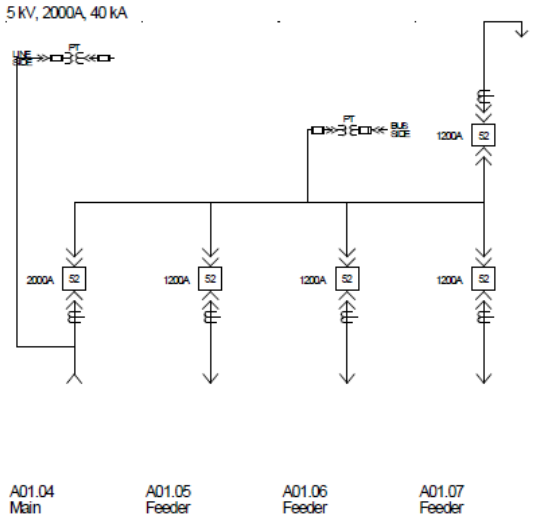
In addition, the use of sensors makes the 2-frames more flexible since current and voltage sensors are not dependent on ratios/ratings (they are programed in the IED).

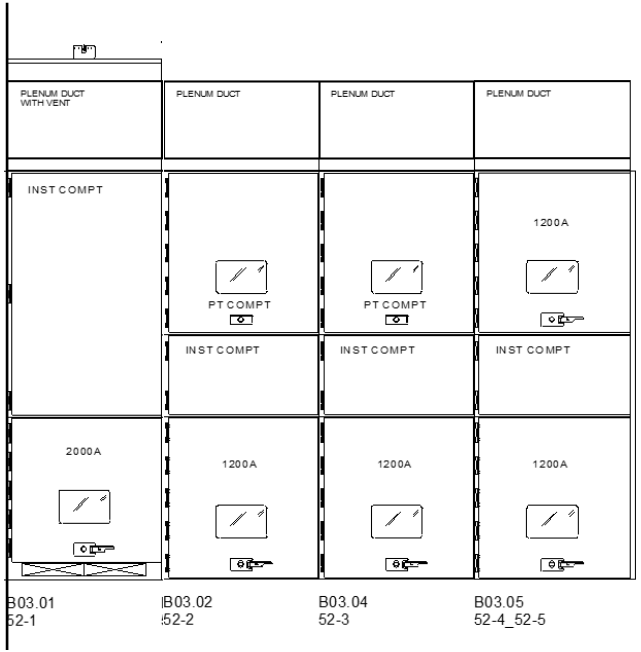
Therefore, regardless of load variances, the same lineup can now be used for the following schemes:

- Open Transition
- Closed Transition
- Fast Transfer
- Zone Selective Interlocking

Digital switchgear benefits

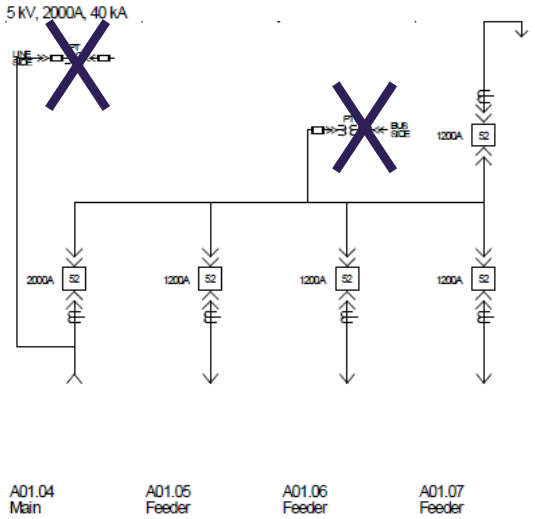
Reference project: ANSI switchgear at a US industrial user

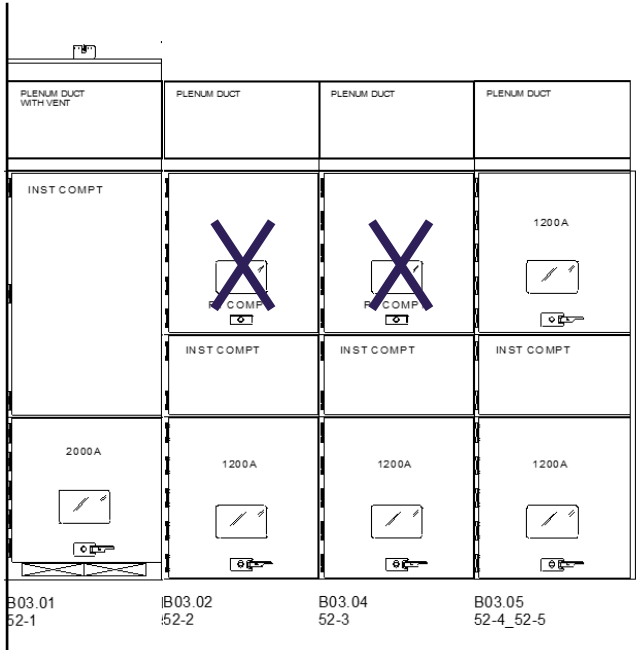




Digital switchgear benefits

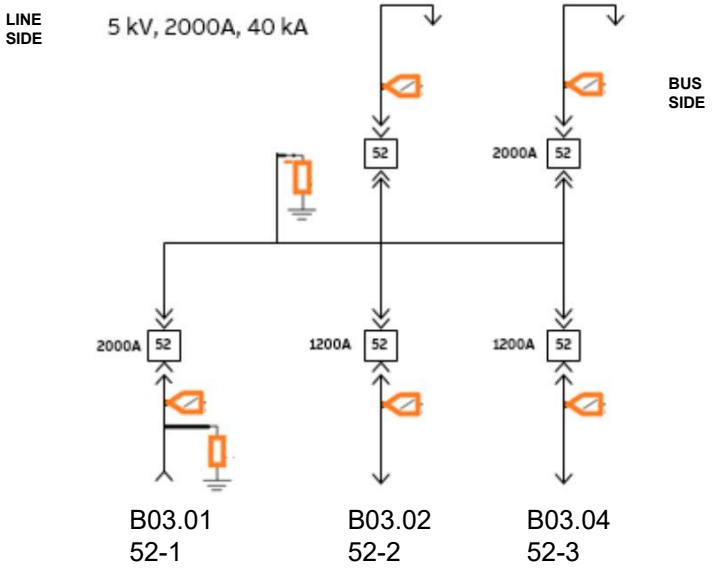
Reference project: ANSI switchgear at a US industrial user

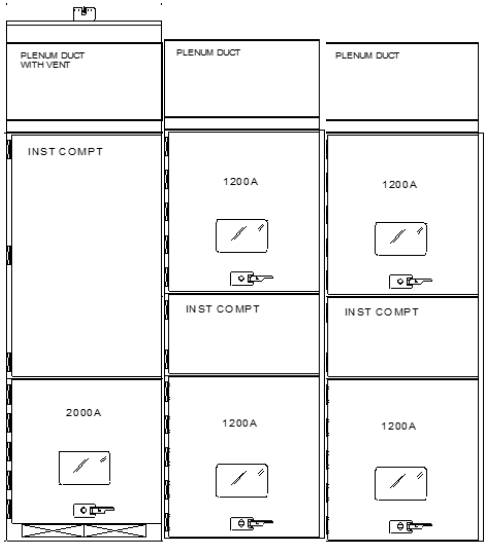




Digital switchgear benefits

Reference project: ANSI switchgear at a US industrial user

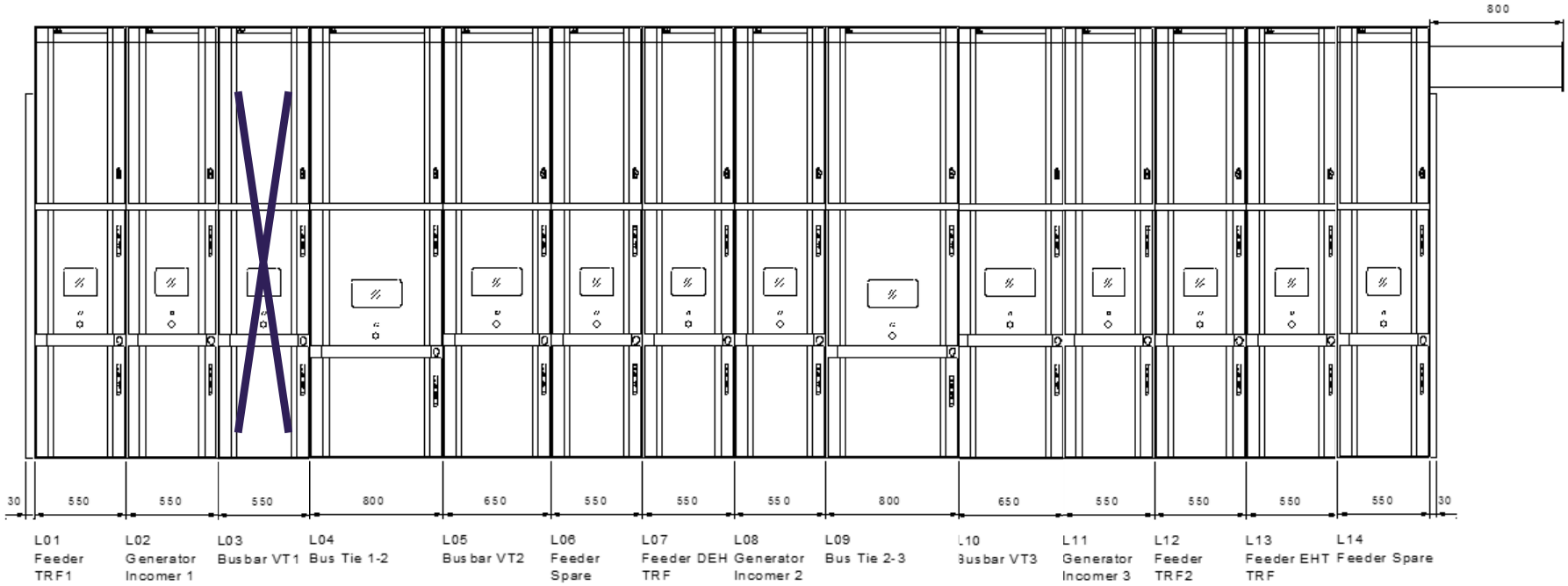




Footprint: -25%, costs: -8.9%

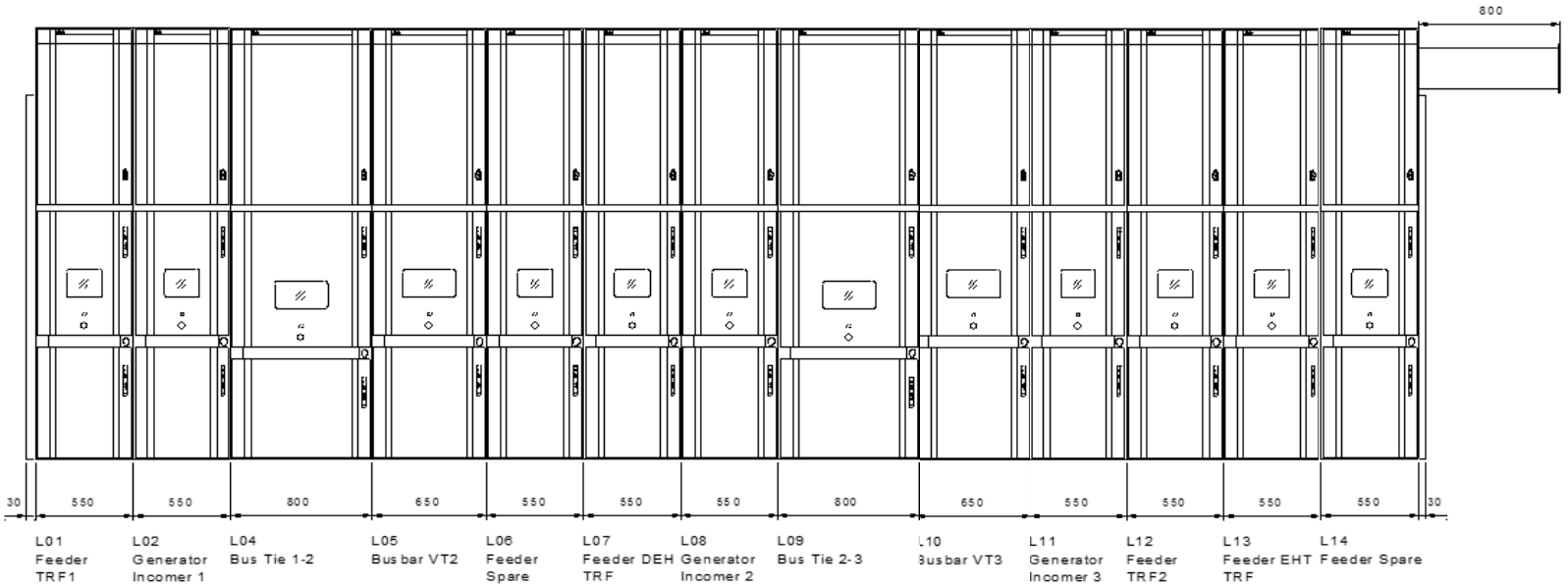
Digital switchgear benefits

Reference project: IEC switchgear on an offshore platform in Europe



Digital switchgear benefits

Reference project: IEC switchgear on an offshore platform in Europe



Footprint: -6.5%, costs: -3%

Digital Switchgear Benefits – Savings

Reduced total cost of ownership

- Reduced losses during operation
  - Sensor losses are low
  - Saving potential of up to 250 MWh over 30 years (sample switchgear with 14 frames & 42 CTs or Sensors)
- Improved equipment reliability
  - Fewer live parts, fewer failure opportunities reducing outage potential and troubleshooting costs
- Reduced inventory need
- Lower inital price due to fewer frames needed.
  - Complete PT compartments can be eliminated
  - Reduced space means lower costs for housing

Savings of energy & CO2 emissions in operation

Power loses per frame [W]	Conventional Switchgear (with traditional CT, PTs)		Digital Switchgear (Smart solution with Rogowski coils, voltage dividers)	
Energy losses per typical substation	[MWh]	[t CO_2e]	[MWh]	[t CO_2e]
In 1 year	22.7	19.6	14.1	12.1
In 30 years	682.0	586.5	422.4	363.3
Difference per typical 10 frame configuration in 30 years	**260 MWh**		**223t CO_2e**	

Prerequisites for power losses calculation:

1. The real resistivity of current path components were measured, and power losses calculated. Low-voltage compartment losses are estimated based on best practice
2. Typical substation consists of 10 frames, 3 IF with In 1000A, 7 OF with In 800A/600A/400A(3x)/200A(2x). Typical frame considered is UG ZS1 12/12/32 type and busbar rating 1000A
3. Transformation formula used CO_2 equivalent kg is: 0.86kg CO_2e

Digital Switchgear Benefits – Inventory Savings

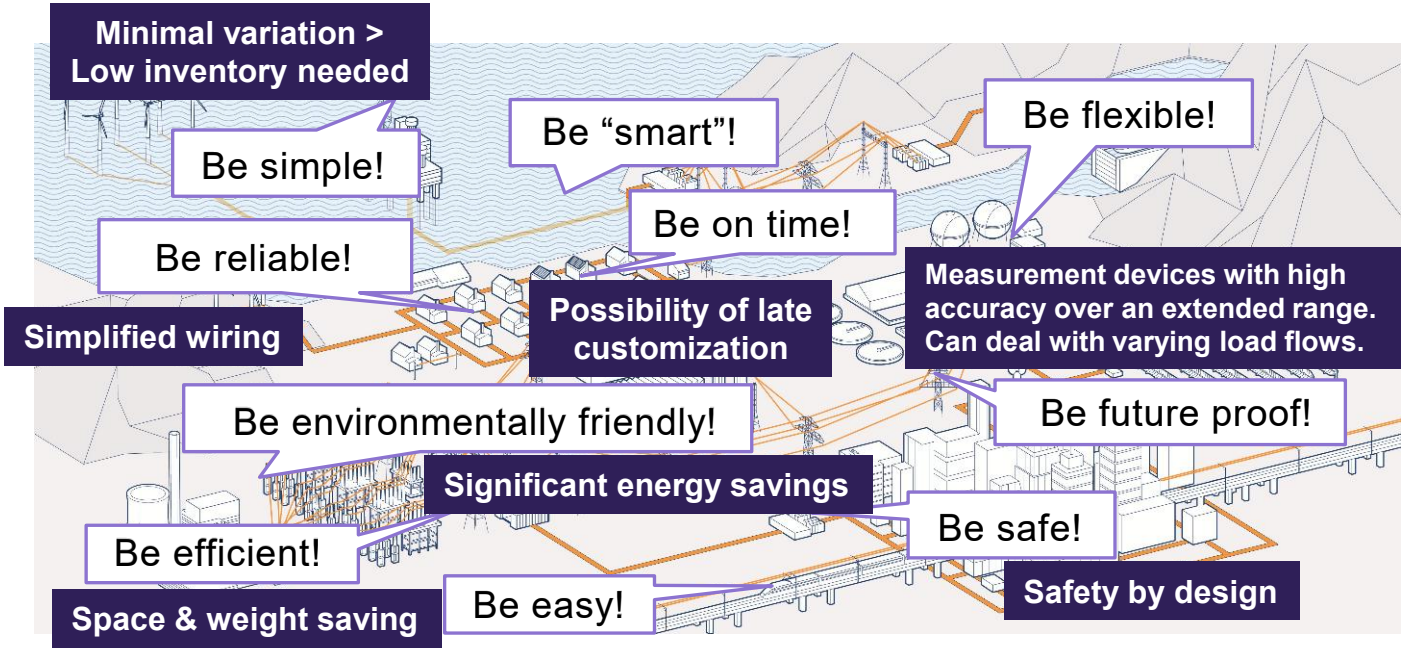
Digital Switchgear Benefits – Sustainability

Lower environmental impact

- Solution uses less material
  - Less steel, less copper, less insulation, …
- Solution with reduced losses
  - Less energy required to operate the gear due to reduced losses in the sensors
- Solution can save significant level of CO_2
- Minimize maintenance

ANSI digital switchgear – In Conclusion

Designed to meet the needs of the future (and today)



Some References

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  - Presented at the IEEE Petroleum & Chemical Industries Conference, September 2019, Vancouver, Canada.
  - *IEEE Industry Applications Magazine*, vol. 27, no. 3, pp. 23-30, May-June 2021. BEST MAGAZINE PAPER AWARD.
- Mirza Danish Baig, Lukas Cesky and Vaclav Prokop, “Smart Sensing of Current and Voltage in Medium Voltage Power Distribution Systems”
  - Presented at the CIGRE Canada conference, September 2023, Vancouver, Canada.
- Vaclav Prokop, Jiri Hula, Petr Jakubik, Romana Kovalova and Jiri Valek, “ Revenue Metering based on Low-power Passive Instrument Transformers complying with IEC 61869-10 and IEC 61869-11 Standards including Legislative View on Legal Metrology”
  - Presented at the CIRED conference, September 2021, Geneva, Switzerland.

Thank you for your attention!

Any further questions?