Working Group on Smart Secondary Substations

Technology Development and Distribution System Benefits

CIRED's point of view

Final Report

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List of Abbreviations

The following list contains commonly used abbreviations in this report.

52	Circuit Breaker according ANSI code
2L+2P	Two MV cable feeders and two transformer feeders with protection
2L+P	Two MV cable feeders and one transformer feeder with protection
3L+P	Three MV cable feeders and one transformer feeder with protection
4L+P	Four MV cable feeders and one transformer feeder with protection
50/51	Overcurrent protection function according ANSI code
ASD	Automatic Switch Disconnector
Co	Zero-sequence Capacitance
DSO	Distribution System Operator
FPI	Fault Passage Indicator
HV	High Voltage
LV	Low Voltage
MV	Medium Voltage
NOP	Normal Open Point
OTS	Overhead Transformer Substation
PEN	Protective Earth Neutral
PQ	Power Quality
R0	Parallel Resistor
Re	Earthing resistor for limiting earth fault current
Rf	Fault Resistance
RMU	Ring Main Unit
RTU	Remote Terminal Unit
TN-C	System in which the neutral conductor is also used as a protective conductor

TN-S	PE and N are separate conductors that are connected together only near the power source
TT	Earthed Neutral System
U0	Neutral Voltage
UCP	Protection and Control Unit (Spanish)
SAIDI	System Average Interruption Duration Index

1. Summary of the report

Due to the increasing amount of decentralized generation and the strictness of national grid legislation in terms of quality of service, the improvement of secondary substations is becoming necessary.

To achieve such improvement, it is necessary to explore existing functionalities of the components currently used by utilities and, consequently, to foresight new substation models with reliable power components, high performance protection schemes, efficient flow monitoring systems and trusty communication infrastructures.

In such a way, the overall control of distribution network could be optimized, in order to:

- manage energy flows and voltage profiles according to load and DER needs
- ensure fast reconfiguration after a failure
- identify and pursue efficiency opportunities.

Therefore, the effort put on this document converge in the description of the state of the art of secondary substations, following a structural analysis based on all the studies and experiences of the members of the working group. In other words, the studies on secondary substations have been described through five main subjects: MV components, LV components, MV/LV transformers, remote control systems and devices, monitoring and protection system and devices.

Finally, future improvements in the secondary substations in terms of reliability and quality of supply, energy efficiency integration from renewable energies and reduction of costs have been depicted. Particularly, the potential functionalities that should be reached in different components of the secondary substations regarding network management and control monitoring, fault management, network self-healing, network protection, transformer protection, load energy management, DER/RER and microgrid management have been studied.

Luca Giansante*, convener of the Working Group, February 2017*

2. State of the art

2.1 MV components

2.1.1 Network type

MV network is designed to be managed in radial way in systems with isolated neutral, resonant neutral, solidly or compensated earthed neutral, is mainly structured as closed ring, in order to ensure the access to customers and producers, respecting the contractual parameters and the quality service standards, ensuring the best compromise between the following technical and economic issues:

- respecting the environment and using the topography at its best
- using materials and components able of supporting the aggressiveness of the environment
- adapting the increase of network extension to the changes of demand
- containing the number of the components
- re-feeding the first level line in case of fault, minimizing the operation and maintenance costs during the life of the plant.

One of the main obstacles faced by the introduction of the components in the existing distribution grid is the diversity of the MV distribution network in terms of voltage, neutral regime, geography.

Basically, there are two different philosophies of distribution networks regarding geographical, economic and/or historical reasons:

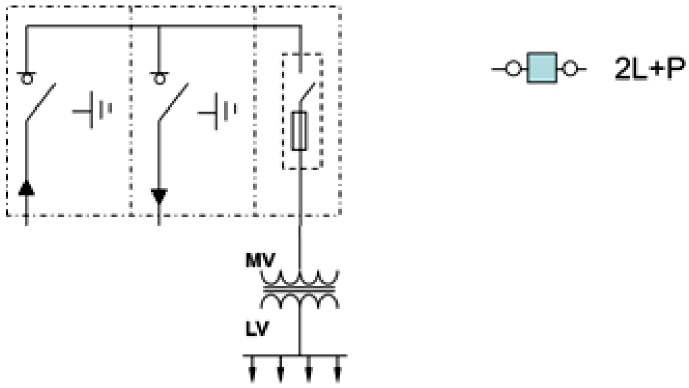
- Underground networks
- Overhead networks

2.1.1.1 Underground networks

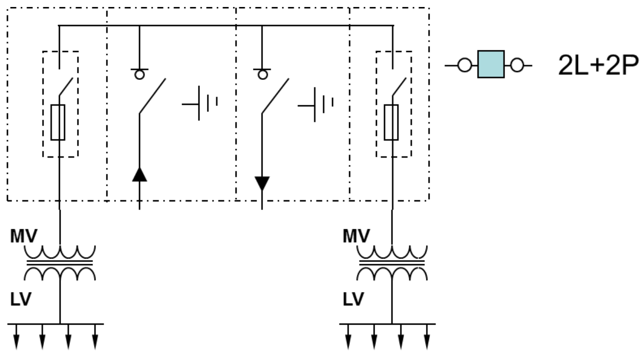
The most common scheme of connection in underground distribution networks is the ring main system. The ring main system can be interconnected or not, depending on the origin of the power supply (it may come from several substations or only from one).

The ring is composed of Ring Main Units (RMU). There are different types of RMU depending, mainly on the number of lines and power transformers installed.

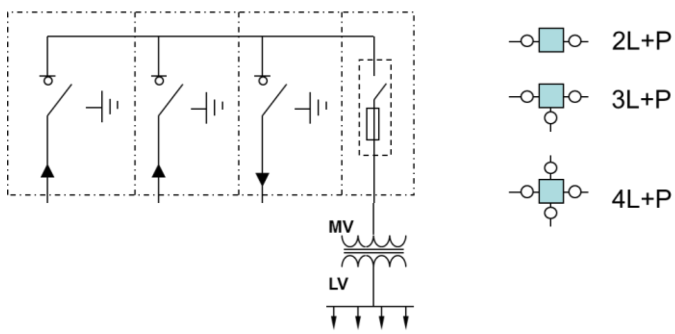
The simplest RMU is a 2L+P, in which there are two MV lines and one MV/LV power transformer.



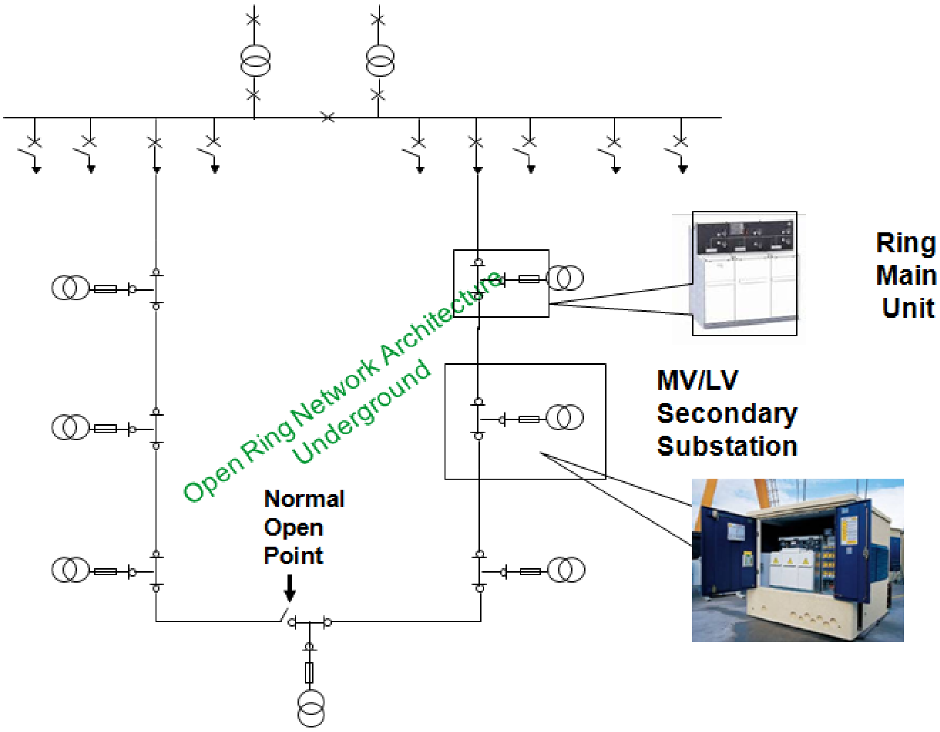
RMU can have more than one MV/LV power transformer.



As for the number of MV lines, RMU can have 3, 4 etc.



The configuration of the main ring can be different, depending on the philosophy and uses of the utility.



The RMU can have one or two power transformers, protected by switch-fuses..

The following figures show the most frequently used electric diagrams.

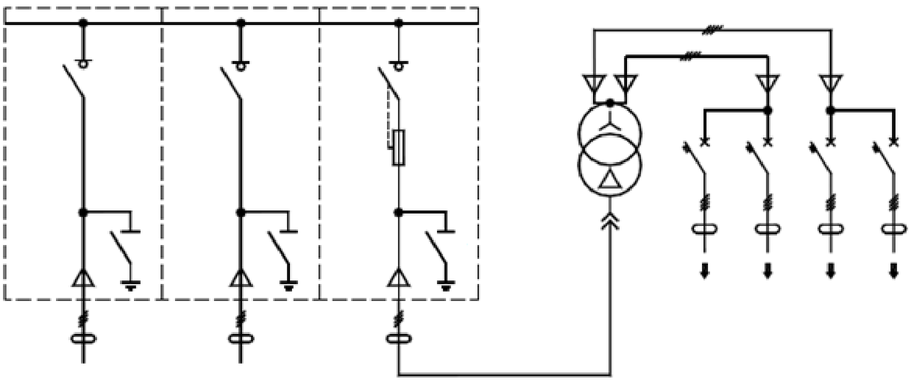


Figure 1: Typical Secondary Substation Layout

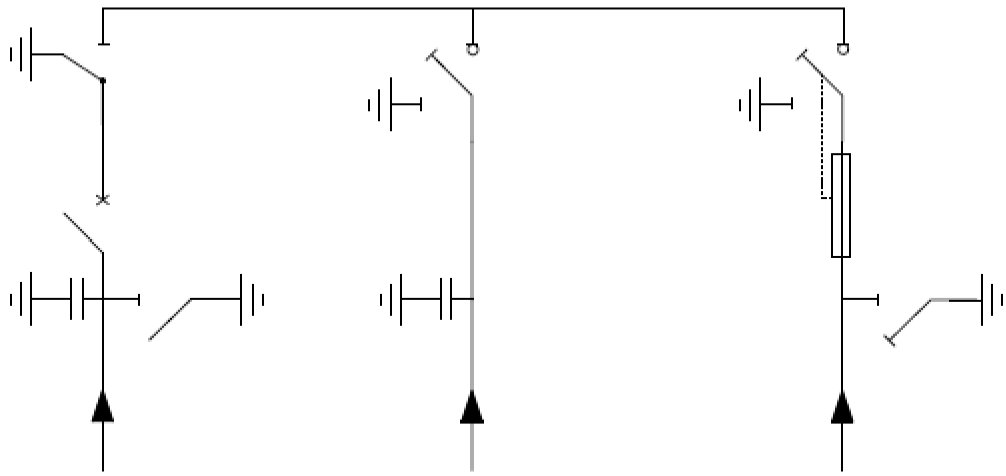
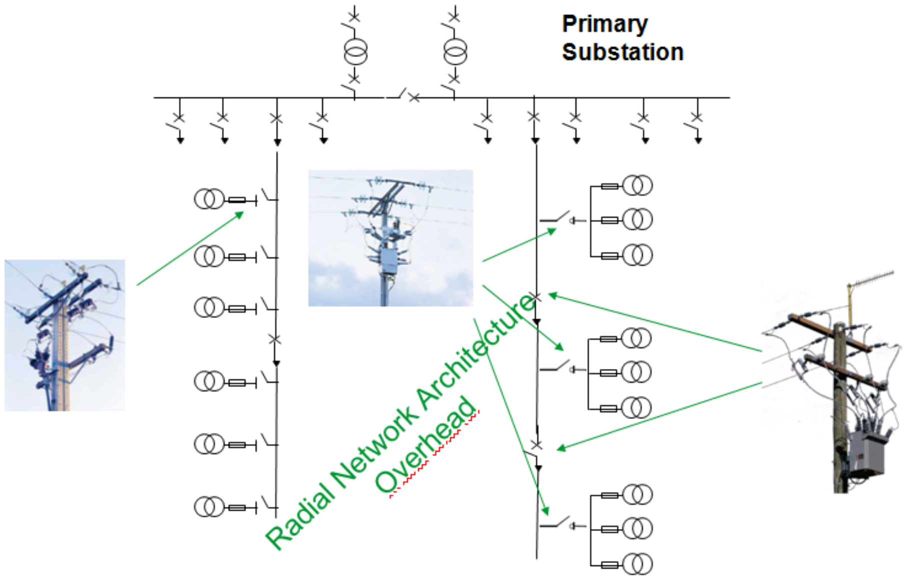


Figure 2: MV section using circuit-breakers

2.1.1.2 Overhead networks

The most common scheme of connection in overhead distribution networks is a simple radial circuit.



This circuit consists of a main line and many different secondary lines, which normally end in one or several overhead MV/LV transformer substations (OTS).

Three types of switchgear are normally used:

- Reclosers or circuit-breakers
- Sectionalizers
- Switch-disconnectors or load break switches

The utility installs along the line up to 3 automatic switch-disconnectors (ASD) or pole-mounted load break switches, in order to minimize the part of the line to be disconnected and isolate the fault when this occurs.

The overhead transformer substation is composed of a power transformer protected by fuses, with two main types of construction:

- housing where the transformer and the protection MV fuses are installed in an indoor space

- directly on the pole close to the customer, with the protection fuses on the previous pole

2.1.2 Switchgears

2.1.2.1 Switching type

- Switch (IEC 62271-103): switching device capable of making, carrying and breaking the current under normal circuit conditions, which may include specified operating overload conditions and also carrying for a definite time currents under specific abnormal circuit conditions, such as those of a short-circuit.

  Typical main ratings are:

  - 12kV/630A/25kA-1s (5C[1], 1000op.)
  - 24kV/400A-630A/12,5kA-16kA-1s (5C, 1000op.)
  - 36kV/400A-630A/16kA-20kA-1s (5C, 1000op.)

- Switch-disconnector (IEC 62271-103 / IEC 62271-102): a switch which, in the open position, satisfies the isolating requirements specified for a disconnector
  Typical main ratings are:
  - 12kV/630A/25kA-1s (5C, 1000op.)
  - 24kV/400A-630A/12,5kA-16kA-1 (5C, 1000op.)
  - 36kV/400A-630A/16kA-20kA-1s (5C, 1000op.)

- Disconnector (IEC 62271-102): a mechanical switching device, which provides, in the open position, an isolating distance in accordance with specified requirements. A disconnector is capable of opening and closing a circuit when either negligible current is broken or made, or when no significant change in the voltage across the terminals of each of the poles of the disconnector occurs. It is also capable of carrying currents under normal circuit conditions and carrying for a definite time currents under abnormal conditions such as those of short circuit.
  Typical main ratings are:
  - 12kV/630A/25kA-1s (1000op.)
  - 24kV/400A-630A/12,5kA-16kA-1 (1000op.)
  - 36kV/400A-630A/16kA-20kA-1s (1000op.)

- Earthing switch (IEC 62271-102): a mechanical switching device for earthing parts of a circuit, capable of withstanding for a definite time currents under abnormal conditions such as those of short circuit, but not required to carry current under normal conditions of the circuit. An earthing switch may have a short-circuit making capacity.
  Typical main ratings are:
  - 12kV/630A/25kA-1s (5C, 1000op.)
  - 24kV/400A-630A/12,5kA-16kA-1 (5C, 1000op.)
  - 36kV/400A-630A/16kA-20kA-1s (5C, 1000op.)

- Switch-fuse combination (IEC 62271-105): a switch in which one or more poles have fuses in series, in a composite unit.
  Typical main ratings are:

[1] 5C means 5 making operations under short-circuit conditions

- 12kV/200A/25kA (5C, 1000op.)
- 24kV/200A/12,5kA-16kA (5C, 1000op.)
- 36kV/200A/16kA-20kA (5C, 1000op.)

- Circuit-breaker (IEC 62271-100): mechanical switching device, capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a definite duration and breaking currents under specified abnormal circuit conditions such as those of short circuit
  Typical main ratings are:
  - 12kV/630A/25kA-1s (E2, 2000/10000op.)
  - 24kV/400A-630A/12,5kA-16kA-1 (E2, 2000/10000op.)
  - 36kV/400A-630A/16kA-20kA-1s (E2, 2000/10000op.)

2.1.2.2 Extinguish medium

Nowadays, there are three main extinguish mediums used in medium voltage switchgears:

- Air
- SF_6
- Vacuum

Circuit-breakers use vacuum and SF_6 as the most common extinguish medium. The rest of switchgears use SF_6 and air as the most common extinguish medium.

2.1.2.3 Enclosure

The enclosure is a part of an assembly providing a specific degree of protection of equipment against external influences and a specific degree of protection against approach to or contact with live parts and against contact with moving parts.
There are different types of switchgears depending on the enclosure typology:

- Metal-enclosed switchgears having an external metallic enclosure intended to be earthed and completely assembled, except for the external connections (IEC 62271-200).
- Insulated-enclosed switchgears having an external enclosure where the main material is of insulating type, with or without added conductive layers (IEC 62271-201).
- Open type switchgear, without any enclosure like pole-mounted air disconnectors.

2.1.2.4 Insulation

Nowadays, there are three main insulation mediums used in medium voltage switchgears:

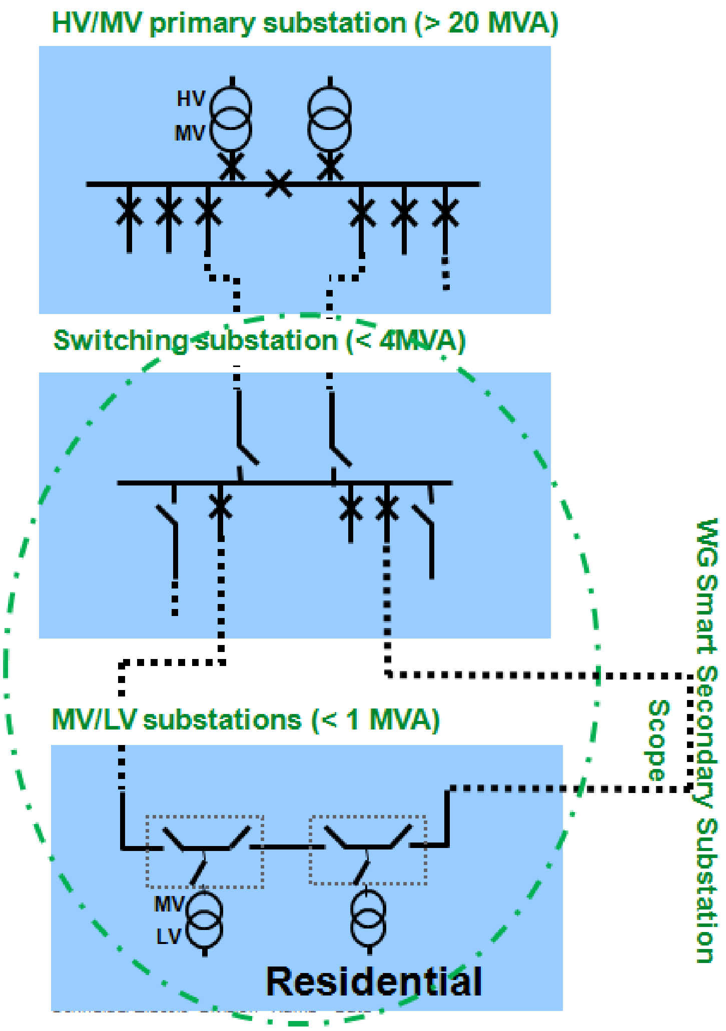
- Air
- SF_6
- Solid

It is common practice to combine different insulation mediums in the same switchgear or equipment.

2.1.2.5 Architecture

Two different types of secondary substations can be distinguished:

- Secondary Transformer Substations, including a MV/LV distribution transformer
- Secondary Switching Substations, to operate the network without any transformer



Depending on the type of networks and distribution philosophies, different types of Secondary Transformer Substations can be identified:

- Walk-in type
- Compact type

- Outdoor type (for underground and overhead networks)

Depending on the DSO (Distribution System Operator) requirements, different types of MV components can be found. The most common ones are:

- **RMU switchgear**: switchgear composed by a manual switch-disconnector on each line and a switch-disconnector combined with fuses (switch-fuse combination) or a circuit-breaker for the transformer protection.
- **Pole-mounted switchgear**: this component for pole installation, depending on the characteristics of the MV line, can be installed in overhead lines. It is used for managing overhead lines.
- **Individual panels**: independent functional units composed by a manual switch-disconnector or a circuit-breaker.

2.1.3 Sensors

Sensors are medium voltage components providing analogical signals of the system to electronic devices for protection, measuring, fault detection and voltage presence indicating or detecting systems (IEC 60044/IEC 61869).
Those analogical signals represent the electrical and physical parameters of the system and/or switchgear.
The main electrical parameters are voltage and current, whereas the main physical parameters are positions, temperature, pressure.

2.1.3.1 Voltage sensors

Voltage sensors include:

- Inductive voltage transformers
- Resistive dividers
- Capacitive dividers

2.1.3.2 Current sensors

Current sensors include:

- Inductive current transformers
- Inductive current transformers with shunt
- Rogowski coils

2.2 LV components

One of the main purposes of MV/LV substations is to give power to a number of low voltage feeders. Low voltage apparatus is, therefore, an essential part, needed to provide connection, switching and protection in a safe and reliable way. To these traditional functions, several more have been added in recent years.

In spite of the possible local variations in environmental and operational conditions, a number of common features are typically found in the LV design. Busbars are typically connected directly to the secondary side of transformers. As opposite to substations used in industry or inside buildings, the use of a main circuit-breaker or switch-disconnector is not common. The typical number of feeders, standardized by each country and utility, ranges from about 4 to 16. Feeder current ratings from 100 A to 630 A are used, with the most common value in the middle of that range (250 A to 400 A). Various types of connection grounding schemes are possible for the transformer, the most common being the star-grounded secondary, which fits with the TT grounding of loads and the TN-C or TN-S distribution systems, where used.

Feeders are typically 3-phase + neutral conductor.

4-pole switching devices are generally used, except in TN-C systems, where PEN conductor is distributed.

400 V is the most common transformer secondary voltage, with other values used in some cases (230 V, 1000 V, 125 V sometimes).

The most important design choice in the low voltage side is that of feeder protection devices. Two alternative classes of devices are used: fuses + switches or circuit-breakers.

2.2.1 Fuses + Switches

Fuses protect safely against short circuit and overload. It is a reliable solution, without nuisance trips. Limitation performance is good and gives the possibility to work with high short circuit currents (up to 100 kA).

On the other hand, disadvantages are the need for planning and distributing stock of spare fuses and the difficulty to obtain selectivity with circuit-breakers installed at customer site. The risk that cables might be damaged in case of low-current fault also needs to be considered.

2.2.2 Circuit-breakers

Circuit-breakers offer the possibility to reclose and a better selective coordination with customers protection devices. Possibility to change settings is also a plus.

Nuisance trips, on the other hand, are a commonly mentioned disadvantage of circuit-breakers.

Circuit-breaker may be with thermal + magnetic release or electronic release. Each alternative has several advantages and disadvantages.

2.2.3 Additional components

Panel boards/cabinets are used to install protection and switching devices. IP, temperature and other requirements vary widely according to local installation practices.

Low voltage feeders (typically 3P+N cables) are connected to busbars by means of cable lugs/cable connectors. Reliability and durability of such connection is one of the main engineering issues, because of the wide range of mechanical and thermal situations where stations can be installed.

Possible additional options concerning LV equipment are:

- circuit-breakers may be motorized: in this case, they also need to be connected to the control devices/communication system. An auxiliary power supply source for the motor operators is required as well.
- low voltage switchgear may implement measurement/supervision functions (e.g., voltage measurement, PQ monitoring, power metering, either with separate devices or integrated with the circuit breakers)
- equipment for ground fault detection and/or protection can be installed at the MV/LV station as well.

2.3 MV/LV transformers

Transformers are one of the most important strategic components for managing the power flow of electric networks, and are widely used all over the world.

Early transformer technology was firstly deployed around the end of the 800’s, and today that technology is still recognizable. Due to the simple magnetic winding and core design principle, it is hard to imagine how this technology will change in the future.

Transformers are key network components, which allow power companies to reduce or transform higher efficient transmission voltages to useful industrial, commercial and domestic voltages in order for their equipment to operate.
This section will fully describe how distribution transformers are deployed by DSOs to efficiently transform medium voltage (10 kV - 20 kV) to low voltage (400 V – 230/110 V) used by commercial and domestic customers.
Distribution transformers are rated depending on the load requirements, and the standard ratings are between 25 kVA - 1000 kVA.

2.3.1 Conventional technology

Typically, transformers consist of a copper or aluminum windings wound around a central laminated iron core. Transformer active parts are contained in an insulating medium, normally mineral oil, but can be immersed in synthetic oils such as Midel or dry type such as cast resin.
Most transformers have a 3-phase design; however, in some countries, single-phase solutions are also used. These are typically up to 100 kVA pole-mounted, and deployed in the rural networks.
The core is usually made of magnetic steel grain oriented material. The typical arrangement for 3-phase transformer is core type; however shell type arrangement and wound type cores are also used for specific applications. In addition to conventional core designs, amorphous type transformers are used outside European countries (North and South America).
Currently, copper or aluminum windings are used. The use of aluminum has led to an economic design whilst maintaining acceptable performance and reliability. The primary windings are made of concentric wire and the secondary are constructed with layers or foils. The choice of foil for the manufacturing of the LV windings improves the ability to withstand short circuits.
The most common insulating/cooling material used in transformers is mineral oil. Mineral oils are specified in compliance with IEC 60296. Other insulating liquids, (e.g., natural ester like MIDEL), have been recently developed and deployed to respond to environmental requirements of customers. Further to liquid insulating materials, cast resin dry type is adopted on distribution networks.

The tank enclosure contains the active part of the transformer and allows the circulation and volume variation of the liquid. Temperature variations due to loading and ambient temperature cause the oil to expand and contract. There are two main types of tank design: hermetically sealed or conservator type. Other solutions, including gas cushion type, are available outside Europe.

Hermetically sealed fully filled transformers have an increased life expectancy because the oil is protected from humidity and oxygen in the air, thus, ageing of the insulation medium is reduced.
For specific situations, dry type transformer can be also adopted, particularly in presence of high risk of fire or environmental issues. However, dry types are less efficient and can be more expensive.

Phase configuration to manage load balances are connected as Yzn11 for small rated transformers and Dyn11 for single-phase and three-phase loads.

Transformers are manufactured in huge volumes in order to supply the energy industry worldwide, and, consequently, are required to perform efficiently for a competitive price. High quality designs and quality materials have to be used to derive a competitive price and to comply with performance requirements. Manufacturers constantly optimize design, industrial processes and materials to respond to customer needs, and each manufacturer adopts best practices to deliver safe, fit-for-purpose products.

2.3.2 Bushings

Globally, sub-components and accessories are not consistently standardized, and as a result, each country or customer tends to require them specifically for its application.
Transformer accessories in Europe including medium voltage and low voltage bushings are essential to ensure the safe operation of the assets. These components are generally specified in agreement with country specific standards.

Several types of bushings are available on the market: air/oil open type, inside cone plug-in, outside cone plug-in, and are specified in agreement with EN 50180. The type of bushing is important to assure interchangeability of the transformer. In terms of connecting to cable, plug-in bushing technology with managed electrical fields has become widespread, due to improved reliability and safety.

2.3.3 Protection of the transformer

Transformers can be protected from overcurrent and earth fault by using fuses or circuit-breakers which are externally coupled to the transformer. Protection devices can be deployed on either the primary or the secondary side.
One of the solutions adopted mainly in France consists in adding a fuse and a disconnecting device inside the transformer main tank. This technology is generally known as a self-protected transformer. This solution is designed and built in compliance with EN 60076-13 “Self-protected liquid filled transformers”.

During a fault interruption, the fuse protection device within the tank automatically disconnects the transformer from the network. Fuse selection is specified depending on the rating of the transformer, and additional devices such as integrated oil level protection or earth fault current detectors allow this protection to be more effective than units with external protection fuses. This solution has an economic benefit, particularly in rural networks, as this removes the requirement for MV switchgear for transformer protection.

The selection of a protection system depends on the grading within the wider associated protection schemes in order to ensure proper operation. The protection chain of each unit may include self-powered relays with optimized current sensors, which bring a high level of availability and safety. This solution provides maintenance benefits and improves protection of the transformer, discrimination with the LV installation, insensitivity to the inrush currents, and detection of low earth fault currents.

2.3.4 Transformer reliability, maintenance and replacement

Transformers are traditionally robust, reliable assets, and are expected to be in operation for more than thirty years without problems. The failure rate is typically low, around 0.5% per year. Pole-mounted transformers are typically less reliable due to the environment where they are used, failure rates can range from 1% to 2% per year.

The competitive cost per unit of distribution transformers, due to their widespread deployment and low failure rates, relies in replacement rather than repair.

Distribution ground mounted transformers have low maintenance costs. Maintenance interventions can range from visual inspections including load checks, to oil sampling. Some utilities install power meters to analyze the transformer loads using data from smart meters.

Pole-mounted transformers generally are visually inspected only and tend to be replaced upon failure.

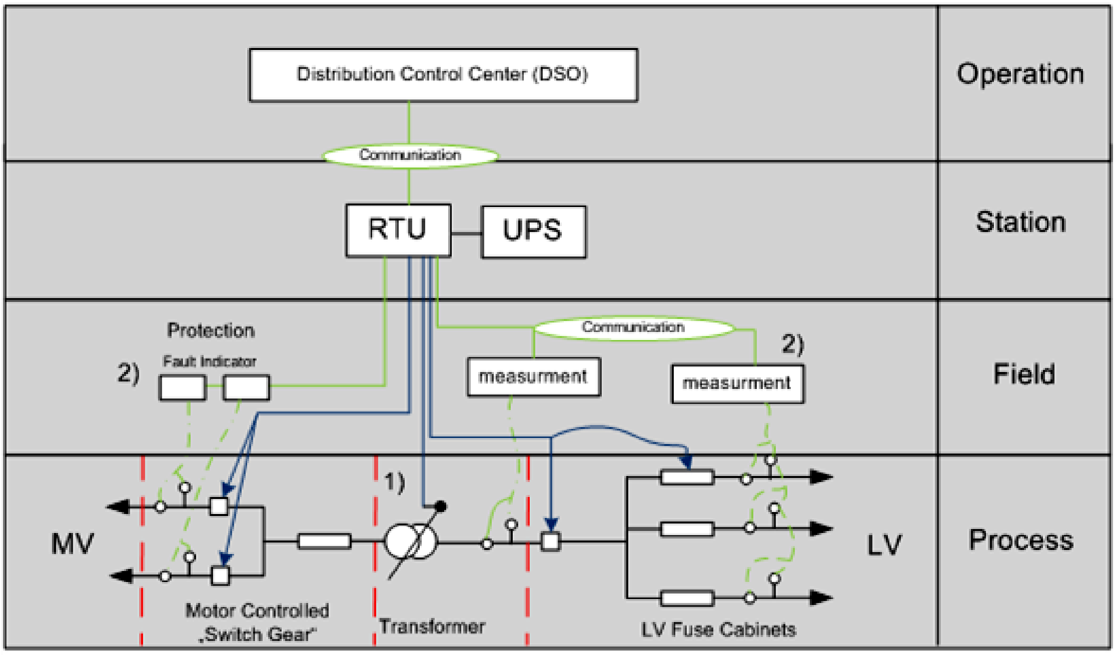
2.3.5 Energy performance and Eco design

The European Commission Directive proposed a reform of the EU Emissions reducing carbon emission by 20% by 2020. In order to meet these targets, the European Commission published Eco design Regulation: N° 548/2014 on the 21st of May 2014. The regulation is practically a law in all European countries.

The scope of the regulation is to increase gradually the efficiency of new power transformers commissioned in the EU internal market. For this reason, the new transformers shall fulfill the minimum losses requirement from 1st July 2015 (Tier 1). Further improvement of the energy performance of new power transformers Regulation will commence from July 2021 (Tier 2). The impact may lead to a significant cost increase, and therefore control measures have to ensure regulation implementation.

2.4 Remote control systems and devices

This chapter deals with the apparatus that makes possible the interface with the primary process (e.g. cables and switchgear) from a central point, like central control databases/systems that facilitate all kind of stakeholders with data. To enable this functionality, there has to be a chain of devices starting with the sensor in or on the primary infrastructure and ending on the screen of a stakeholder. This chapter will use a top down approach with a brief description of SCADA/DMS systems because they are currently the most common central systems. Then, an overview of the most common data-communication technologies is presented. Finally, the heart of this system is described: the Remote Terminal Unit (RTU). RTU is the intermediary between the primary process and the central system to connect all the data and make logical operations with the data. The other end of the chain in the form of sensors and actuators will not be discussed because it has been already mentioned in other chapters of this report.



1) Regulation MV to LV Transormer
2) Measuremend and Control of LV Feeders (possibly LV automation)
3) External Measuremend (Oil-level and temperature), SF6 pressure, door open, etc.

2.4.1 SCADA and DMS

Traditionally, if secondary substations are equipped with any form of automation, they send data to a Supervisory Control and Data Acquisition (SCADA) system. This SCADA system makes it possible for controllers to watch over the grid 24/7. A SCADA system uses a Real Time Database for real time operation; of course, relevant data are shared with off line databases, allowing back office analysis. SCADA systems typically manage elements called “points”. A point represents a single input or output value, which is monitored or controlled by the system. Points can be either "hard" or "soft". A hard point represents an input or output, while a soft point results from logic and math operations applied to other points. The system monitors certain conditions, so as to determine if an alarm event has occurred (alarm handling functions) and, possibly, to perform consequently proper actions (e.g., activation of automatic procedures). SCADA system's databases and software programs offer a human machine interface (HMI) to provide schematics, trending, diagnostic data and so on.

Where many SCADA systems are quite straightforward, Distribution Management Systems (DMS) can provide the controllers (and other stakeholders) real-time and offline calculations such as state estimation, power flow, optimal switching etc. A DMS system is fed by SCADA and corporate archives with dynamic data such as status of switches/breakers, measurement etc. and more, “static data” such as network size, load and generation profiles, characteristic of conductors etc.

The different SCADA and DMS solutions adopted have direct impact on:

- Naming convention

- Network representation (diagrams, schemes, …)
- Devices configuration (directly by the SCADA and/or by means of concentrators and/or converters/data gateways)
- Network management
- Network operation, both in case of manual and remote controlled operations
- Update of the connection state of the network
- Automation functionalities, both at grid and substation level.

2.4.2 Communication to Secondary Substations

External communication is intended as the link between the substation and other systems. This can be communication between substations to a SCADA/DMS system or to a remote management tool. Different types of data communication technologies will be described.

2.4.2.1 xDSL

Digital subscriber line (DSL) has a relative high-speed technology based on two-wire twisted pair lines like existing telephone cables. DSOs can use this technology from third party suppliers or can use the technology on their own old existing networks. This can be an interesting solution for areas with no wireless communication or when there is an existing network available.

2.4.2.2 FO (Fiber Optic) Glass fiber

Glass fiber is based on optical signals. Therefore, it’s ideal for high speed and long distance and with lowest latency of all communication systems. This way of communication is not so common for secondary substations because it’s quite costly to install them, if not done while installing power cables.

2.4.2.3 PLC/BPL

PowerLine Carrier (PLC) or Broadband over PowerLine (BPL) uses the energy grid for communication. Usually, the data from the secondary substation are communicated over the MV network to a primary substation from where they are communicated through a different technology.

2.4.2.4 Dial-up

Older serial connections use dial-up modems. These can be wired or wireless. In most wireless cases, the dial-up connection is triggered by events. Dial-up connections should be included in security checks.

2.4.2.5 WiMax

In rural areas, WiMax is an alternative to make wireless communication reliable and independent from public communication networks. Speed and latency are similar to Fiber Optic communication. Applications using WiMax are up-to-date mainly on overhead lines including tower substations.

2.4.2.6 GPRS/UMTS/LTE

For countries with a good mobile network, this is often used for the automation of secondary substations. The advantage is that it's affordable and widely available. The disadvantage is that it's harder to get secured and the availability depends on the traffic of other users of the network. It's necessary to ensure that the base stations of the public network are using backup power supply to be available during blackouts. The mobile networks in Europe support now the 4G technology also known as Long Term Evolution (LTE). Earlier generations are the 3G UMTS technology and the 2G GPRS technology.

2.4.3 RTU

The expectations and tasks to be performed by RTU have increased over the years as result of Smart Grid requirements. Traditionally, it secures collection of analog and digital inputs, provision of commands and, on top of that, communication through standard protocol to the SCADA system. Besides these traditional tasks, it may also perform other tasks, e.g., communication with IEDs (Intelligent Electronic Device), integration of automation functionalities or just communication gateway securing data processing of independent metering and control units. The usual RTU has modular architecture with several cards securing specific functionalities in order to be scalable.

In general, we can see modular or integrated RTUs depending on customers' requirements in terms of functionalities and needs and also with in-build or external communication.

The main tasks of the Remote Terminal Unit are:

- facilitating efficient and reliable communication between secondary substation and control center
- collecting and processing information from the secondary substation and communicating the information to SCADA
- enabling the monitoring and controlling of the secondary substation

The Remote Terminal Unit shall be placed either indoor, inside the secondary substations, or outdoor, depending on the type of the secondary substation itself. Therefore, these operational conditions and the installation features shall be taken into account, for example, the IP protection shall be increased for outdoor installations.

The basic specifications for the RTU system with the limit values for climatic performance are determined by the IEC 61850-3 "G" standard (Ed. 2.0):

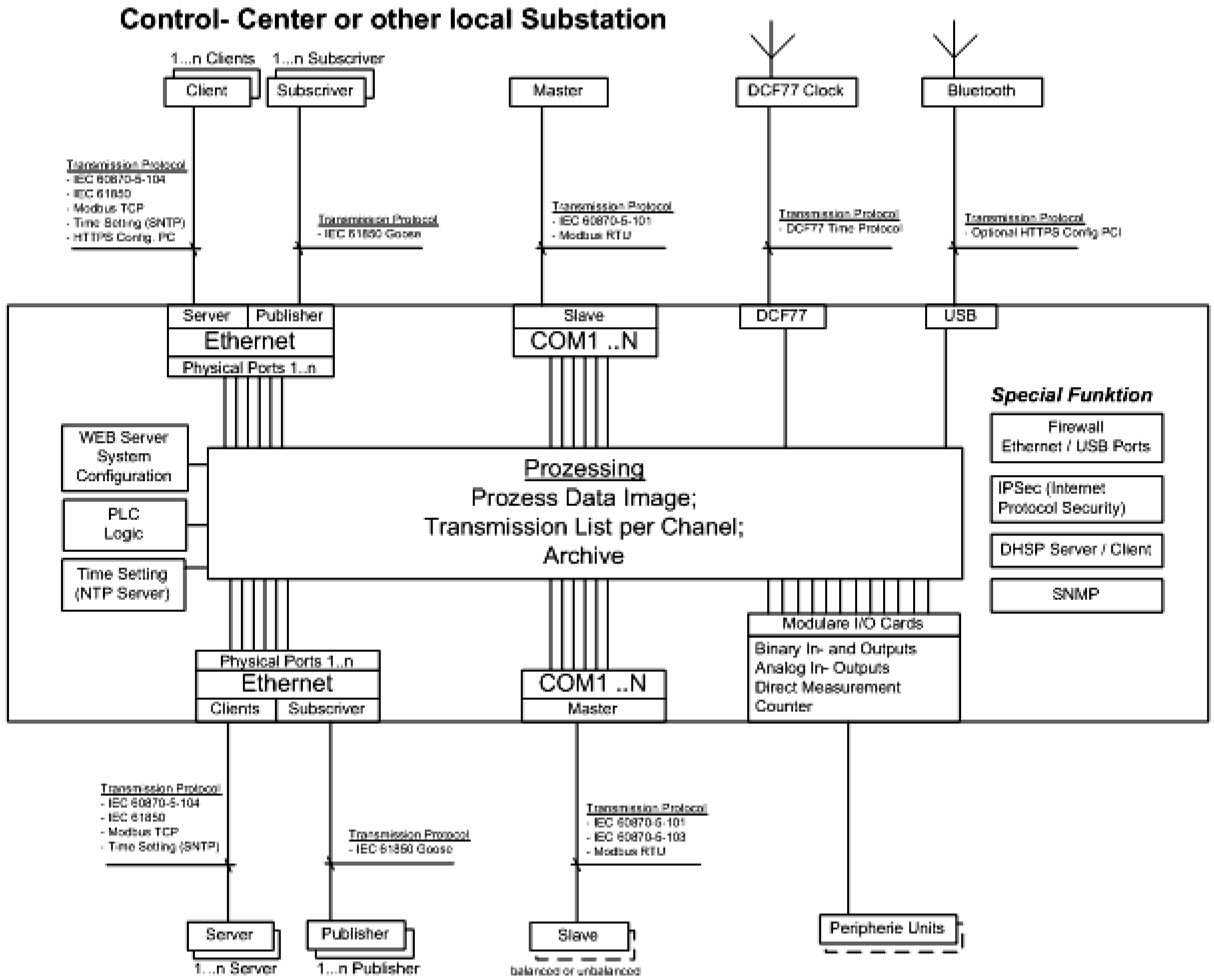


Figure 3: Network topology and block diagram of a RTU

2.4.3.1 Main RTU Functions

Some important functions are briefly presented in the following table:

Function	Basic Function	Special Function
Hardware	Hardware watchdog timer Hardware clock (RTC) Operation without ventilator	
Time setting	Recife Timestamp with Protocol IEC 60870-5-101(4); SNTP or DCF77 (GPS) Antenna	Send Timestamp on Substation with Protocol IEC60870-5-101(3);(4) or SNTP
Firewall	Switch On / Off every Ethernet an USB Communication Port with the integral Firewall on Board off the CPU	
Security	Encryption Telegram with different algorithm via Tunneling or Transport mode between RTU and Control Center or RTU and Substation	Authentication with Pre shared Key or Route Certificate
DHCP Client or Server	The IP address of the device can be assigned by an external DHCP server, or stored as a fixed setting in the form of static IP address.	Optional, with the DHCP server on Board of the RTU you can dispense with the parameter assignment of the network addresses of the DHCP client. Thus, the clients don't require a fixed allocation of the IP address.
Patch- and Update-Management	Local Update Firmware CPU and Parameter RTU from the Central Station	Remote automatic Update Firmware CPU and Parameter RTU from the Central Station
Data Logging	Archive Data (System information an Process data) local on the CPU on SD-Card or internal Flash-Card	Archive Information for IT Security logging Information
Documentation on Board of the RTU	On Board of the CPU (internal Flash Card) is a User manual that describes the functionality, installation and commissioning of the processing unit for a local network substation. Additionally, the diagnosis functions and service functions are described.	
Communication between RTU and central processing unit for Grid network systems	The availability and performance of the System (communication services for RTU and Central Unit) are 99.95% for commands and 97% for remaining less priority communication.	The communication for send a command and answer from the RTU to the Central Processing Unit are max. 3 sec.

2.4.3.2 Flexible I/O card and communication interface

In order to meet the needs of today's energy supplier, a Remote Terminal Unit is required with a modular system platform. This system platform should have an open scalable architecture that is easy to adapt to future requirements without any hardware upgrade.

The RTU should have at least the following physically separate communication interfaces:

- 2 Ethernet Ports RJ45 (Full or half Duplex Communication Ports)

- 2 COM Ports RS232 and / or RS485 (RS422)

In addition to the described communication interfaces, the RTU has more interfaces for the direct detection of signals like single and double points, counter and transformer tap position, measured values or the outputs of commands and set points. This also includes modules for the direct measurement of current and voltage in the medium and low voltage.

2.4.3.3 Binary or analogue input or output

The requirements of the binary and analog input or output cards are:

Card	Voltage	Signal	Attribute
Binary Input	24-220V DC	single- double; point indication; counter and Tap Change information	Timestamp, Qualifier
Binary Command	Relay	Single- double Command or Signal Output	Timecontrol, Qualifier
Analog Input	mA; V; PT100	Bipolar or unipolar Measurement (scaled, normalized, float)	Timestamp, Qualifier
Analog Output	mA, V	Bipolar or unipolar Measurement (scaled, normalized, float)	Timestamp, Qualifier
Direct Measurement	0… 100V√3 1/5A or 300V 1/5A	UL1; UL2; UL3, IL1; IL2;IL3; P;Q;S UL12; UL23:UL13; IL1; IL2;IL3; P;Q;S and F, CosPhi, ….	Timestamp, Qualifier

2.4.3.4 Internal communication

The state of the art of the infrastructure into the substation is a communication per Fieldbus RS485 via Modbus or IEC 60870-5-103. In the future, we might see the internal communication LAN inside the secondary substation via Ethernet (TCP IP, UDP protocols IEC61850). A communication switch is then needed to enable LAN inside secondary substation.
Another possibility might be external router used not only for RTU communication, but also for other devices.

2.4.3.5 External communication

The state of the art of the infrastructure from substations to superior systems is a communication per Ethernet or RS232 interfaces using IEC 60870-5-101, IEC 60870-5-104. In the future, we might see the communication with IEC 61850 more often using it as a communication to control centre and between the secondary substations as a very quick way to share grid status.

2.4.3.6 Serial (RS-232, RS-485), Modbus, IEC 101-103

The requirements of the serial communication ports are:

Protocol	Port	Baud-Rate	Function
IEC60870-5-101	RS232	50…. 38k4 Bit/s	unbalanced / balanced
IEC60870-5-103	RS485	9k6 or 19k2 Bit/s	unbalanced
Modbus RTU	RS485	50…. 38k2 Bit/s	unbalanced

2.4.3.7 Ethernet (network equipment), IEC 104, IEC 61850

The requirements of the Ethernet communication ports are:

Protocol	Function	Port	Virtual Connection
IEC60870-5-104	Client Server	RJ45 or Fiber full or half Duplex Communication with 10/100Mbyte/s	1…N 1
Modbus TCP	Client Server	RJ45 full or half Duplex Communication with 10/100Mbyte/s	1…. N 1
Time setting SNTP	Client Server	RJ45 or Fiber full or half Duplex Communication with 10/100Mbyte/s	1…4 1
HTTPS	Client	USB or RJ45 for Service and Engineering from Local or Remote	1…N

2.4.4 Measuring, Monitoring and Control

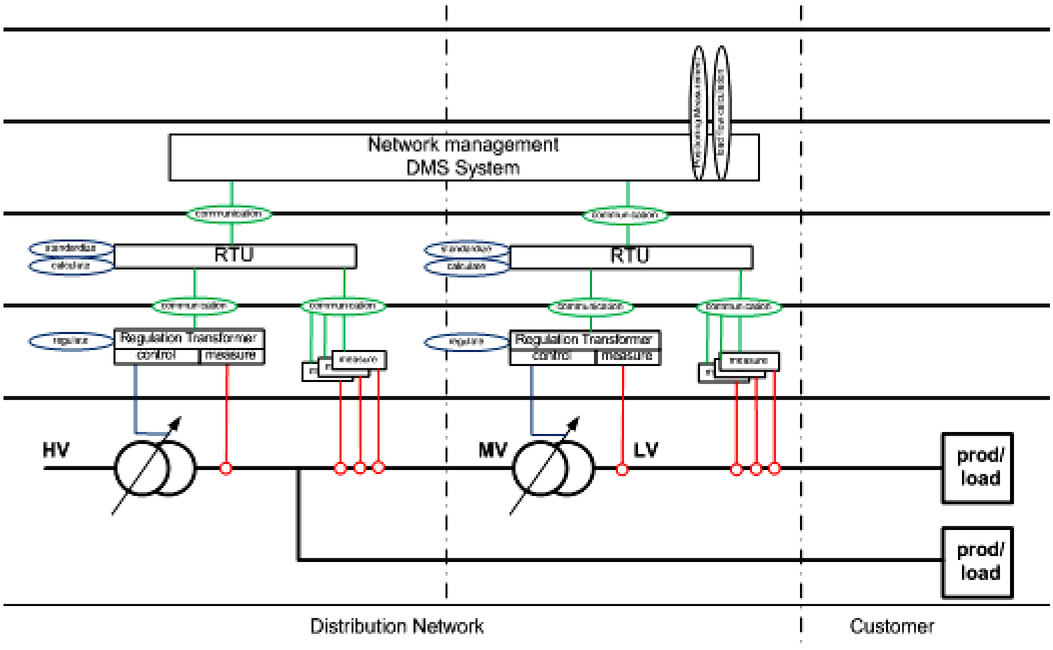


Figure 4: Voltage regulation and flow control in the distribution network

The essential function of the RTU is used for the monitoring the Distribution Grid.

Grid monitoring

- Short-circuit and earth fault detection
- Monitoring of switch status and device condition (e.g., loss of SF_6 pressure)

- Detect unwanted isolated networks in the high and medium voltage.

2.4.4.1 PLC (logic function)

As described in the previous sub-chapter, the RTU is the first level of the transformation of a substation into a smart secondary substation. For higher-level automation, signals can be processed inside, using a Programmable Logic Function, which is typically named after former additional processor needs PLC (programmable logical controller).

Algorithms written with the PLC function can be part of automated switching solution or Volt/VAR control applications and make operation therefore independent of superior systems.

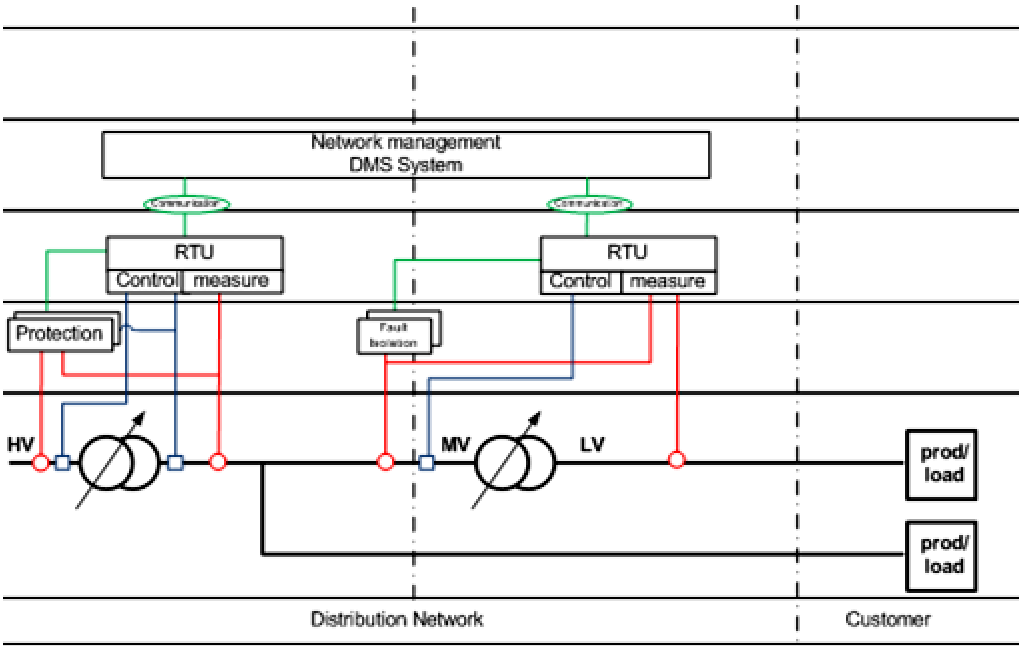


Figure 5: Connection and disconnection of network equipment by remote control

Automated switching for Fault Isolation and Service Restoration

- Derive necessary action to isolate faulty section
- Execute close command on normal open point to restore power
- Reconfigure to normal after fault clearance

Voltage stability

- Voltage regulator in the distribution substation (ONS) or in-phase regulator in the field
- Active and reactive power control for decentralized generating plants and loads
- Wide-area control for transformer and in-phase regulator

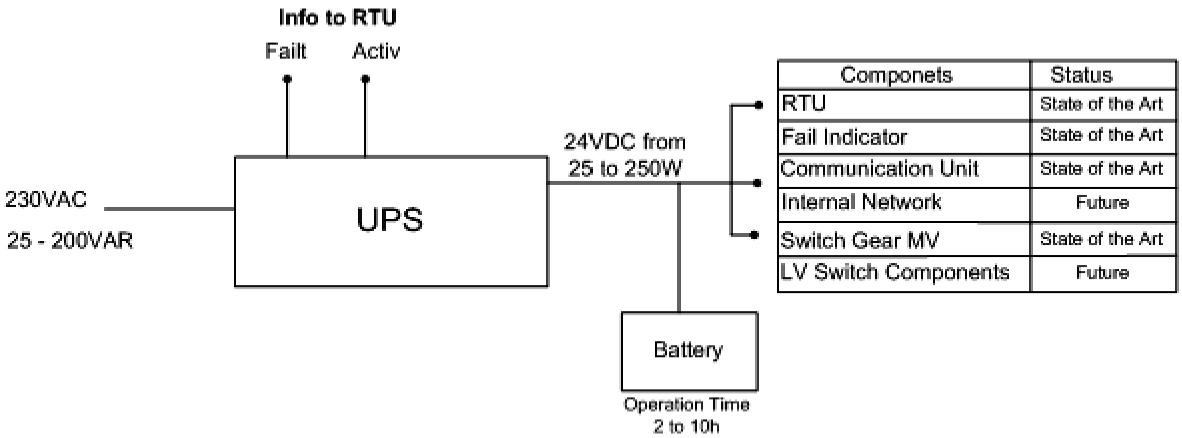
Load and Flow Control

- Load flow control based on the overall grid state

- Monitoring of the grid capacity to avoid equipment overload

2.4.5 UPS

All mentioned active devices in this chapter and in some other chapters like protection relays, work on Direct Current (DC) typically 24V, but other voltages are also possible. In order to keep the communication with the substation and protection in the substation active during outages, there is a need for an uninterruptable power supply (UPS) that keeps the devices active during a period of several hours.



2.4.5.1 AC/DC converter

The main task of AC/DC converters is to secure sufficient and reliable power supply to RTUs and other devices installed in secondary substations. The power supply concept might be based either on separate modules (usually installed together with modular RTU) or with integrated ones (compact RTU). The power output should reflect expected consumptions of all devices; in certain applications, the redundant configuration might be needed. Below mentioned list represents the usual set of functionalities to be considered by the project designer:

- Requested current and voltage output
- Possible UPS integration (extra connection)
- Power supply and battery management
- Communication capabilities (protocol and interface)
- Protection (overvoltage, over current)
- Operation conditions (temperature, humidity, ...)
- Temperature management – heating/cooling

2.4.5.2 Battery, Lead-acid, Powercap

The conventional battery system requirements are:

- Capacity fulfilling requested needs (e.g., 4/8 hours of supply of operation including 10 switching operations at reference conditions)
- Size
- Operation conditions (low temperature is crucial)
- Maintenance requirements (e.g., maintenance free, ease of replacement)
- Type of battery – Pb, Li-IOn, LiPo (regular backup) or super capacitor covering rather shorter outages but with lower price and faster charging/discharging
- Expected lifetime and its degradation (e.g., 10 years of capacity not lower than 80%)

2.4.6 Main applications

2.4.6.1 Network operation: remote control and supervision

- Asset supervision
- Remote controls of the MV switchgears (circuit-breakers, disconnectors)
- Measurements
- Monitoring and presenting the information on the state of the switches (breakers, disconnectors)
- Alarm processing, display and dispatching to control center
- Earth fault and short circuit indications (indications must work both in isolated and compensated network and also in intermittent fault conditions)

2.4.6.2 Asset management

- Measurements: current, voltage, temperature, e.g., transformer
- Based on the need of the utility current and voltage measurements on LV, MV or both LV and MV
- Security: SF_6 pressure alarm, temperature alarms, door alarm, fire alarm …

2.4.6.3 Power quality

Power quality measurements according to EN 50160 standard are:

- variation of the voltage level (10 min averages min, max and average + ranged limits been exceeded)
- variation of the current level (10 min averages max and average + ranged limits been exceeded)
- active and reactive power (hourly values)
- phase voltage and current distortion level THD

- event information: voltage dips and rises, interruption information and records

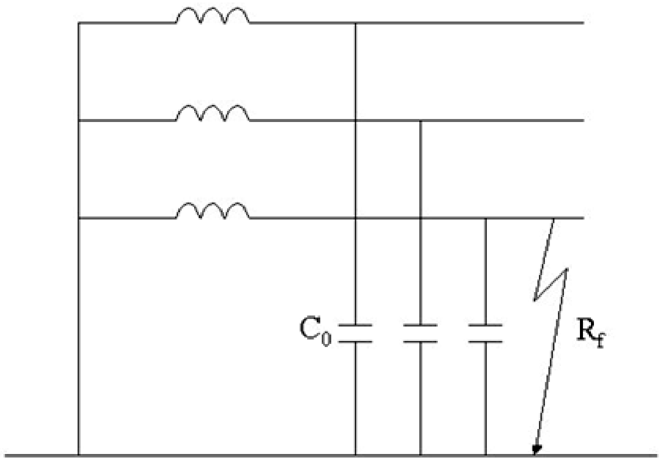
2.5 Monitoring and protection system and devices

2.5.1 Neutral point earthing

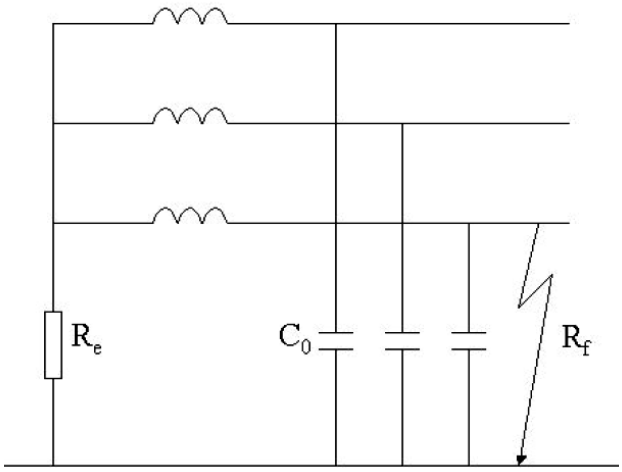
The way the neutral point is connected to the earth, determines the behaviour of a power system during a single-phase to ground fault. From a safety point of view, the earth fault current causes a hazard voltage between any exposed parts and earth (e.g., frame of a faulty equipment). In this chapter, the basic properties of different neutral point earthing methods are discussed.

As a simplified summary of the state of the art, it can be assumed that traditional earthing systems are divided into the following categories:

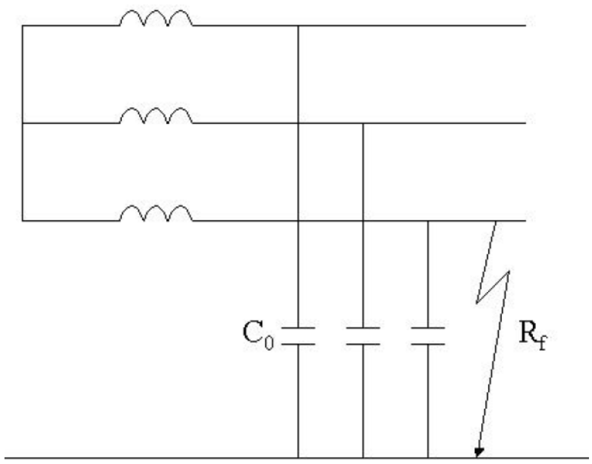
- **Solid earthing** i.e., the neutral point of the power system is connected directly to earth. It gives rise to high fault currents and low overvoltages. The following figure shows an earth fault in a system with a solidly earthed neutral.



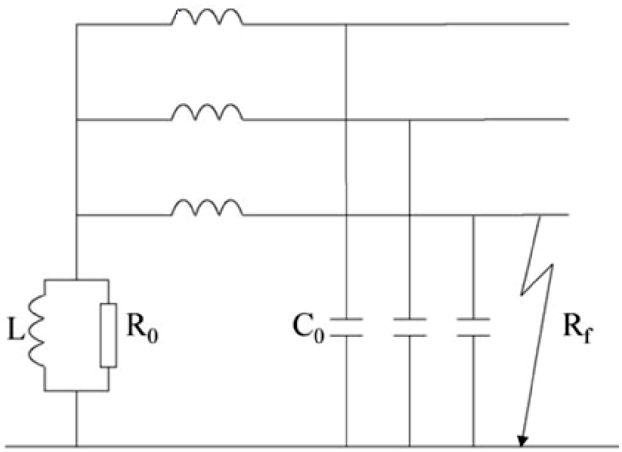
- **Resistance earthing.** To improve the earth fault detection in a power system, a resistance can be connected between a transformer neutral point and the substation earthing system. A system where at least one of the neutral points is connected to earth via a resistor is called a resistance-earthed system. The following figure shows an earth fault in a system with a resistance earthed neutral.



- **Isolated neutral**. A system where all transformer neutrals are unearthed is called an isolated neutral system. Variable earth-fault current, depending on feeders' capacitance, low fault currents and high overvoltages. The following figure shows an earth fault in a system with one unearthed neutral.



- **Compensated (or resonant) networks.** To limit the reactive part of the earth fault current in a power system, a neutral point reactor can be connected between the transformer neutral and the substation earthing system. A system in which at least one of the neutrals is connected to earth via an inductive reactance, a Petersen coil, and the current generated by the reactance during an earth fault approximately compensates the capacitive component of the single-phase earth fault current, is called a resonant earthed system. Earth-fault current is kept below some tens of amperes, with high overvoltages and longer fault durations. The following figure shows an earth fault in a system with a resonance earthed neutral.



2.5.2 MV earth fault protection considerations based on neutral point earthing

- **Solid earthing**. The earth-fault current in solid earthed networks has the same order of magnitude as the short circuit current in the network. Expected load currents under peak load conditions set a lower limit to the setting of the phase overcurrent relays. This limits the sensitivity of the earth-fault protection. More sensitive protection against earth faults can be obtained by using a relay, which responds only to the residual current ($3I_0$). The residual overcurrent relay is unaffected by phase-to-phase faults and by symmetrical short-circuit currents. The setting of the residual relay may be lower than 10% of the rated current of the current transformers.
- **Resistance earthing**. Earth fault current has to be artificially increased if the earth fault current is so small that it can't be reliably measured. One way to increase the earth fault current is to connect a high-resistance resistor to the network star point. The earth fault current is affected then mainly by the earthing and the fault resistances. Protection can generally be carried out with residual overcurrent relays. If sufficient sensitivity is not achieved by residual overcurrent protection, then directional earth fault protection can be used as in the isolated or compensated network systems.
- **Isolated neutral**. The sensitivity of a protection scheme using non-directional residual overcurrent relays may not be sufficient to detect high-resistance faults. The total fault current will drop below the capacitive earth-fault current of the feeder when the fault resistance assumes a sufficiently high value. This value may be lower than the value required by authorities or by the utility itself. A directional element can increase the sensitivity of earth-fault protection in MV distribution systems with isolated neutral. Usually, the neutral displacement voltage (U_0) is used as the polarizing quantity in the directional element.
- **Compensated (or resonant) networks**. Protection schemes using non-directional residual overcurrent relays are usually not suitable for Petersen coil-earthed systems. The

reason is that the fault current at a single phase-to-earth fault is much smaller than the total capacitive earth-fault current. The fault current is sometimes also smaller than the capacitive earth-fault current of the protected feeder. The residual current, however, will have a small resistive component that is in phase with the neutral displacement voltage. This resistive component can be increased by the installation of a neutral point resistor in the feeding substation that is normally connected in parallel with the Petersen coil.

2.5.3 MV/LV substation structure and functional elements

In order to clarify the structure of MV/LV substations, it is important to have an idea about the different MV distribution systems.

The voltage level of the systems described below is not higher than 36 kV.

Those MV distribution systems can be divided in overhead or underground distribution networks according to the type of construction classification.

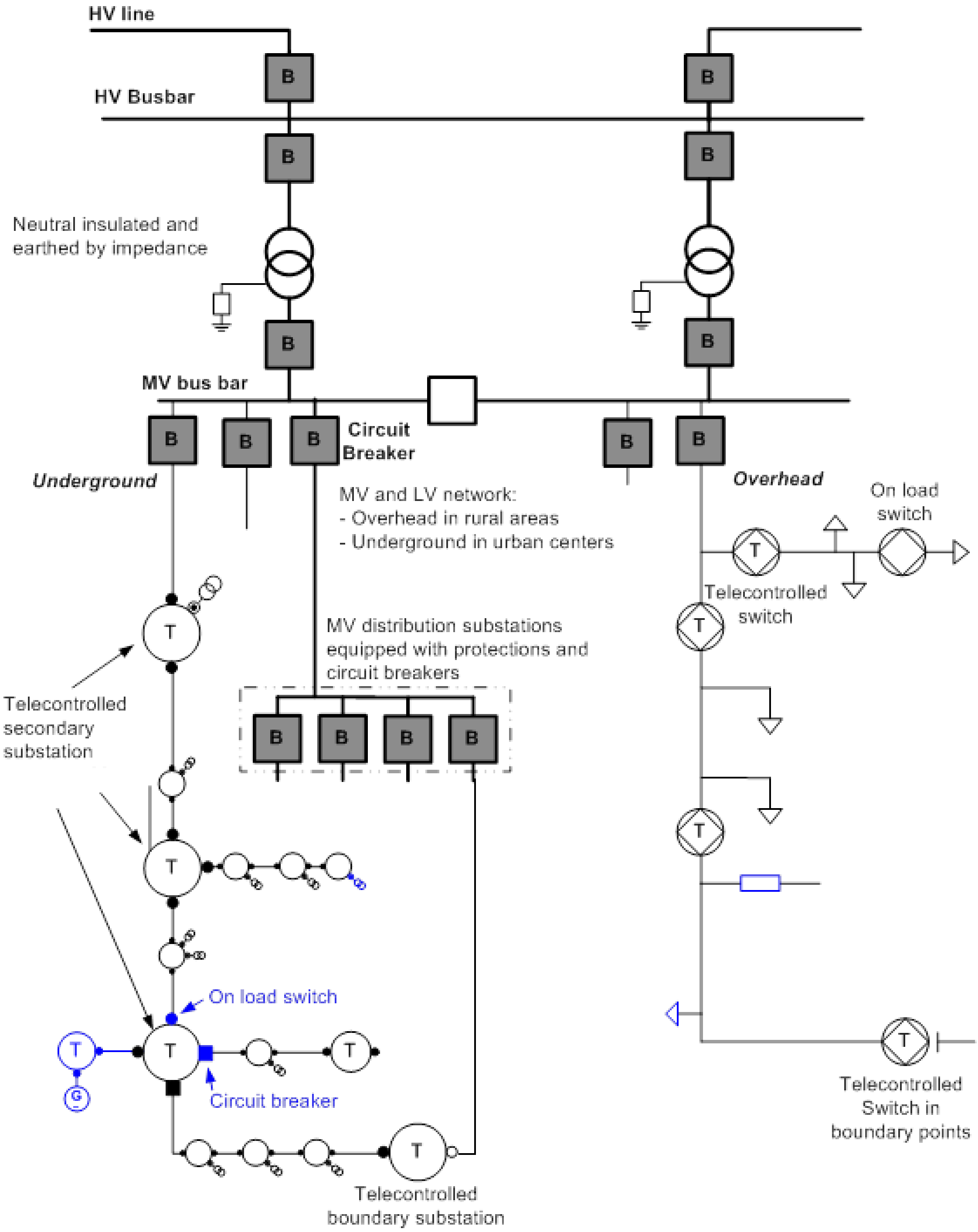


Figure 6: Power delivery overview - MV network model adopted by European DSOs

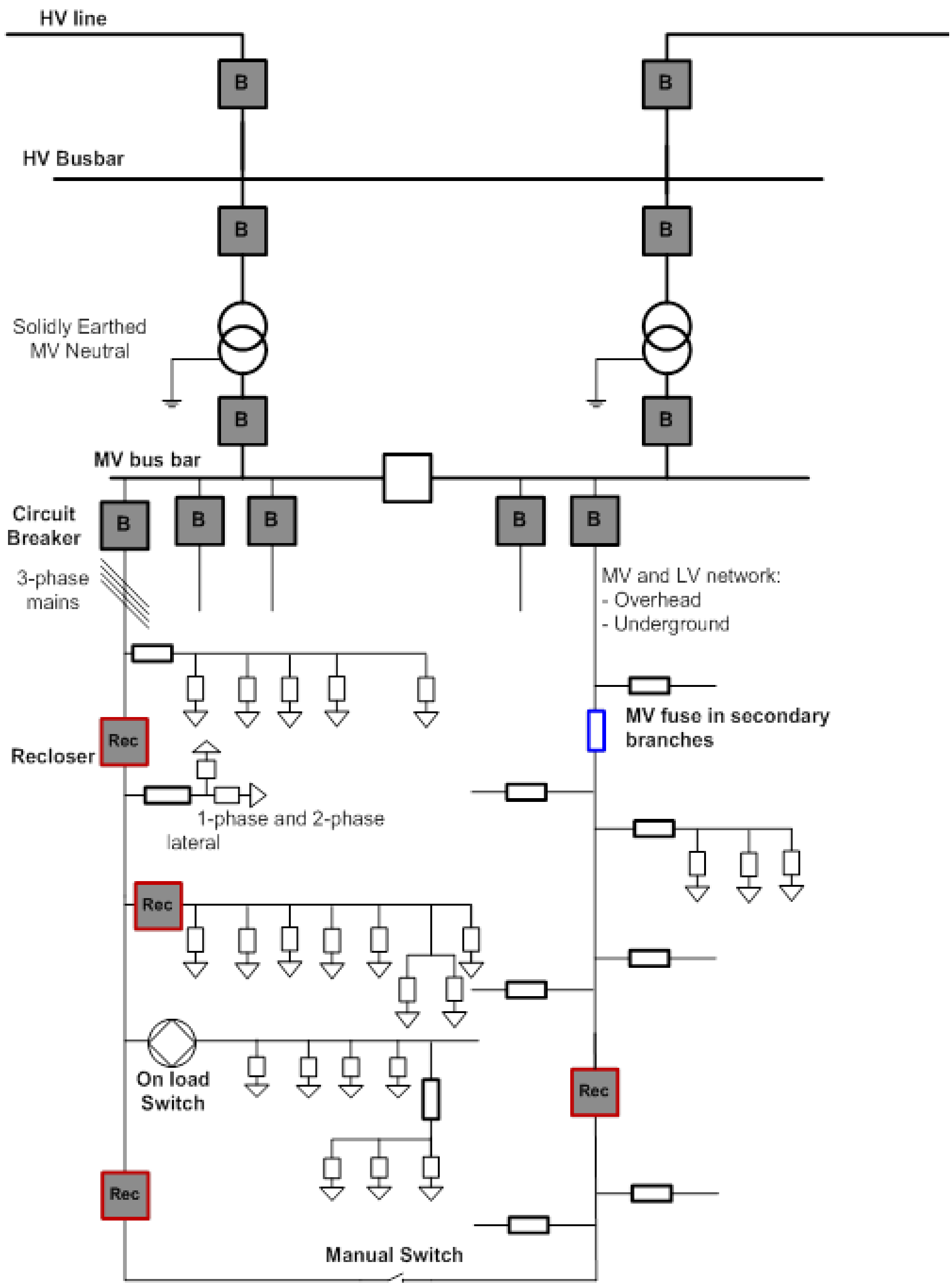


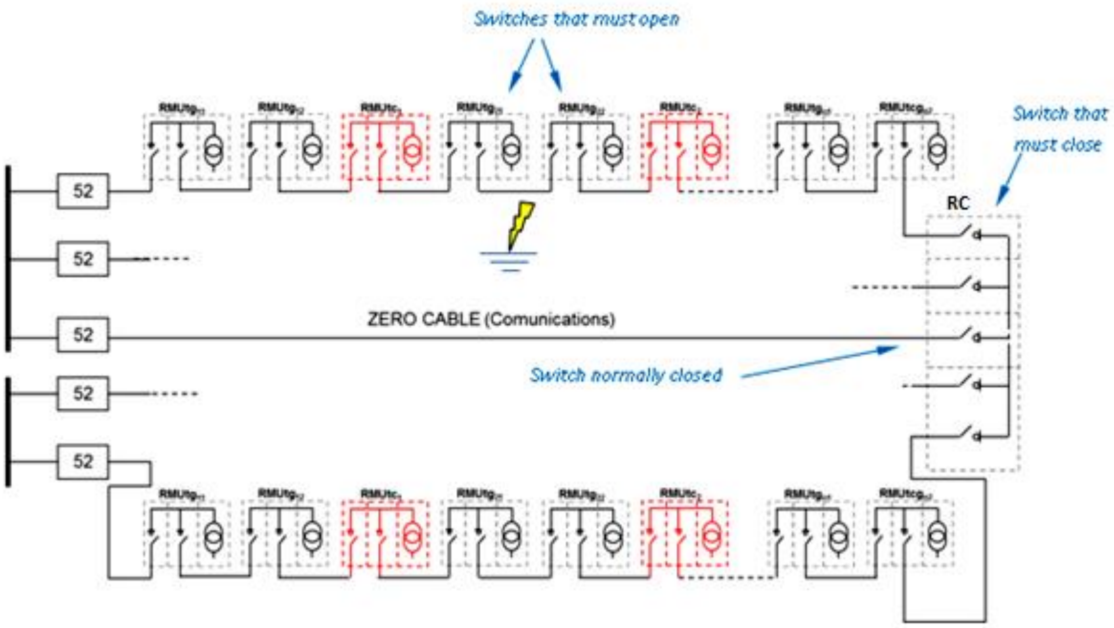
Figure 7: Power delivery overview - MV network model adopted by South American DSOs

2.5.3.1 Underground distribution networks

The most common RMU is a 2L+P, which ends in a common center called Reflection Center (RC) where all the different rings can be connected directly to a substation by a “Zero Cable“ that can be used for communication purposes.

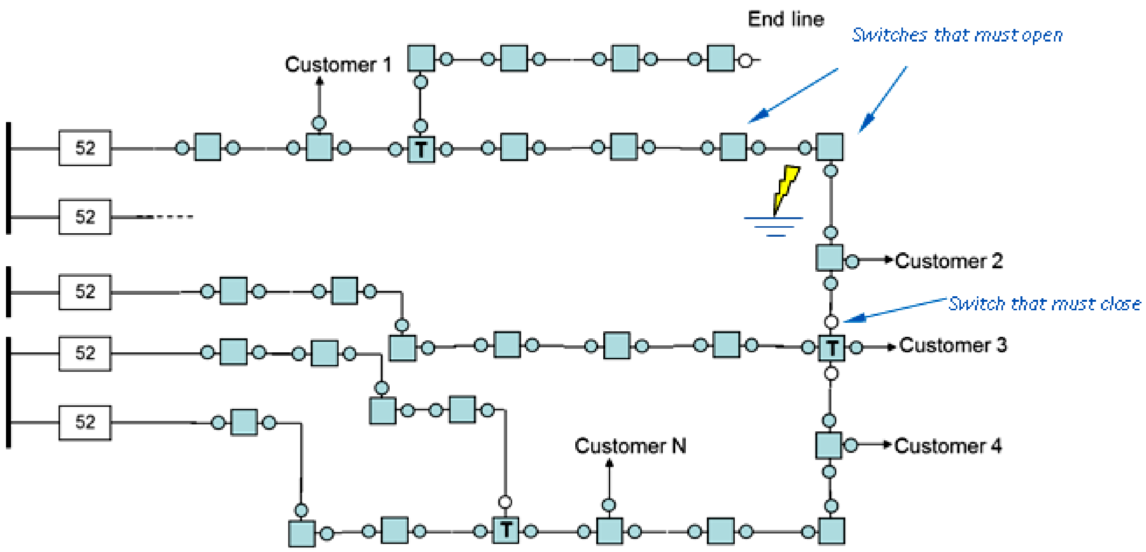
In this case, the normal configuration of the network is radial, like in overhead lines, with all the switches closed except the last one that connects the line with the RC. However, if there is a fault, the ring must be reconfigured.

Once the fault section is detected, by fault indicators and/or “test and error“ reconnections and visual inspection of the line and RMUs, this section is isolated by opening the switches upstream and downstream of the fault, and powering the RMU connected downstream of the fault by the RC.



The configuration of the ring can be composed by different feeders depending on the needs of the utility.

In this case, the RMUs are 2L+P commonly and 3L+P or 4L+P.



If there are some open switches, it means that energy comes from the substation downstream.

In the case that fault occurs, the reconfiguration of the line is solved by detecting the fault part of the ring with the fault indicators installed and/or “test and error“ reconnections and visual inspection of the line and RMUs.

When the fault area is identified, it is isolated by opening the switches upstream and downstream of the fault.

In that moment, it is possible to reenergize the downstream part of the ring in fault, closing the switch opened at the end of this ring.

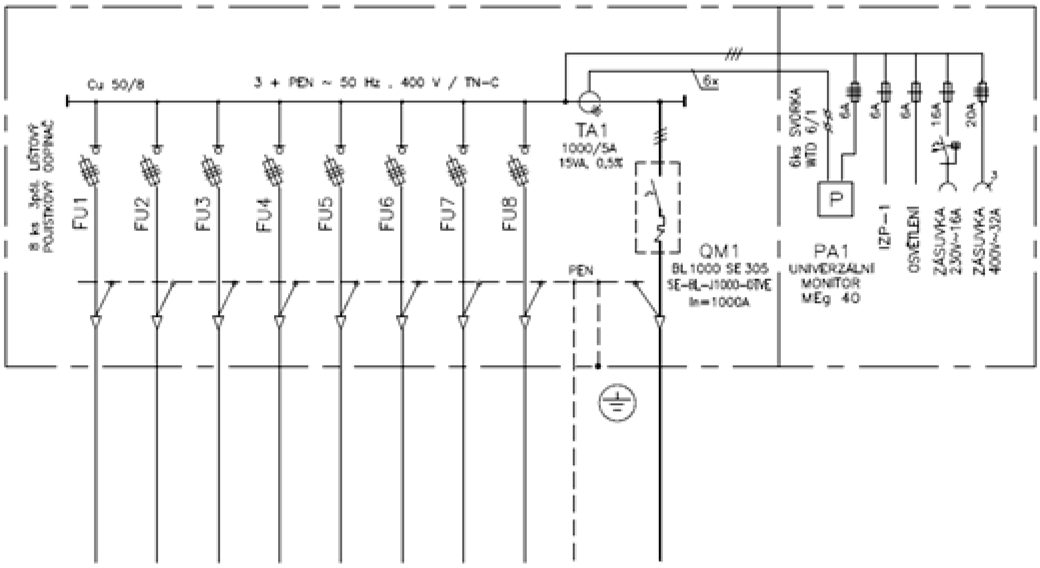


Figure 8: LV section using fuses protection

2.5.3.2 Overhead distribution networks

The operation of these lines, in order to prevent or minimize damage to electrical equipment and improve the reliability of the service to the customer, consists in removing the smallest section of the circuit for a given fault.

The circuit-breaker of the line (52), in the main substation, is tripped by the 50/51 protection associated, when it detects the fault.

Normally, it starts a reclosing period (up to 3 or 4 times), where it tries to restore the service by reclosing the circuit-breaker immediately. Approximately in the 70% of the time, the fault disappears and the service is restored with the first reclosing time.

The circuit-breaker trips again if the fault doesn’t disappear.

The cycle goes on with a second reclosing period, approx. 20 or 30 seconds later, if there are switches or disconnectors installed along the line. In this case, the furthest one would open while the line is without voltage (1).

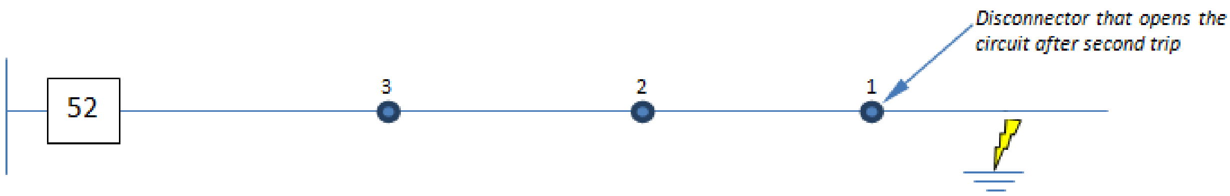


Figure 9: Restore service after second reclosing

In the case that the fault is upstream, the circuit-breaker trips again. The disconnector 2 opens while there is no voltage in the line.

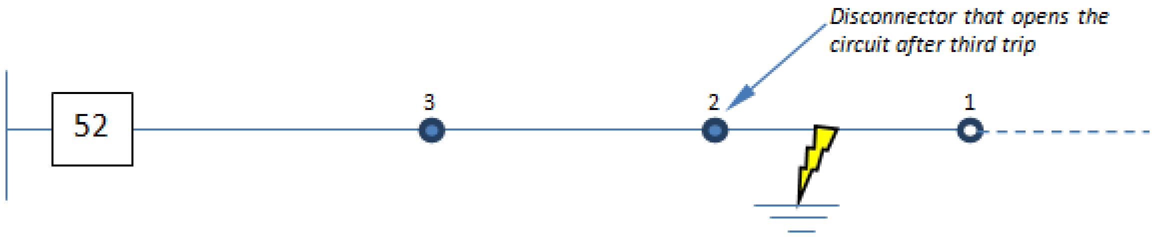


Figure 10: Restore service after third reclosing

The reclosing period continues if the fault persists. In this case, it's because the fault is located upstream of disconnector 2.

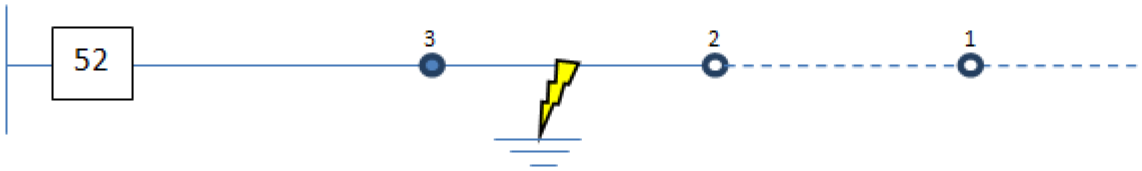


Figure 11: Restore service after fourth reclosing

The circuit-breaker trips and the disconnector 3 now opens.

This method of restoration of the service does not require remote control to work. It is only a local adjustment of the disconnector that counts faults and reconnections. However, the circuit-breaker must trip several times in some cases.

2.5.4 MV section: protection functions

On MV side of the substation, typically only the MV/LV transformer is protected. Fault Passage Indicators (FPI) are also installed on some lines.
With reference to FPI, Italy and Romania use an Enel standardized device called RGDAT (in the Outdoor and Indoor versions), while the other DSOs commonly adopt commercial solutions.
In South America, aerial reclosers with integrated MV over current protection are adopted and power switch devices too.
To protect MV secondary branches (laterals), MV fuses are widely adopted by LATAM DSOs.
For the MV/LV Transformer protection, different solutions are adopted.

2.5.5 Fault passage indicators

Incoming MV feeder (there is 1 incoming feeder and 1 outcoming feeder – in special cases there are more outcoming feeders) in distribution MV/LV substations is equipped with fault passage indicator – without remote signaling (i.e., in case of failure someone has to go and check the indicators).

Fault Passage Indicator registers short-circuit current in a phase of the MV grid – the benefit is to have faster identification and localization of the failure (and less manipulations in the grid with restoration). It is a three-phase device, which evaluates current in all three-phases separately. This device is applicable in network with one-directional power flow.

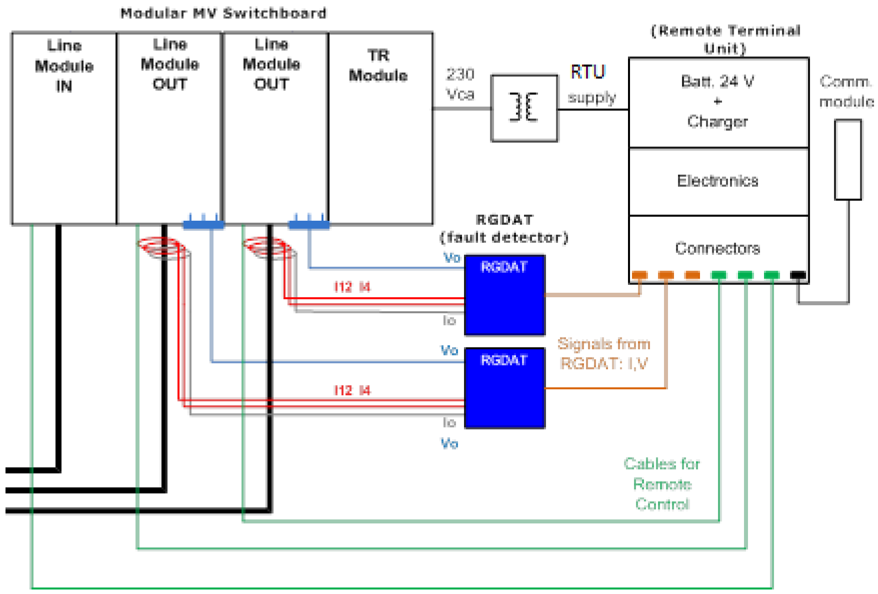


Figure 12: Standardized architecture of a remote controlled and automated secondary substation applied in Italy and Romania

Both Spain and South America commonly use functional specifications but adopt commercial embedded solutions developed by several suppliers (each one based on its own standard). The MV RTU and the protection devices communicating with it (if any) are often embedded in the cell/switchboard provision, as shown in the picture below.

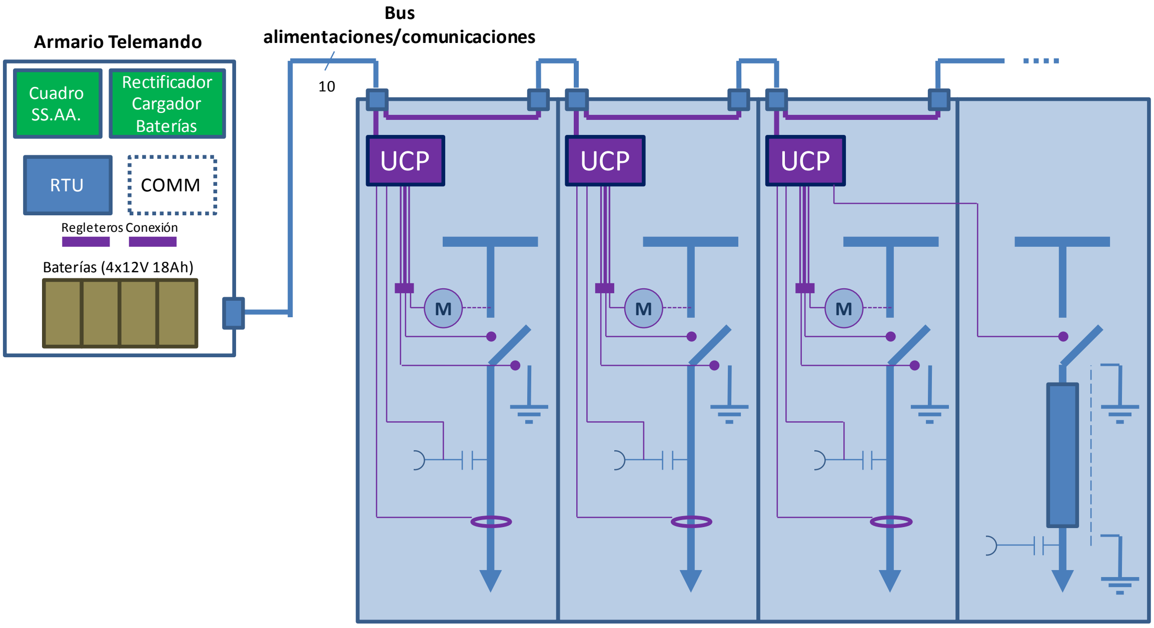


Figure 13: Example of embedded remote control solution applied in Spain

2.5.6 LV structure

The following figure provides a representation showing the differences between American and European practices transitioning from medium voltage (MV) distribution to low voltage (LV) service.

The European approach provides multiple three-phase or single-phase services from a three-phase distribution transformer that is significantly larger (250 kVA - 500 kVA) than the single-phase (25 kVA - 50 kVA) transformers used in the North American system. In both systems, power quality conditions (voltage regulation, harmonics, unbalance and flicker) on the secondary voltage systems can be impacted by individual customers. In Italy and Spain, there are more customers on a secondary system, but each customer has a smaller impact on the overall power quality. In rural applications, there is little difference between the two approaches to service.

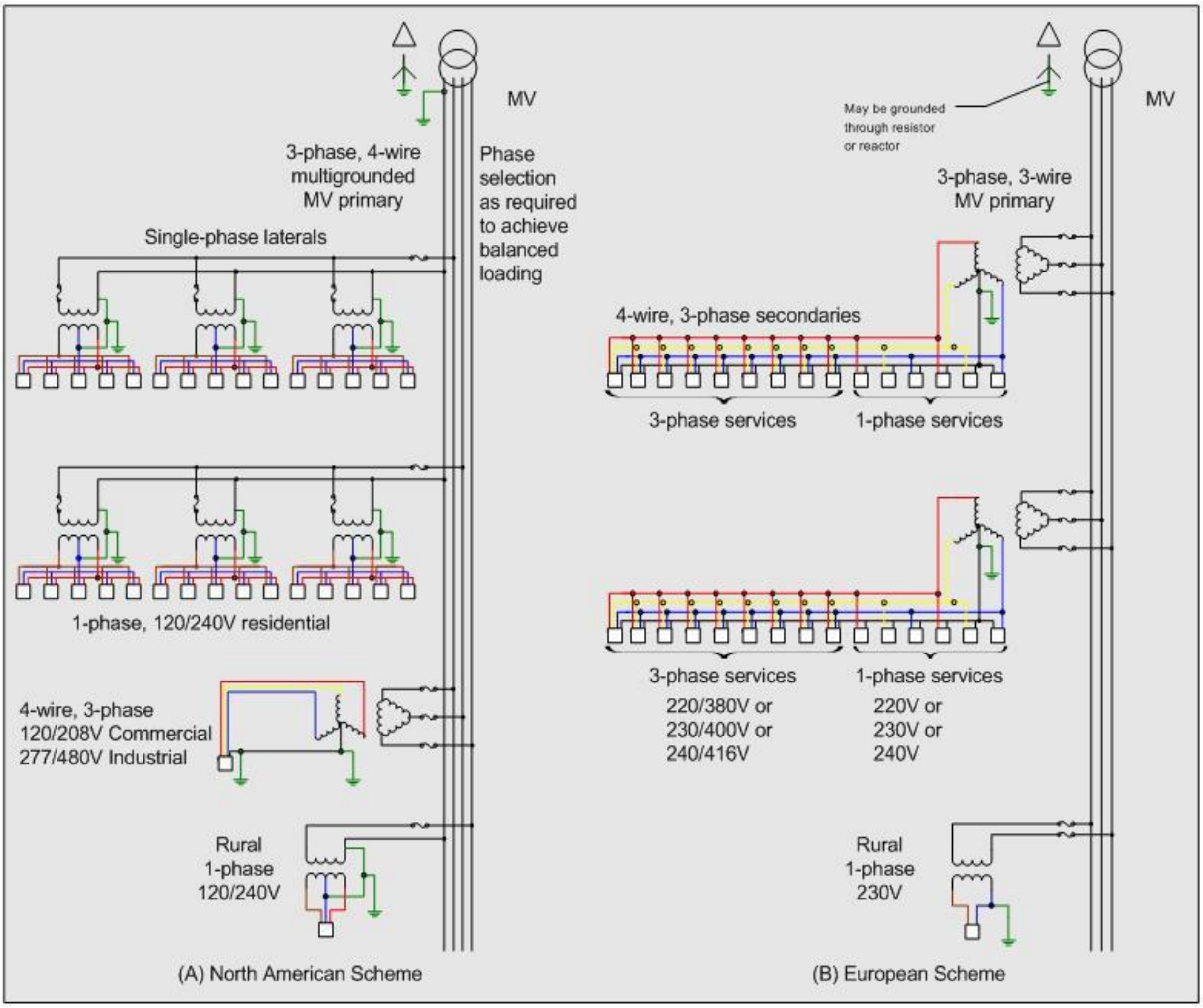


Figure 14: American and European typical LV network layout

2.5.7 Protection setting criteria

In this chapter, the most common protection schemes are discussed. The focus is oriented on standard MV/LV distribution substations. Switching stations will not be discussed in detail because they represent relatively a small part of nowadays MV/LV substations.

As for the protection system for LV networks, a variety of solutions can be identified.

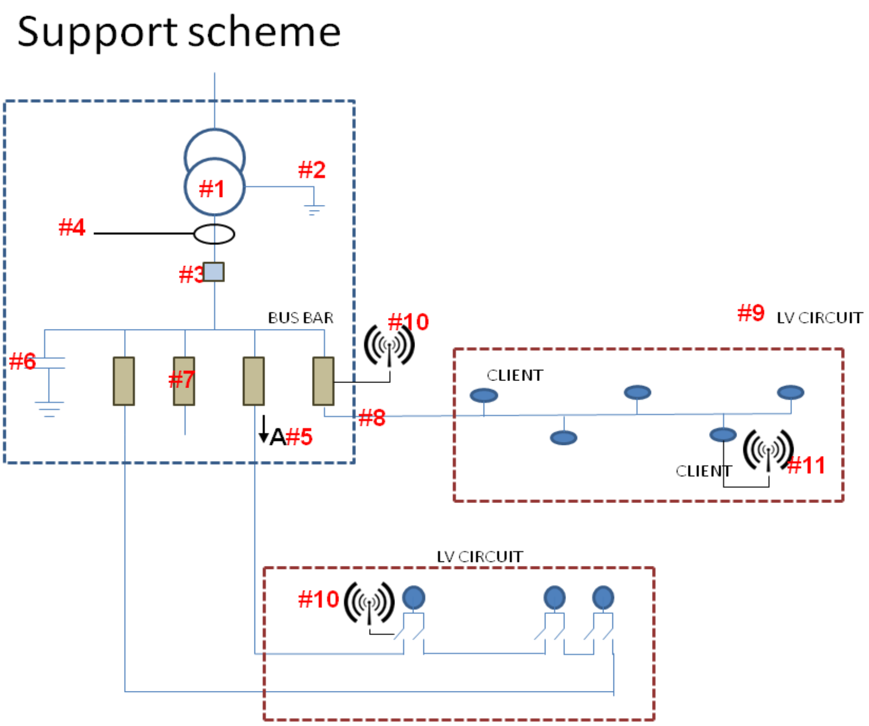


Figure 15: Support Scheme for LV Grid protection

The protection of LV switchboard is performed by a circuit-breaker (#3) and/or fuses; most of the utilities do not use any protection at LV busbar level.

Most utilities use the fuse to protect LV outgoings (#7), with the exception of Italy, which uses circuit-breaker with overcurrent protection. It would be an important point to take into consideration, in order to extend the remote control and automation techniques to LV networks.

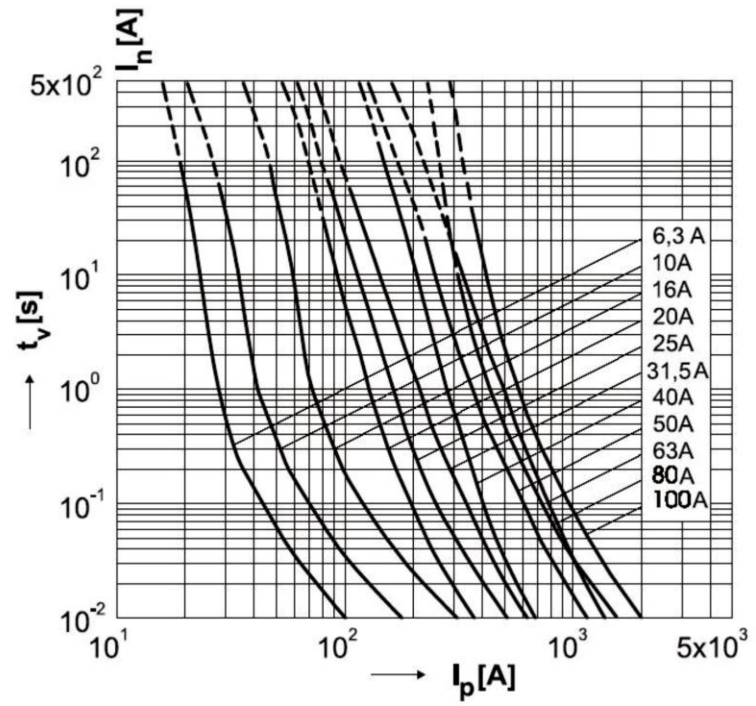
Intermediate protections along LV circuits are not used, with the exception of Spain, which sometimes places fuses in intermediate line locations.

2.5.7.1 MV fuses

At the MV side, the MV/LV transformer is mainly protected with standard MV fuses. Their function is to protect transformer against overcurrents and short-circuit currents. In the table below, there are examples of MV fuses used according to the installed power of particular MV/LV transformer. However, these values are just examples; different countries or different DSOs may have slightly different values.

Power of distribution transformer	Rated current of MV fuse
250 kVA	16 A
400 kVA	20 A
630 kVA	31,5 A

For a right protection of the MV/LV transformer, from MV side it is important to select appropriate A-s characteristic of MV fuses. An example of this characteristic can be found in the figure below. On the X-axes there is the current magnitude and on the Y-axes there is the duration after which the fuse blows up and opens the circuit.



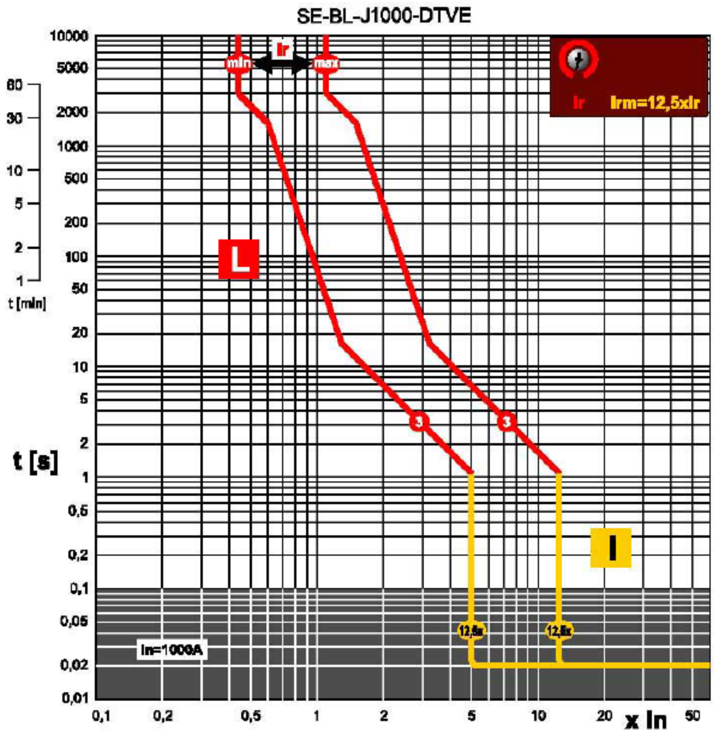
2.5.7.2 Main LV circuit-breaker

Main LV circuit-breaker is installed between low voltage side of the MV/LV transformer and LV switchgear, to protect secondary (low voltage) side of MV/LV distribution transformers against overcurrents and short-circuit currents. However, this is not the only solution: there is often just a simple disconnector, which is not protecting the transformer at all. Its function is to disconnect manually the MV/LV transformer from LV switchgear if needed.

In the table below, there are examples of typical settings of the main LV circuit-breaker for the most typical MV/LV transformers.

Power of distribution transformer	**Settings of the trigger I_r (A) at the supply voltage 400 V or 420 V**	
	400 V	**420 V**
250 kVA	360 A	345 A
400 kVA	577 A	550 A
630 kVA	909 A	866 A

For a right function of the main LV circuit-breaker, it is important to set appropriate A-s characteristic. An example of this characteristic can be found in the figure below. On the X-axes there is a multiple of the rated current and on the Y-axes there is the duration after which the trigger opens the circuit.



2.5.7.3 LV fuses

The protection of LV feeders is ensured with standard LV fuses with appropriate rated current and A-s characteristic. The selection of fuse is variable depending on the rated current of LV feeders, grid operation, etc.. In most cases, the LV fuses are up to 400 A.

2.5.8 PQ monitoring

Nowadays, PQ monitoring is not a standard state-of-the-art solution for MV/LV substations. However, in many substations, this monitoring is implemented and the implementation is ongoing. In some cases, this functionality is embedded in a concentrator for smart metering. In other cases, universal PQ monitor is installed at the LV voltage side of MV/LV distribution transformer. This device measures and registers voltages, currents, apparent power, active power, reactive power, energy, power factor and events. One of the examples can be found in the picture below.

3. Future tendencies

"*Study the past if you want to define the future*" said Confucius.

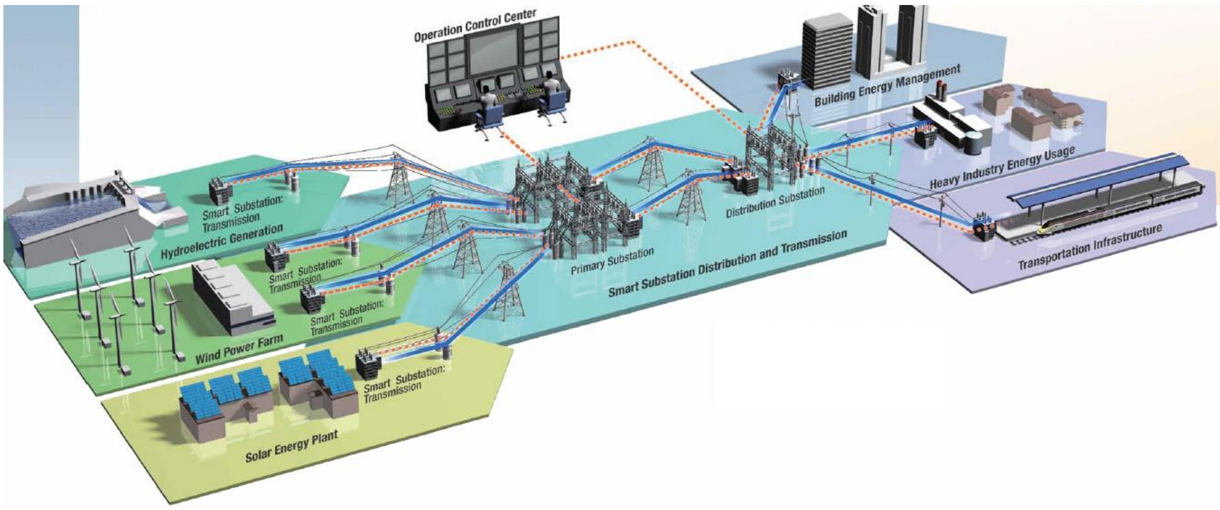
All the studies and experiences have brought us to the state of the art described in previous paragraph 2 referring to a standard power grid.

Today's grids are facing four main problems and these are growing in severity:

- global electricity demand is rising faster than demand for any other final energy source; in addition to this, the end-user demand is concentrated around peak hours, stressing grids and making rapid expansion a necessity;
- aging infrastructure tends to compromise reliability of power supply and exacerbate energy losses to the detriment of economies undergoing rapid electrification;
- as the share of Variable Renewable Energy (VRE) in the energy mix grows, the power grid will need to become more flexible to match supply and demand in real time;
- as the penetration of Distributed Generation (DG) rises to very high levels in some areas, issues relating to power quality and bi-directional electricity flows arise and cannot be properly managed by traditional grids.

Therefore, "evolving" the power grid into a *smart grid* has become a real need. The smart grid is a much more modern electric network that monitors, protects and optimizes the operation of its interconnected elements.

The transition to a smart grid requires the deployment of new power infrastructure, along with different kind of devices, such as electronic sensors and computer systems, throughout the electric network and their interconnection via high-speed communications networks using standardized protocols.



With this idea in mind, it's necessary to establish some goals which represent the main drivers towards the future tendencies, such as:

- reduction of operational and investment costs

- increasing reliability and quality of supply
- increasing energy efficiency
- integration of renewable energy

3.1 Network management and control monitoring

Its aims are:

- real-time remote availability of the information on the status of the network,
- real-time remote availability of the values of the electrical parameters (current and/or voltage)
- remote network reconfiguration capability.

Smart switches and smart breakers can be used in combination with sensors, in order to monitor electrical parameters and perform network reconfiguration, which will allow for automatic load transfer, with the supervision of the system operator. This procedure can be implemented under the following situations:

- After a fault is detected and isolated (further discussed in section 3.2);
- In case of overload or violation of the technical voltage limits;
- In a programmed action (for example, a programmed interruption for maintenance);
- When ordered by the system operator.

To enable this functionality, the grid must be structured as a closed ring, explored in a radial way and have remote control devices along some of its lines.

An algorithm can be used to define the final solution for the topology, as well as the sequence of maneuvers that should be executed. The main goal is to minimize the undistributed energy and the duration of the interruption in the affected section of the grid. The number of possible topologies will be dependent on the number of remote control devices involved. The information from smart meters and sensors can be used to describe the state of the grid before the fault and evaluate the necessity of controlling storage systems or the flexibility of consumers to take part in the reconfiguration of the grid. For example, energy storage systems, if controlled by the DSO, can be used to reduce the load in the Secondary Substation during reconfiguration actions, in order to avoid MV/LV transformer overload. On the other hand, the flexibility of distributed resources from LV clients can be managed so that the LV load is reduced.

Furthermore, sensors can also be used to monitor technical losses, based, for example, on unbalanced phases, harmonics, power factor and temperature. Non-technical losses can also be monitored based on consumption patterns.

Moreover, sensors can help monitor the condition of the grid equipment, particularly of transformers and cables. By analyzing phase unbalances, harmonics and temperature, the lifetime of the equipment might be extended. The information collected by sensors may also be used for predictive maintenance

3.1.1 MV components

Switchgears:

- a switch, a switch-disconnector or a circuit-breaker installed in a RMU, an individual panel or a pole-mounted switchgear are appropriate devices.

Auxiliaries:

- auxiliary contacts for the network management. These contacts give information about the position of the switchgear apparatus;
- auxiliary contacts related to alarms such as temperature of the switchgear, gas pressure or the removal of panels or doors related to the accessibility inside the switchgear;
- motors to open and close the switch or switch-disconnectors or circuit-breaker.

Additional auxiliaries:

- sensors to measure the apparatus parameters, operation times, operation speed, motor consumption, number of operations;
- voltage presence or absence contacts taken directly from the VPIS or VDS devices;
- sensors to monitor the partial discharges level.

3.1.2 LV components

- Circuit-breakers with electronic protection unit, with measurements and communication;
- signalling from circuit-breakers/protection in case of fault
- motorised circuit-breakers or switches.

3.1.3 MV/LV transformers

Transformers will need to operate in a more dynamic network and to be inherently more flexible due to the penetration of new technologies such as PV, electric vehicles and heat pumps, with the subsequent effect on voltage fluctuations. Moreover, bidirectional power will be a standard design requirement for distribution transformers.

Voltage regulation and control is becoming more important as distributed generation affects distribution networks. The deployment of smart regulated distribution transformers has already been commissioned by utilities on live networks.

Traditionally, MV/LV transformers are regulated using integrated off load tap changers (DETC). The smart regulated MV/LV transformer will improve the voltage stability on load.

Different technologies including voltage booster or tap changers may be used by transformers manufacturers to provide on load regulation for the LV output, with settings of around ±5% of the rated voltage.

The regulation consists in a local algorithm and a decentralized optimization in order to:

- allow flexibility to connect DG at the low voltage side: the voltage is dropped locally when the photovoltaic in feed is high; to avoid exceeding local voltage limits on the LV feeders, some end-point measurements or smart meters may be connected to the smart transformer;
- provide a way to stabilizing the LV voltage for MV voltage fluctuation due to the wind power plants connected on the same MV feeders, transformer will adjust the voltage locally within the rated voltage parameters;
- provide a way to shave the peak hours by remotely sending from the control centre a voltage setting in order to temporary lower the voltage;
- improve efficiency to reduce losses of the distribution network during periods of heavy consumption combined with low distributed production. The transformer control centre increases temporary the voltage setting point of the transformer;
- have the possibility of using energy storage systems in the Secondary Substation to help regulate voltage level.

Suppliers keep on studying and developing experiments aimed at integrating power electronic components in distribution transformers. The goal is to develop a solid-state transformer with automatic voltage variation and reactive compensation design functionality.

Developing state-of-the-art materials is key to improving the performance of new transformers, and material product alternatives for core material including Fe-Si. In addition, an alloy laser scribe has been developed to cut material to 0.2 mm or even less, which will reduce losses and reduce the dimension of transformers.

Although loss levels are very low, transformers designed with amorphous magnetic materials have not penetrated the European market. The inability to withstand short circuit faults and the higher sound levels compared with conventional transformers have not encouraged their use. In addition to this, the use and quality of grain oriented magnetic steels has progressed during the last years, reducing the performance gap compared to amorphous materials.

3.1.4 Remote control systems and devices

RTUs are expanding their functionality from a pure collection of switch status and measured values to processing those data and creating additional benefits by providing profile information about the utilization of the distribution network. The RTU design and communication technology, which is not any longer a bottleneck, allows sending related data and back-office information to the Control Centre with different services to both stakeholders.

The use of sensors in the grid requires a communication network capable of serving the necessary systems for condition monitoring of equipment and exploration of the grid. These systems have to be able to locally process big volumes of data, as well as remotely compare patterns and results from different types of equipment, in order to calculate the probability of occurrence of a defect and offer advice for improvement actions. The bandwidth and the transmission rate will vary depending on the data the sensor will need to transmit. Novel sensors are appearing on the market including wireless self-powered sensors, which may communicate through the most common standards for IoT (WiFi, Bluetooth Low Energy, ZigBee, Z-Wave, 6LoWPAN, LoRaWAN, SigFox, NB-IoT, LoRa, among others). There are also sensors available on the market, which use wired connections and communicate, for example, via Ethernet to a local router. Some sensors may also be able to communicate through secure web services.

The increase of grid automation will raise concerns about cybersecurity, which need to be addressed by each DSO

3.2 Fault management and network self-healing

Aims at minimizing the number and duration of interruptions, at getting remotely the information on the status of the network and the information about fault passage indicators (detection and location).

A critical first step towards the evolution of the distribution system was the substitution, typically in a secondary substation placed in a central position of the MV line, of the switch with a vacuum circuit-breaker capable to interrupt short-circuit current. This substitution has enabled new automation strategies just with the disconnection of the strictly necessary utilities, i.e. only those directly affected by the fault and with the minimal breakdown for other customers. The secondary substation with the circuit-breaker becomes the centre of the protection device that performs the functions of chronometric selectivity, voltage regulation, and measures detection. In any case, this functionality reduces the breakdown but it doesn't zero it.

The most important innovative feature linked to network automation is constituted by the logic selectivity along the line. This function has the purpose to isolate the section of the grid affected by a fault, without the trip of circuit-breaker in primary substation, even in the case of high-current faults.

To enable this functionality we need to replace switches with circuit-breakers equipped with protection, measure and communication innovative systems in some of the secondary substations along the MV line.

The function of logic selectivity in the case of passive line, in the presence of multi-phase fault, operates in the following way: the protection system upstream of the fault detects its presence and sends an inhibitor message to all upstream protection systems and to the protection system in primary substation. The only protection system that does not receive the inhibition message in a determined time (below 50 ms) commands the opening of the circuit-breaker associated, without problems on the "health" of the upstream section (the users upstream of the fault do not have any interruption).

In this way the isolation of the faulted section occurs with a single operation, without trip of the circuit-breaker in primary substation (unless the fault is in the primary section), without lengthening clearance of the short circuit, with a strong advantage for the quality of service.

The critical aspect of this function is related to the reliability and speed of the communication system: all block signals must be sent using the communication network very quickly via GOOSE messages to be realized in the IEC 61850 protocol.

A further evolution of this function is the implementation of automatic backwards supply, to ensure the restoration of supply to the greatest number of possible users in a short time (less than 1 second).
In this case, downstream of the opened switch along the line, the system that has intervened (which has not received lock signal) will carry out a fast reclosing cycle, with a first reclosing after a waiting time of 300-400 ms, followed, in case of permanent fault, by subsequent reclosing to operate after a programmable time. At this point two situations may occur:

1. If the fault is temporary, fast reclosing operates successfully, the fault is extinguished and all users in temporary fault section will only be subject to a breakdown. Furthermore, the protection system via remote tripping reconnects all the generation downstream previously disconnected.
2. If the fault is permanent, downstream of the fast reclosing, during the neutralization time, the fault continues to persist and will operate through more complex logics which are capable to isolate the fault section in less than one second.

The implementation of this advanced automation is linked to the development of an evolved remote control system; it is in fact necessary to remotely control and monitor in real time all the elements of the grid in order to identify and evaluate possible alternative configurations minimizing the number of users subject to interruption, enabling then the appropriate backwards supply.

The selectivity functions just described, realized through an innovative communication system, may also be translated in meshed networks.
The ability to develop and operate meshed networks presents considerable advantages, first, to have available alternative power supply, not only to establish a reserve, but also to improve the load distribution among different power sources.
Through this methodology, it is possible to ensure the complete fault selectivity, with the opening of the only switches in fault section, thus making possible the exercise of the distribution grids in complete safety.

The logic of fault selection must be developed including also the DG; in presence of a fault, the protections must be able to send a message to generators to ensure their disconnection in a short time only in case of fault upstream of the line at which the sensor is connected.
By exchanging GOOSE signal between grid protection and user protection it will be possible to identify any MV and LV generators in fault section and proceed to the disconnection avoiding “islanding” problems.

3.2.1 MV components

Switchgears:

- a switch, a switch-disconnector or a circuit-breaker installed in a RMU, an individual panel or a pole-mounted switchgear are appropriate devices in order to ensure the opening of the line in case of fault realizing the logic selectivity. They will be equipped with sensors to detect any fault condition.

Sensors:

- phase-current sensors are the basic sensors to fulfill this functionality;
- homopolar current sensors for isolated neutral systems, especially when high sensitivity is required;
- voltage sensors for directional fault identification and when an isolated neutral system needs to be protected.
- Directional fault detector and measurements: fault detection device with protection function, measurements of electrical network parameters, control and automation. This device is able to detect multi-phases faults and earthing faults, detect the absence of voltage on the line, measure the voltage and the active and passive power on the MV line, order the opening or closing of the circuit-breaker in case of fault. It also interacts with the generators present on MV line in order to coordinate the voltage adjustment;

Auxiliaries:

- auxiliary contacts for the network management. These contacts give information about the position of the switchgear apparatus;
- auxiliary contacts related to alarms such as temperature of the switchgear, gas pressure or the removal of panels or doors related to the accessibility inside the switchgear;
- motors to open and close the switch or switch-disconnectors.
- voltage presence or absence contacts taken directly from the VPIS or VDS devices (when no voltage sensors are needed).
- communication router, modem/radio/antennas or fiber optic: in order to manage the messages and information to and from the secondary substation to and from primary substation router.

3.2.2 LV components

- circuit-breakers with electronic protection unit, with measurements and communication;
- signalling from circuit-breakers/protection in case of fault;
- motorized circuit-breakers or switches;
- remote control of circuit-breakers;
- advanced protections;
- utilization of fault data for fault location;

- automatic reclosing.

3.2.3 Remote control systems and devices

Despite of only forwarding fault information, RTUs can incorporate the functionality of fault detection and localisation as an internal RTU function. An advantage is that an easier deployment is achieved, especially in brown field, because only one unit has to be connected and supplied. With precise information about the faulty grid section, fault isolation and service restoration time will be reduced.
RTUs can support a self-healing application in different way depending on the grid layout and the chosen solution. Having a communication between all secondary substation, RTUs are able to identify the faulty section and isolate it, as well as restore power supply to the healthy part of the grid. A self-healing algorithm is running on all RTUs to handle faults in a short period of time.
Nearly the same result can be achieved by sending fault information to a superior system, which is isolating and restoring power based on a generic algorithm. In this case, the RTU is only sending fault information and receiving commands to be carried out. Using a control centre for the outage management, the RTU task is as well to send information and carry out commands sent by the control centre.
For more information concerning sensor communication, see section 3.1.4.

3.3 Load and energy management

It aims to get remotely the information about electrical parameters (voltage, current, accuracy, active and reactive energy calculations) for load reconfiguration, power factor management or voltage regulation.
These features also enable Distributed Energy Resources (DER) and Renewable Energy Resources (RER) management. To this second aim, we will also have to assure the control of islanding and the subsequent reconnection to main grid.
The integration of storage systems in the distribution grid can also support the operation of the grid and increase efficiency and quality of service. The installation of a storage system in the Secondary Substation may have the following aims:

- Reduce energy losses on the MV grid;
- Manage power flow in the Secondary Substation, namely due to the large-scale integration of renewable production and electrical vehicles;
- Avoid the violation of technical voltage limits and the overload on the grid equipment, particularly in MV lines and in the MV/LV transformer;
- Participate in the system recovery after fault isolation on both MV and LV grids.

Concerning the operation of the MV grid, the control of the storage system can be done through grid analysis applications. In that case, the storage systems should be capable of receiving active and reactive power set points, from centralized management systems.

On the other hand, concerning the operation of the LV grid and the Secondary Substation, the control of the storage system may be based on the information from the sensors installed on the Secondary Substation and on the LV grid.
The charging of the storage system can be adjusted based on the load of the Secondary Substation, in order to minimize the impact on LV grid operation and guarantee sufficient capacity to support its operation. For example, the storage system should be powered by the excess electricity generation, avoiding the inversion of power in the Secondary Substation and discharge the energy stored during hours with a higher consumption, namely to face the exceeding load resulting from electrical vehicles. On the other hand, there should be enough reserved capacity to avoid or correct overload on the Secondary Substation. The storage system may also be used for reactive power compensation. The aim of this functionality is to avoid overload of the MV/LV transformer, allowing for its decongestion and minimizing losses.

3.3.1 MV components

Switchgears:

- a switch or a switch-disconnector installed in a RMU, an individual panel or a pole-mounted switchgear are appropriate devices.

Sensors:

- phase-current sensors are the basic sensors to fulfill this functionality; additionally, voltage sensors are needed if energy management is considered.

Auxiliaries:

- auxiliary contacts for the network management. These contacts give information about the position of the switchgear apparatus;
- auxiliary contacts related to alarms such as temperature of the switchgear, gas pressure or the removal of panels or doors related to the accessibility inside the switchgear;
- motors to open and close the switch or switch-disconnectors.

3.3.2 LV components

- circuit-breakers or other measurement device with communication;
- current, voltage, active/reactive power;
- power quality monitoring (harmonics, interruptions, voltage variations);
- voltage profile monitoring;
- signaling for Demand Response application;
- utilization of smart meter data for optimization;
- advanced protection;

- detection of unwanted islanding;
- Fault Ride-Through.

3.3.3 Remote control systems and devices

RTUs are not the only sources for the current grid situation, but can take an active role as well. Like the controllers of distribution transformer tap-changer, they can regulate the voltage level. RTUs can also balance the load and production in their grid section or interact with building automation and electric vehicles charging systems.

RTU gets information directly from the power production and it is the interface for actualizing the power production demand according to the grid situation. Distributed generation requires distributed storages and they can be controlled and monitored via RTU.

Processor power is, nowadays, not any longer a limitation and allows new perspectives on electronic components in small application as secondary substations. If RTU and protection functionalities are combined in one device, the efficiency of the applications will increase. It will give more flexibility in the use and reduce maintenance effort and the need of training for the engineers as well. One IED (Intelligent Electronic Device) for a smart substation and its flexibility to adapt to the needs will give benefit to all stakeholders involved.