DISTRIBUTION NETWORKS:
protection schemes
MV neutral point
MV network automation
voltage regulation

TOPIC 1 - Electric Power Systems

Requirements to the Distribution System

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- A primary objective of all distribution networks is:
  - to maintain a very high level of continuity of service, and
  - when intolerable conditions occur, to minimize the outage times.
- Interruptions, voltage dips and overvoltages will occur because it is impossible to avoid the consequences of:
  - natural events (lightning, wind, ice, fire, falling trees, physical contact of animals, and so on);
  - physical accidents (faults resulting from vehicles hitting poles or contacting line equipment, digging into underground cables, and so on);
  - equipment failure;
  - misoperating owing to human error.
- Considerable effort (i.e., protective relaying) is made to minimize damage possibilities, but the elimination of such problems is not yet achievable.
- Faults may always happen

Fault types

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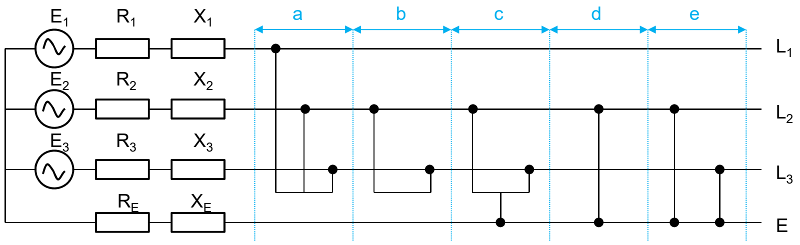
- Fault occurrence can be quite variable, depending on the type of power system (e.g., overhead vs underground lines) and the weather conditions.
- The percentages of occurrence are:
  a. three phase 3 – 2%
  b. phase to phase 10 – 8%
  c. phase to phase to ground 17 – 10%
  d. single phase to ground 70 – 80%
  e. cross-country faults



Fault current formula

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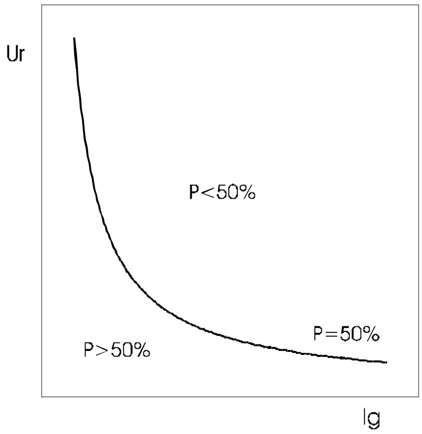
- The initial values of ac fault currents can be calculated as follows.

Kind of fault	Fault current formula
Three-phase fault	$I''_{F3ph} = \dfrac{1{,}1 \cdot U_N}{\sqrt{3} \cdot Z_1}$
Phase-to-phase fault	$I''_{F2ph} = \dfrac{1{,}1 \cdot U_N}{Z_1 + Z_2}$
Phase-to-phase to ground	$I''_{F2phE} = \dfrac{\sqrt{3} \cdot (1{,}1 \cdot U_N)}{Z_1 + Z_0 + Z_0 \cdot \left(\frac{Z_1}{Z_2}\right)}$
Single phase to ground	$I''_{F1phE} = \dfrac{\sqrt{3} \cdot (1{,}1 \cdot U_N)}{Z_1 + Z_2 + Z_0}$

Fault extinction

- In many instances, the flashover caused by such events (transient faults) does not result in permanent damage if the circuit is interrupted quickly.
- Equi-probability curve for extinction as a function of arc current (I_g) and recovery voltage (U_r):
  - the higher the arc current the lower the probability of self-extinction;
  - the higher the recovery voltage (U_r), the lower the probability of self-extinction.
- The transient nature of faults can be exploited (auto-reclosure)



Abnormal operating conditions

- Apart from the relatively frequent faults and disturbances which afflict electrical power system and their components, there are also other more infrequent phenomena (only concerning particular items of plant).
- The most important of those are:
  - overload: electrical plant can be thermally overloaded either by exceeding the max permissible load currents – usually over a prolonged period – and/or by a reduced cooling effectiveness;
  - real power deficit;
  - power swings in power grids;
  - underexcitation of synchronous generators;
  - overfluxing of power transformers;
  - asynchronous operation of synchronous motors;
  - mechanical defects.

Detecting faults and abnormal operating conditions (I)

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- The principal criteria for detecting faults and abnormal operating conditions on electrical power systems are:

	Kind of fault	Variable used for detection
1	Phase faults in general	Phase current I Current difference ΔI Difference of current phase angle Δφ Phase voltage U Power direction P → Impedance Z
2	Asymmetric faults (ground, phase-to-phase, phase-to-phase to ground)	As above plus: Negative and zero sequence components of current (I_2, I_0), voltage (U_2, U_0) and the power direction (P_2, P_0) →
3	Ground faults	Zero-sequence component of: Current I_0 Voltage U_0 Power direction P_0 →

Detecting faults and abnormal operating conditions (II)

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- The principal criteria for detecting faults and abnormal operating conditions on electrical power systems are:

	Kind of fault	Variable used for detection
4	Overload	Phase current I Temperature θ
5	Asymmetric configuration Asymmetric load Interrupted conductor	Negative-sequence component of current I_2
6	Real power deficit	Frequency f Rate-of-change of frequency df/dt
7	Real power excess	Frequency f

MV NEUTRAL POINT

TOPIC 1 - Electric Power Systems

System grounding principles

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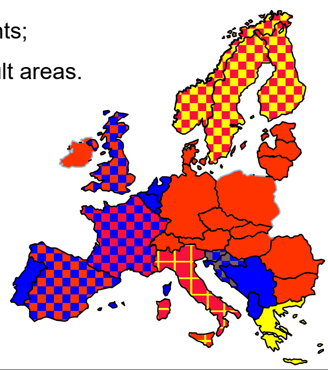
- Power system grounding is very important, particularly because the large majority of faults involve grounding.
  - It has a strong effect on the protection of all the components of the grid
- The principal purposes of grounding are to:
  - minimize potential transient overvoltages;
  - comply with codes for personnel safety requirements;
  - assist in the rapid detection and isolation of the fault areas.
- MV neutral point can be:
  - isolated → yellow;
  - solid (low impedance) earthing → blue;
  - resonant earthing (Petersen coil) → red;
  - high resistive earthing.



MV neutral point: isolated

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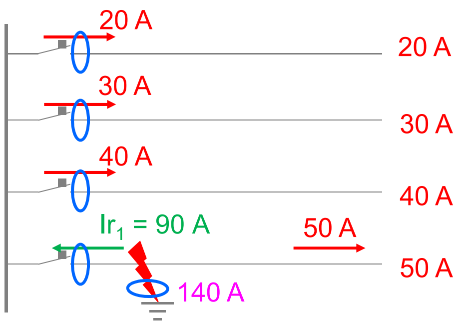
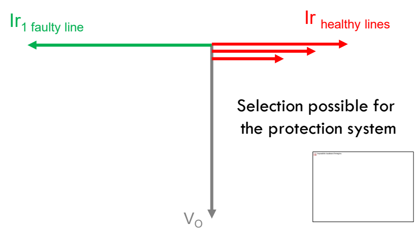
- Till recent past (2000) Italian DSOs operated MV networks with the neutral point isolated
- Advantages
  - Very simple to operate
  - Low costs
  - Low level for the earth-fault current
- Disadvantages
  - Stress for devices due to overvoltages
  - Intermittent arc





MV neutral point: Italian compensated solution

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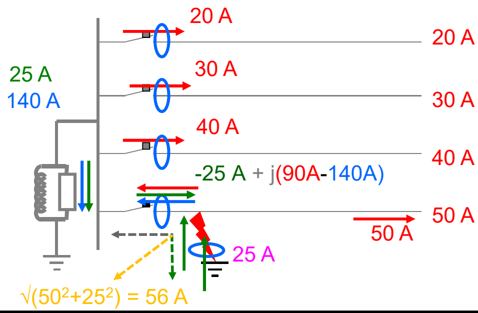
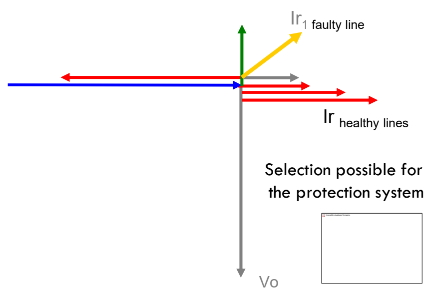
- New Italian solution is MV neutral connection to earth by means of an impedance (Petersen coil + resistor in parallel)
- Advantages
  - All advantages provided by compensation (Petersen coil)
  - Possibility to detect earth fault quickly and automatically by relays and FPI
- Disadvantages
  - Additional costs in comparison with “simple” Petersen coil solution





MV NETWORK PROTECTION

TOPIC 1 - Electric Power Systems

Protection systems

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- Protection systems: are composed of relays that monitor system conditions (voltage and current) and are programmed to send "trip" signals to circuit breakers if the thresholds are exceeded (due to fault) to remove the faulted equipment from the energized power system.
- Protective relays are manufactured as:
  - overcurrent relays (to select short circuit and overload currents),
  - directional relays (phase to earth faults),
  - distance relays (for HV lines), and
  - differential relays (for transformers).
- Protective strategy is based on:
  - time graded selectivity;
  - current selectivity.

Basic objectives of protection systems

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- The fundamental objective of protection systems is to provide isolation of a faulty area in the system quickly, so that…
  … as much as possible of the rest of the grid is left to continue service.

- The five basic characteristics of system protection are:
  - speed of operation → min fault duration and equipment damage;
  - selectivity → max continuity of services with minimum system disconnection;
  - reliability → assurance that the protection will perform correctly;
  - simplicity → minimum protective equipment and associated circuitry to achieve the protection objectives;
  - economics → maximum protection at minimal total cost.

MV lines protection

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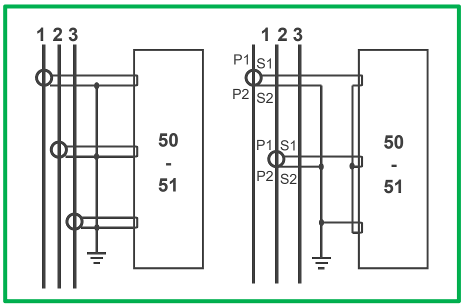
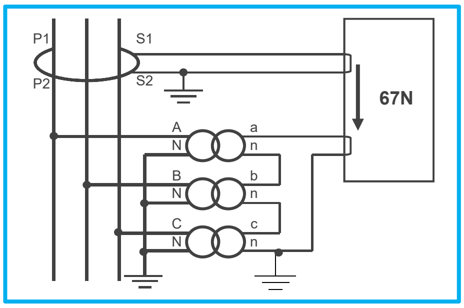
- The kind of protection employed and the amount of protection installed for protecting cables and overhead lines depend mainly on the importance of the particular feeder and the type of power system grounding.
- The protection techniques used to detect faults on MV lines are:
  - overcurrent (delayed and instantaneous);
  - directional.





Overcurrent relay (50-51)

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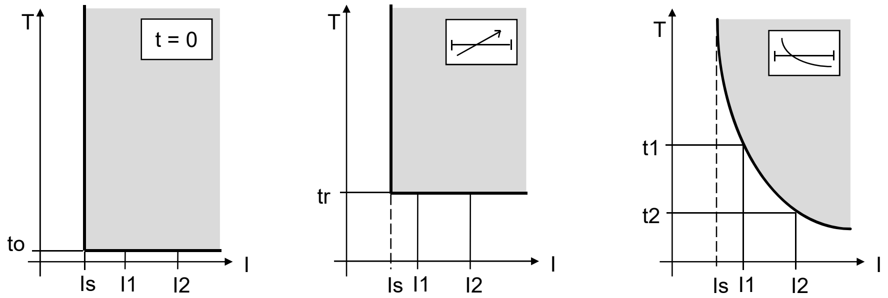
- Overcurrent protection devices continuously monitor the current being conducted by the protected unit and issue a tripping command to the CB when the current exceeds the setting to isolate the respective item of plant from the power system.



Instantaneous
t_0 = base time 5÷50 ms

Indipendent time
t_r = time delay

Inverse time

$I_2 > I_1$; $t_2 = t_1 = 0\ (t_o)$

$I_2 > I_1$; $t_2 = t_1 = t_r$

$I_2 > I_1$; $t_2 < t_1$

Instantaneous overcurrent protection (50)

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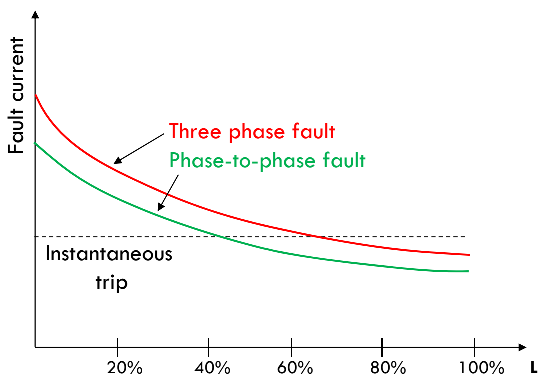
- The instantaneous overcurrent protection operate without intentional delay.
- The reach of instantaneous overcurrent protection devices depends on the pick-up current setting and the magnitude of the fault current.
- The pick-up current is chosen such that it is higher than the maximum load current I_{Lmax} of the protected unit and lower than the minimum initial ac fault current at the relay location for a fault at the end of the main zone of protection.



Time delayed overcurrent protection (51)

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- The current setting value must be selected in order to permit the detection of the lowest short circuit current without having any unwanted tripping or starting of the function under normal load conditions
- The decisive factors for the setting of inverse time characteristic are the allowable time for disconnection of fault (t>, trip time) at minimum fault current that the function shall operate for together with selectivity at maximum fault current

$$t> \; = \; K \cdot \frac{\beta}{\left[\frac{I}{I>}\right]^{\alpha} - 1}$$

k set by the user to select the trip curve
α, β depending on the type of protection selectable
I fault current
I> trip threshold selectable by the user

- The different inverse time characteristics are (α and β can take on the following values according to the curve selected):
  - Normal Inverse time-delay curve (NI) α = 0.02 β = 0.14
  - Very Inverse time-delay curve (VI) α = 1 β = 13.5
  - Extremely Inverse time-delay curve (EI) α = 2 β = 80

Directional ground fault relay (67N)

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- Directional ground fault schemes are used in:
  - ungrounded systems;
  - systems with Petersen coil (+ resistor in ||).
- The real power component of the neutral current measured by the relay is used to locate ground faults in systems with Petersen coil.
  - If the neutral voltage U_0 is chosen as the reference voltage to determine the phase angle of the current; the power direction is given by phase-angle φ_0 between U_0 and I_0.
- To ensure reliable location of ground faults, the real component is artificially increased (up to 50 A) by a grounding resistor in parallel to the Petersen coil.

MV NETWORK AUTOMATION

TOPIC 1 - Electric Power Systems

What is ‘Distribution Automation’?

- The objective of (Advanced) Distribution Automation function is to enhance
  - reliability of the power system (distribution grid);
  - power quality;
  - power system efficiency;

  by automating the following three processes of distribution operation control:
  - data preparation in near-real-time;
  - optimal decision-making;
  - the control of distribution grid operations

    → also in coordination with transmission and generation systems operations.
- MV network automation is the result of a long evolution process…

  … which is still in progress for further improvements.

Auto reclosure (79)

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- Statistically, the majority of faults are of a transient nature and disappear if the supply of energy to the fault location is briefly interrupted.
- The purpose of auto-reclosure is to reenergize a line as quickly as possible after a fault caused it to be tripped and thereby reestablish the normal state of the power system and the supply to isolated areas.
- It is assumed that this will normally be successful and only in seldom cases it will be necessary for the protection to trip again, because the fault persists.
  - In the former case, the fault disappears during the dead time (arc extinguished and the voltage withstand re-established), while in the latter case, the CB closes onto an existing fault and trips again.
  - The two trips in quick succession are interpreted by the auto-reclosure as a permanent fault and no further reclosure is performed, i.e. the CB is "locked out" (→ in MV systems, two or more shot schemes are possible)

Auto reclosure and coordination with line protection functions

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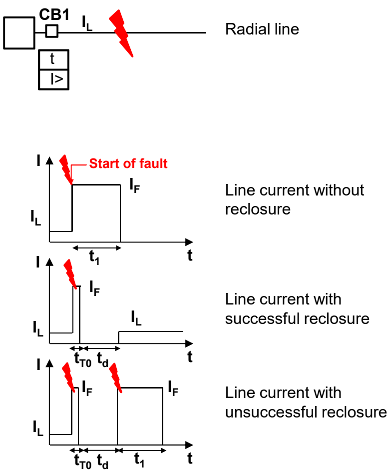
- In a overcurrent protection scheme with auto-reclosure, the CB is tripped undelayed upon the detection of the fault.
- The CB is closed again at the end of the dead time td.
- If the reclosure attempt is successful, the normal load current I_L flows after reclosure.
- If the fault still persists after reclosure, the CB is tripped again by the overcurrent relay, but this time after the set grading time t1, i.e. the instantaneous trip function tT0 is blocked
- In Italy, three-shot schemes are employed:
  - O-0,4-CO-30-CO-70-CO-(70-CO)

    < 180 s → short interruption



t_1= grading time set on RI1
t_0= time without intentional delay
t_{TO}= fault tripping time without intentional delay
t_d= reclosure dead time

1. Fault clearing and manual fault localization

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- During the first step (no QoS incentive regulation):
  - the fault clearing was performed only by the protection and the CB at the beginning of the MV feeder;
  - the fault localization is randomly performed by personnel on field based on the rule to recursively divide the network in two parts, one healthy and the other one faulted, until to find the fault.
- Fault localization time was very long → tens of minutes or more.

1. Fault clearing and manual fault localization

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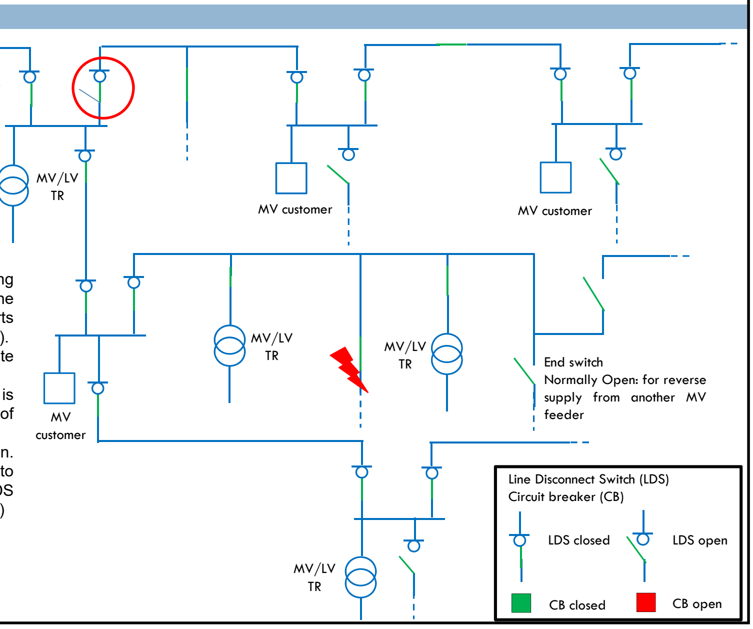
MV feeder relay + CB

The Auto Reclosure completes its cycles with a failure
→ CB remains open

All the MV feeder is without supply

Fault localization starts, performed by human personnel in field

1. The first opening operation divides the feeder in two main parts (tens of minutes or more).
2. CB is closed from remote from Control room
3. CB opens again. Fault is on the other half branch of the feeder.
4. The LDS is closed again. Personnel moves to another LDS (tens of minutes or more)



1. Fault clearing and manual fault localization

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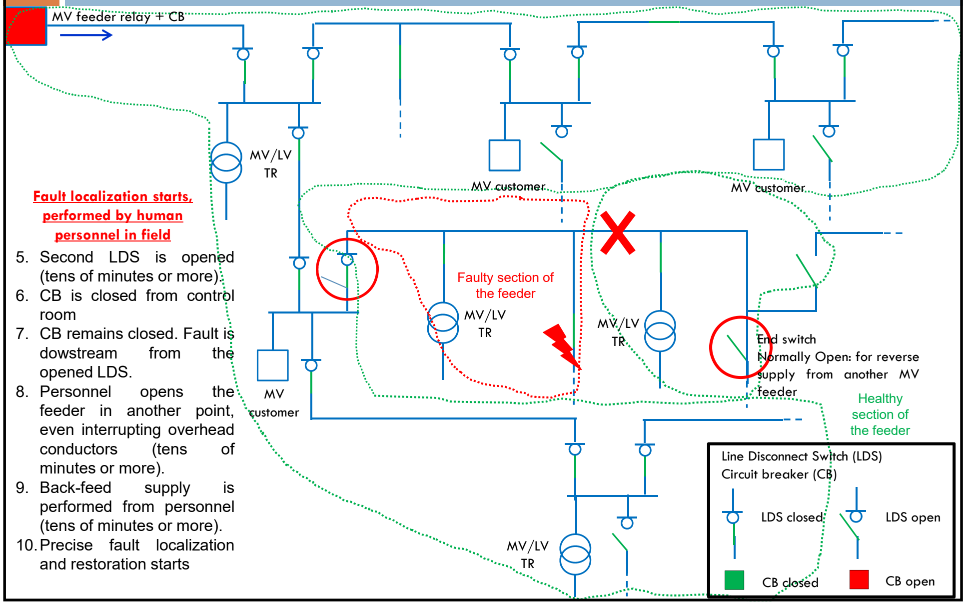

Fault localization starts, performed by human personnel in field

5. Second LDS is opened (tens of minutes or more).
6. CB is closed from control room
7. CB remains closed. Fault is dowstream from the opened LDS.
8. Personnel opens the feeder in another point, even interrupting overhead conductors (tens of minutes or more).
9. Back-feed supply is performed from personnel (tens of minutes or more).
10. Precise fault localization and restoration starts

2. Fault clearing and remote control/manual fault localization

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- After the introduction of the QoS incentive regulation (1st regulatory period), it became mandatory to reduce SAIDI index for LV customers.
- The first intervention was the introduction of remote controlled LDS, able:
  - to perform most part of switching operations from remote, in some ten seconds instead of minutes or hours
  - to leave only the final stage of fault localization to personnel in field.
- The fault localization occurs as in the previous case but with faster time

1. Fault clearing and manual fault localization

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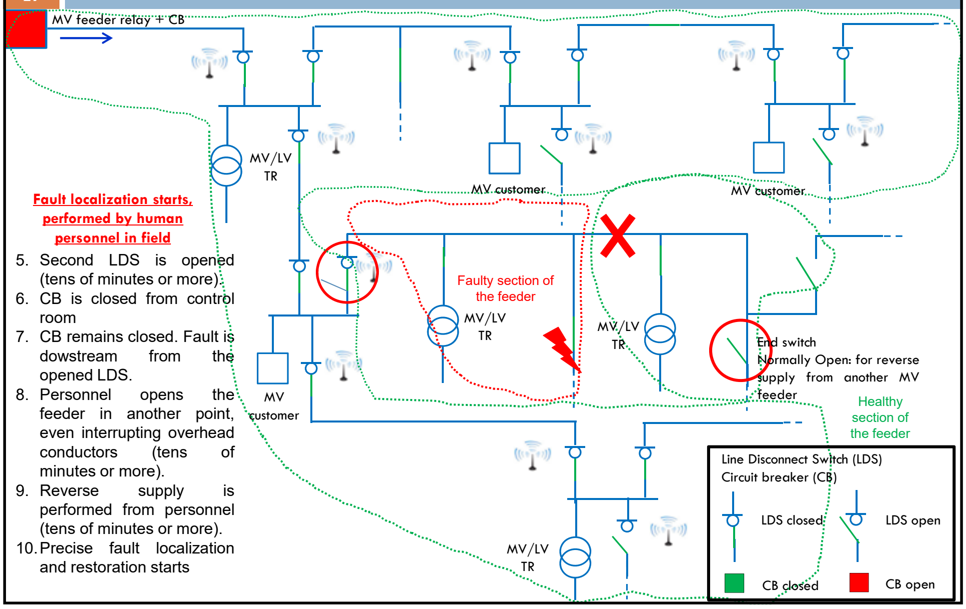

Fault localization starts, performed by human personnel in field

5. Second LDS is opened (tens of minutes or more).
6. CB is closed from control room
7. CB remains closed. Fault is dowstream from the opened LDS.
8. Personnel opens the feeder in another point, even interrupting overhead conductors (tens of minutes or more).
9. Reverse supply is performed from personnel (tens of minutes or more).
10. Precise fault localization and restoration starts

3. Fault clearing and fault localization fully automated

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- To reduce further SAIDI and SAIFI indices (3rd regulation period), the remote control system was further improved (MV automation system).
- The fault clearing and the fault localization are based on automatons (housed in RTUs in SS) able to detect the direction of the fault (upstream/downstream):
  - in case of overcurrents, from overcurrent FPI;
  - in case of earth faults, with directional FPI.
- Finally, the fault restoration is manually performed (by personnel).

Secondary Substation RTU

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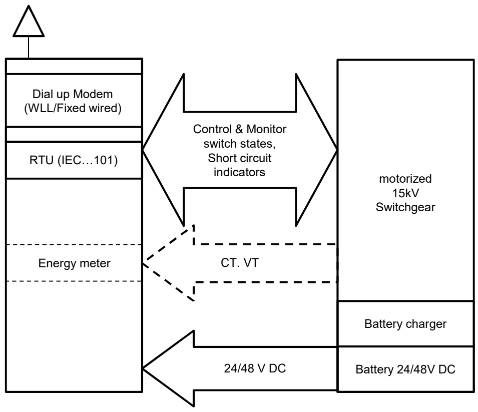
- SS use RTU and switched telephone communication facilities (fixed wired or mobile communication) to transfer data on demand.
- The demand for data exchange can be initiated by the control centre or by the relevant PS.
  - The control centre needs to control switchgears remotely, to ask for data update or just to test the connection.
  - The SS need to call in the control centre if there is some urgent data to transfer (a fault indication on a 15 kV incoming/ outgoing line).
- In Italy, the key point is the adoption of the existent GSM network.



Secondary Substation FPI; Line Disconnect Switches; end-switch

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- Fault Passage Indicator (FPI) is able to discriminate short circuits and single-phase earth faults as follows:
  - overcurrent (cross country) fault detection (non directional);
  - directional phase to earth fault detection:
    - varmetric for insulated neutral networks;
    - wattmetric for compensated ones.
- Line disconnect switches (LDS): are used to isolate sections of line or to transfer load from one circuit to another.
  - Normally, power lines are first deenergized by CB (high current interrupting ratings), followed by the opening of the LDS for isolation.
  - LDS are operated with manual or motorized operation
- The end-switch is normally open.
  - The network reconfiguration is obtained by managing the open/close status of the end-switch.

FPI position on three hierarchical levels: an example

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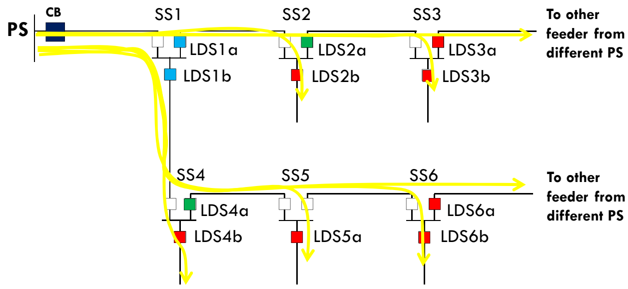
There are (maximum) 3 LDS in series for each subline:

- SubLine 1:
  - LDS3a (level 1)
  - LDS2a (level 2)
  - LDS1a (level 3)
- SubLine 2:
  - LDS2b (level 1)
  - --------- (level 2)
  - LDS1a (level 3)
- SubLine 3:
  - LDS3b (level 1)
  - LDS2a (level 2)
  - LDS1a (level 3)
- SubLine 4:
  - LDS4b (level 1)
  - --------- (level 2)
  - LDS1b (level 3)



- SubLine 5:
  - LSD5a (level 1)
  - LSD4a (level 2)
  - LSD1b (level 3)
- SubLine 6:
  - LSD6b (level 1)
  - LSD4a (level 2)
  - LSD1b (level 3)
- SubLine 7:
  - LSD6a (level 1)
  - LSD4a (level 2)
  - LSD1b (level 3)

6 SS, 7 SubLines, 11 (LDS+FPI)

MV network automation

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- Automation on MV network is based on a group of automatons resident into the RTU, operating fault detection and selection through actions and delays triggered locally by two signals:
  - presence/absence of voltage an the line input;
  - intervention of FPI.
- The experimentation of “MV automation system” started with the activation of two techniques called respectively “FNC” and “FRG”.
  - ***FNC technique*** consists of automatic selection of single phase faulty branch by means of switches and fault detectors along the MV line (without opening the circuit breaker at the line departure)
  - ***FRG technique*** allows the automatic selection of faulty branch (multi-phase faults) by reclosing cycle of MV line breaker and fault detectors along the line

FNC

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- FNC is an automation procedure implemented for MV networks equipped with Petersen coil in order to select ground faults.
- A ground fault is isolated without CB tripping → faults are cleared directly by LDS based on automaton (FPI) information.
  - LDS along the feeder are coordinated with time selectivity.
- The maximum number of LDS in series for each subline is 3 (this choice is based on the maximum allowable intentional delay for MV feeder protection = 20 s).
- If the ground fault becomes a short circuit, the procedure is blocked by the automatons and the CB trips (fault clearing).
- Of course, a fault in the first section (between the PS and the first automated LDS) is cleared by the tripping of the CB after 20 s of delay.
- Time delays for LDS are the following from the end of each line up to the CB
  - LDS level 1: T1=2s
  - LDS level 2: T1=8s
  - LDS level 3: T1=14s
  - MV feeder CB (level 4): Td=20 s

FNC example

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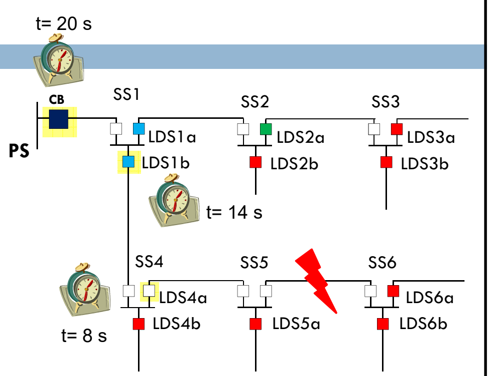
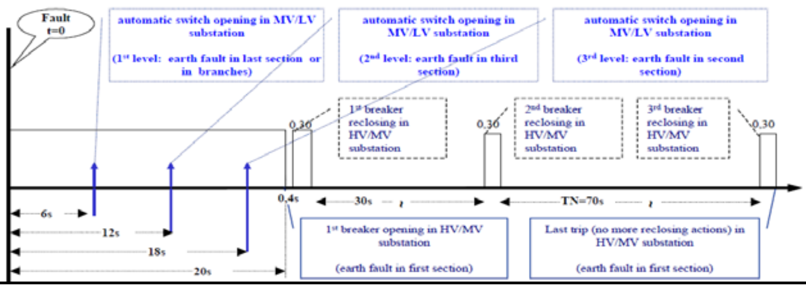
When a fault occurs:

1. LDS4a, LDS1b and CB are activated by FPI information;
2. LDS4a has a time delay equal to 8 s, LDS1b has a time delay equal to 14 s, CB has a time delay equal to 20 s
3. LDS4a trips before the others → the fault is correctly isolated without opening the CB atop the feeder





FRG

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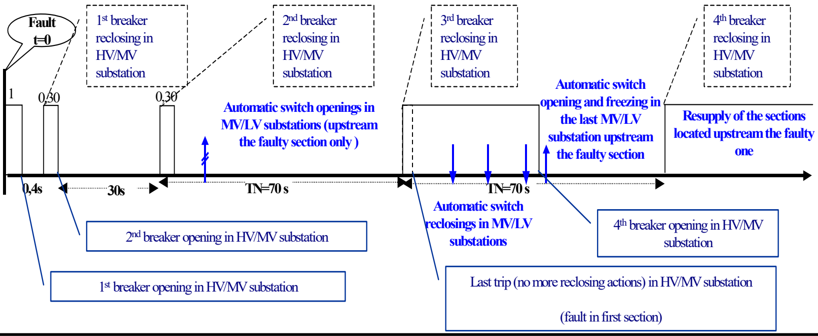
- FRG is adopted to select:
  - short circuits (and ground faults in MV networks with isolated neutral);
  - short circuits for MV networks equipped with Petersen coil.
- FRG allows the automatic selection of faulty branch by means of reclosing cycle of CB and LDS+FPI along the line.
- The automation system allows the automatic selection of the fault and the automatic supply of the healthy branches upstream the faulty one.



FRG example

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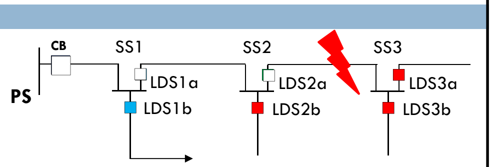
When a permanent fault occurs:

1. LDS1a, LDS2a and CB are activated by FPI information
2. t=0 → CB 1st opening
3. t=0,4 s → CB 1st reclosing (0,4 s)
   → permanent fault
4. t=0,4 s → CB 2st opening (instantaneous)
5. LDS1a & LDS2a open
6. T=30,4 s → CB 2st reclosing (30 s)
7. LDS1a closes after voltage check (2 s of voltage presence)
8. It does not see the fault current and remains closed



9. LDS2a closes after voltage check (2 s of voltage presence)
   → fault localization
10. CB 3rd opening
11. LDS2a remains open and makes a phone call to the control room
12. CB 3rd reclosing (70 s)
13. Resupply of the sections located upstream the faulty one

HP: the tripping time of CB and LDS is neglected as well as the base time of protection system

VOLTAGE REGULATION

TOPIC 1 - Electric Power Systems

Needs for controlling network voltage and available control means

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- The variation of voltage (amplitude) at which consumers are supplied is one of the elements characterizing the QoS.
- Consumers operate at best (in terms of performance and continuity) when they are supplied at the nominal voltage
  - Any deviation deteriorates the performance.
- The voltage variations are reflective of:
  - disturbance (variation of load, and of the system structure)
  - control actions of reactive power sources (synchronous machines, condenser, reactors, compensator…)
- *Voltage control* is the set of actions carried out in order to keep the voltage in all busses within values that do not deviate significantly from nominal ones and that ensure the good operation of loads.

EN 50160: the scope

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- This European Standard defines, describes and specifies the main characteristics of the voltage at a network user's supply terminals in public low, medium and high voltage electricity distribution networks under normal operating conditions.

- This standard describes the limits or values within which the voltage characteristics can be expected to remain over the whole of the public distribution network and does not describe the average situation usually experienced by an individual network user.

Supply voltage variations: requirements

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- Under normal operating conditions, excluding the periods with interruptions, supply voltage* variations should not exceed ± 10% of the nominal voltage Un.

- In cases of electricity supplies in networks not interconnected with transmission systems or for special remote network users, voltage variations should not exceed + 10% / - 15% of Un.

* Supply voltage: r.m.s. value of the voltage at a given time at the supply terminal, measured over a given interval

Voltage control in MV and LV network: available control means

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- Voltage drops: in distribution networks (unlike in transmission grids), R (resistance) is comparable to and sometimes greater than X (series reactance).
- As a result, the voltage drop expression is:

$$\frac{\Delta V}{V_n} \cong \frac{RP + XQ}{V_n{}^2}$$

- The measures needed to limit voltage drops are:
  - adopting OLTC for HV/MV transformer in PS;
  - adopting high nominal voltage V_n;
  - correcting the load power factor by introducing shunt capacitors;
  - increasing the conductor cross-section;
  - making the lines shorter;

HV/MV transformer: regulation by OLTC

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- The means for controlling voltages on distribution networks mainly consist of HV/MV and MV/LV transformers.
- HV/MV transformers are equipped with OLTCs and they can regulate the voltage in the busses downstream of the primary substation, within the variation range of the turn ratio of transformer m
- The OLTC has the function of decreasing (increasing) the turn ratio m when, for whatever reason (e.g. an increase/decrease of load level), the load voltage tends to decrease (increase).
- From the viewpoint of load voltage control, the turn ratio should be maximized m_{max} (1,1 – 1,2 p.u.) near the minimum loads
  - In this way, upon load increase, the regulating action will occur with m → m_{min} (0,8 – 0,9 p.u.)

MV/LV transformer

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- For practical ad economic reason, MV/LV transformers are not provided with OLTC but merely with *no-load-tap-changers*
  - They have a number of taps, MV side, connected to a changer which is adjustable when the transformer is installed.
- The taps are usually 5 and the turn ratio may be adjusted within the range

$$0{,}95 \leq m \leq 1{,}05$$

- Unlike the HV/MV transformers, MV/LV transformers do not automatically regulate voltages
- They only offset the voltage drops in the distribution network

Supply voltage variation: voltage regulation (RECALL)

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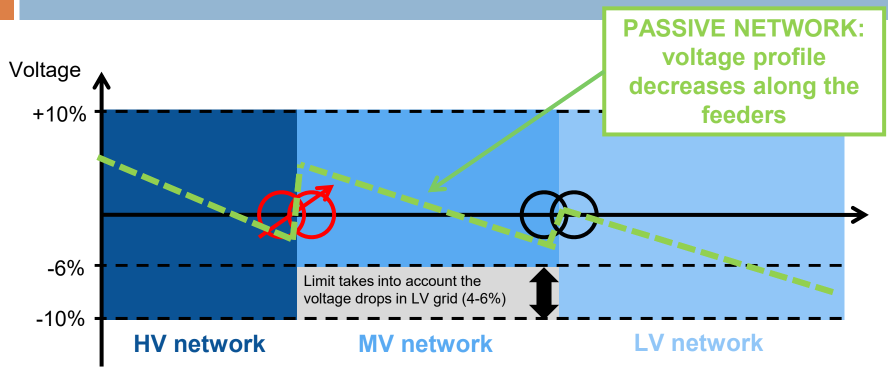

- Voltage profile is controlled by means of a fixed voltage set-point in the MV busbar of the HV/MV transformer, where an OLTC control is installed.
  - The set-point is determined in the condition of maximum load and no generation, as the minimum value which allows to fulfil lower voltage limits in all busses of the MV feeders belonging to the network.