Distributed Intelligence in Critical Infrastructures for Sustainable Power

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Fault detection, analysis and diagnostics in high-DG distribution systems

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Document Description

This document gives an overview of current knowledge on fault diagnosis in public distribution EPS. The expected impacts of the DG on the existing fault protection and localization systems are described. A proposed method for a more efficient and fast fault localization is proposed. This method is based on various interlinked ICT through the MV network. The document serves as an input for WP2-simulations and WP3-tests in the CRISP-project.

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Acronyms and Abbreviations

Acronym	Means
CRISP	Distributed Intelligence in CRitical Infrastructures for Sustainable Power
DG	Distributed Generation
DR	Distributed Resources
DSM	Demand Side Management
DNO	Distribution Network Operator
EPS	Electric Power System
FCI	Faulted Circuit Indicator
FDD	Fault Detection and Diagnostics
FPI	Fault Passage Indicator
HF	High Frequency
HV	High Voltage
ICT	Information and Communication Technology
IEEE	Institute of Electrotechnical and Electronics Engineers
IEC	International engineering consortium
LV	Low Voltage
MV	Medium Voltage
PLC	Power Line Carrier
PMU	Phasor Measurement Unit
PQ	Power Quality
SCADA	Supervisor Control and Data Acquisition
SDM	Supply and Demand Matching
RES	Renewable Energy Systems
TSO	Transmission System Operator

Executive summary

The fault in the electro technical meaning is defined in the document. The main part of faults in overhead lines are non permanent faults, what entails the network operator to maintain the existing techniques to clear as fast as possible these faults. When a permanent fault occurs the operator has to detect and to limit the risks as soon as possible. Different axes are followed: limitation of the fault current, clearing the faulted feeder, locating the fault by test and try under possible fault condition.

So the fault detection, fault clearing and fault localization are important functions of an EPS to allow secure and safe operation of the system. The function may be improved by means of a better use of ICT components in the future sharing conveniently the intelligence needed near the distributed devices and a defined centralized intelligence. This improvement becomes necessary in distribution EPS with a high introduction of DR. The transmission and sub-transmission protection systems are already installed in order to manage power flow in all directions, so the DR issue is less critical for this part of the power system in term of fault clearing and diagnosis. Nevertheless the massive introduction of RES involves another constraints to the transmission system which are the bottlenecks caused by important local and fast installed production as wind power plants. Dealing with the distribution power system, and facing a permanent fault, two main actions must be achieved: identify the faulted elementary EPS area quickly and allow the field crew to locate and to repair the fault as soon as possible.

The introduction of DR in distribution EPS involves some changes in fault location methods or equipment. The different existing neutral grounding systems make it difficult the achievement of a general method relevant for any distribution EPS in Europe. Some solutions are studied in the CRISP project in order to improve the current state of fault diagnosis (investigation time and solution cost involved with a dedicated use of ICT) and make this power system function adequate with the future high DR situation expected.

The approach followed to improve the fault diagnosis inside the MV distribution involves new consideration and understanding about the control of MV cells. The document describes the concept of MV level one cell, which is important for the future fault location tools. This level one cell groups all the possible configurations of linked feeders by emergency EPS switches. This concept will be used in the future as a logical and topological reference cell for different functions: load flow, DSM, disconnecting protection.

The improved flexibility and coordination between feeders, as proposed in the HTFD application, will have links with the other expected functions needed to make the distribution EPS more autonomous or intelligent.

1. Introduction

The document presents an overview on fault, fault clearing and fault location methods in a distribution electric power system, with or without distributed resources. The fault in this document is defined as an abnormal connection between conductors. It may induce high currents, generally higher than currents observed during normal supplying conditions, but also low current as in a single-phase fault occurring in a compensated neutral system. The purpose of the fault location methods is underlined in this document, this subject being targeted for the experiments with ICT scheduled in Grenoble (France) during the project CRISP.

The fault is cleared when the detected event on the EPS is no more detected. When this event occurs in a public EPS, various equipments and systems are used in order to limit the extension of the trouble in time and in space.

The fault location may have different meanings, two main meanings being:
- The identification of the faulted circuit branch which should be isolated from the remaining safe EPS (elementary faulted EPS area),
- The exact fault location for the maintenance work. This second aspect is an important feature for the EPS composed of underground cables in order to repair fast enough and to avoid a too high cost of soil extraction engineering (critical situation in an urban area). A precision as 1m may be required for this type of operation.

This second aspect is not under the scope of this document. It may be fulfilled by dedicated mobile equipment using acoustic properties to perform a high level of precision. Our scope is the fault clearing and fast identification of the elementary faulty area.

The main function of an electrical network is to lead the energy from the power plants to the customers. Historically the distribution EPS works as an interface between the generation, the transmission and the customers. The DNO and the TSO keep an acceptable level for the safety and the security. Any fault occurring in the EPS is detected and cleared fast enough. The profit losses induced by no supply lead the DNO and the TSO to reduce the outage to the smaller EPS area as possible.

The fault detection and location in the existing distribution EPS is described without DR firstly. Then the possible impacts of DR connection are described. Because of the multiple MV derivations, expected generation dispersion and load dispersion in the distribution EPS, the technical solutions in use on the transmission grid cannot be transposed to the distribution system easily, neither the existing solutions that do not take DR into account. Moreover the equipment price must be convenient with the distribution EPS financial constraints: new kinds of solutions need to be found.

The interruption's volume and duration are two main criteria used to quantify the quality of the supply. The intentional islanding in an area will be no more considered as an outage in the future, so a massive DR connection may involve a more reliable supply in the future. But even in that long term situation, protection and fault location system will have to be adapted to the variations of the short-circuit current amplitude.

After detection, clearing and location of the fault, another step of reconfiguration may be carry out in order to operate properly the remaining powered distribution EPS in term of economy, security and safety. This step is not considered by this study, and is relatively simple if the fault localization is fast and accurate, and also if the previous generation and consumption (just before the fault) inside the cleared area are known.

ICT may help to find a better solution in combination with previous principles of the protection and fault detection systems. It may allow the protection settings to become more flexible and adapted to the diverse and more variable electrical situations.

2. Fault description and causes

In the field of electrical power systems, a fault is defined as an abnormal electrical link between conductors, this link being maintained or not in the time. The impedance of the fault (the link between the two conductors may be composed of various material or arc) is an important parameter:

- a low impedance fault for a direct connection between active conductors results in high current,
- a low impedance fault for a earth-fault in compensated neutral results in very low current.

The following faults may occur (as mentioned in CRISP document D.1.1):

- 3-phase fault: short-circuit of the three phases (earthed or not).
- 2-phase fault: two phases or one phase to neutral (earthed or not).
- 1-phase or single-phase fault: one phase to neutral or to ground.

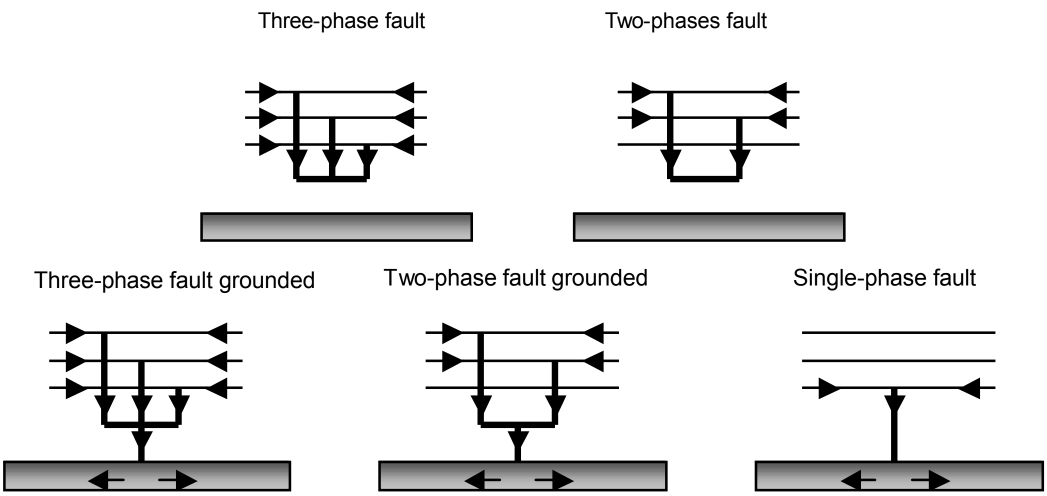


Figure 2-1 Fault types

The fault may vary from a 1-phase to a 3-phase fault because of arc propagation and material degradations: it defines a changing fault. Following the detecting systems and the protection sequences generally used in distribution EPS, the fault inside the area EPS may be considered as:

- Self-clearing: disappearing itself without a breaking operation (in nearly 10ms).
- Intermittent fault: re-striking self-clearing earth-fault (fault lasting nearly 10ms and coming back every 100ms to 200ms, associated to a compensated neutral), the weakness location should be detected before the occurrence of a second earth fault on another phase, the intermittent fault may be defined as a permanent fault,
- Fugitive: it disappears following a short and unique automatic sequence open-close cycle (in a few 100ms), or also after a fast and specific earth shunted operation (in a few 100ms).
- Semi-permanent: it disappears after one or two slow and automatic open-close cycles (nearly 10s opened and nearly 300ms closed if the fault is still present)

- Permanent: it has not disappeared after the previous clearing check, the faulted circuit must be isolated (in order to clear the fault) and a dedicated work team must repair or replace equipment.

Another intermittent 1-phase fault may occur from time to time in the same part of EPS, or with a certain periodicity, depending on the choice of neutral connection to ground. The fault is not permanent but occurs periodically and at the same location. This may occur when an overhead line is near a branch of a tree for example, the contact being influenced by wind.
A rare event and difficult to deal with is the double fault: two single-phase faults appear on two different phases and at two different locations.

Even if the fault is 1-phase or 2-phase, the opening of the main feeder breaker concerns actually the three phases. This breaker is installed at the sending-ends of the high voltage feeders.
In the case of an earth fault occurring on a compensated neutral EPS, some DNO maintain supplying the faulty feeder during a given time (a few minutes to a few hours) depending on the equipment used and the magnitude of the earth current.
For instance in Germany and Austria, the compensation is automatically set to maintain a zero earth current and a typical 2 hours faulty condition is accepted.

When the fault occurs inside a private installation or behind an EPS fuse, it is cleared fast enough generally, enabling to avoid a breaking action of the main high voltage feeder breaker: it is a main principle of selectivity as illustrated on Figure 3-3.

The faults have different possible origins:

- Electric: degradation of the equipment insulation materials (solids, liquids or gases)
- Climatologic: storms, ice, snow, seism, lightning, fire (forest, building for instance).
- Human activity or error: wrong action or connection, mechanical incident (soil extraction).

The faults do not have the same occurring probability for overhead line or underground cable, and are not of the same type. The statistical studies show that the fault is mainly not permanent (nearly 90%) and 1-phase (nearly 75%) in the French typical MV network. The main causes are the storm or the fall of a cable on the ground. For the underground cables, the fault is mainly permanent (nearly 100%) and 1-phase or 3-phase depending on the cable type (radial or non radial). For a radial cable the fault is mainly 1-phase, the shield being directly connected to earth. For a non radial cable the fault becomes 3-phase in general because of a fast material thermal degradation.

3. Fault protection system and sequences without DR

The protection system is different between transmission EPS and distribution EPS.

In an economical point of view, transmission circuit is more important than distribution circuit because of the level of flowing power and the number of customers concerned, so a more expensive protection is now installed in transmission EPS.

In a topological point of view, the description of lines in a transmission EPS is easy. This principle is illustrated in Figure 3-1.

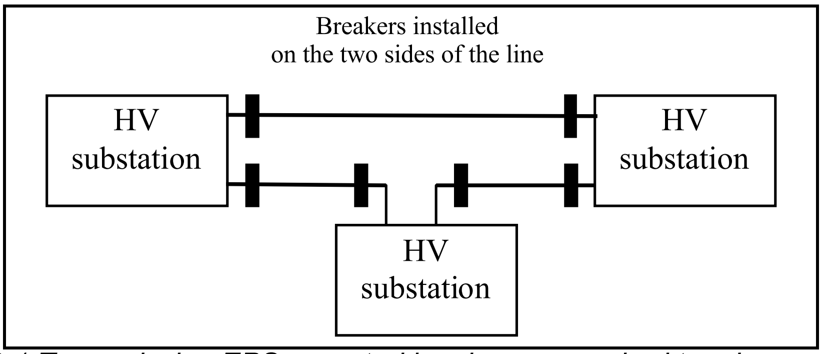


Figure 3-1 Transmission EPS operated in a loop or meshed topology

In a design point of view, transmission lines have only two ends: they connect a substation to another substation, so differential protections and distance protections can be used and set properly. The operator is automatically and quickly informed in case of a permanent fault event and its consequences can be checked by the SCADA system.

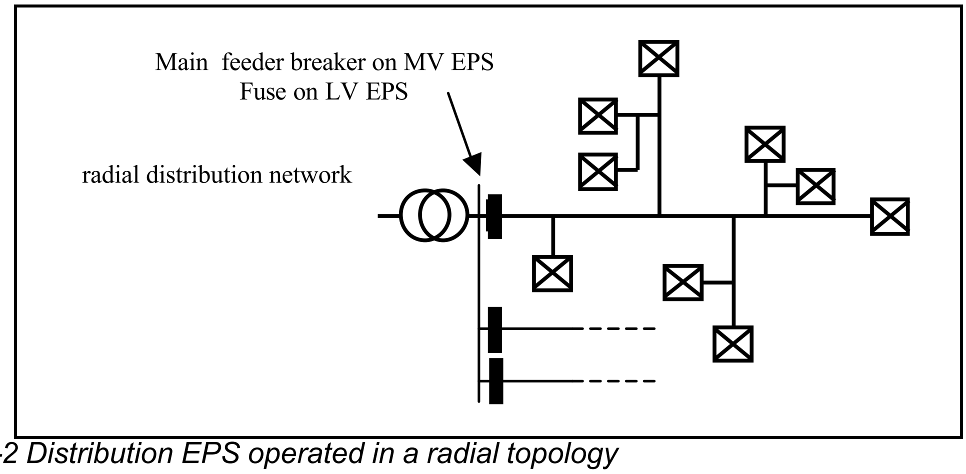


Figure 3-2 Distribution EPS operated in a radial topology

In the Distribution EPS, the fault detection and location is based on measuring data (in the substation) and on equipment state data supervised (along the conductors): if the fault occurs under fuses in the distribution EPS, the source of information may become the customers concerned by the lack of power, who call its DNO.
In France, the boundary between observable and not observable fault state is around the MV/LV public transformer, in general in the LV transformer side.

In USA, this boundary may be on the sending-end of the MV derivations. This kind of operation entails some difficulties in term of selectivity. An advantage of this method is to have a partial fault location during the clearing process.

A mean to understand this aspect of selectivity is to look at the protection coordination inside an industrial network. The following figure shows an example with selectivity in time and in fault current magnitude.

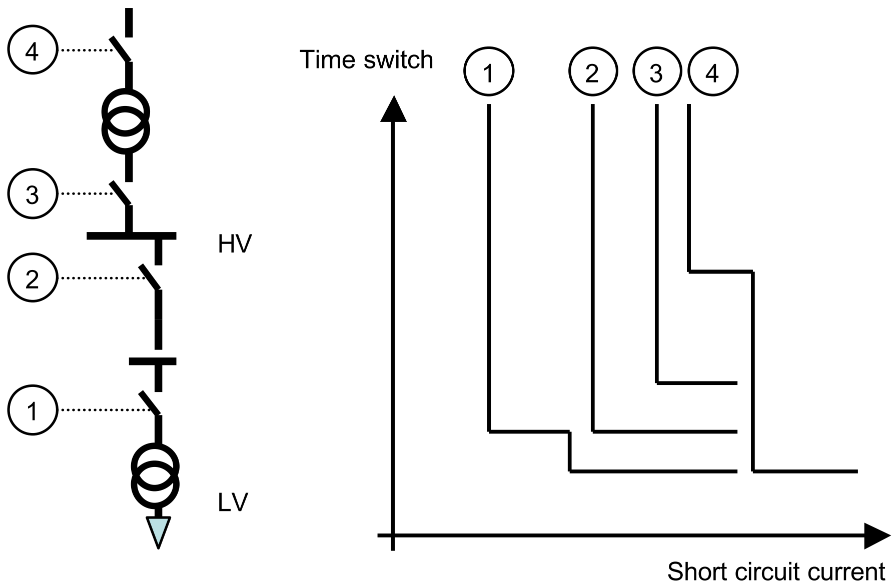


Figure 3-3 Selectivity example

3.1 Distribution EPS

Two main categories of faults detection may be considered:

- 1-phase fault to ground
- the other types of faults

In many countries, the 1-phase fault to ground is detected in the neutral connection of the very high voltage to high voltage transformer (typically of the 20kV side neutral for a 63kV/20kV in France) and is characterized by limited current magnitude. The other types of faults are detected at each sending-end main high voltage feeder by the appropriate relays and the current amplitude may be rather high (but always limited to maximal amplitude by minimum series impedance imposed in the transformer above).

Three main steps occur for detection and location of a permanent fault in a distribution EPS:

- The fault detection is indicated by one or several relays or sensors located in the HV/MV substation (a few 10ms at fault occurrence or when automatic re-closing is in process). The final situation of this step is a power break for the whole feeder involved and for the three phases.
- A preliminary analysis indicates the type of fault (1-phase or multiple phases), identifies the phases involved. A specific process is used to limit the power break to the elementary faulty area (a few minutes to several tens of minutes): this step is done by the maintenance and operation teams in general.
- The exact location in the elementary faulty area is achieved by dedicated equipment (a few tens of minutes to several hours, maybe more for the underground cables): this step is done by the maintenance teams.

In the case of a single-phase fault occurring in a compensated neutral EPS, there is a high probability of re-striking earth-fault before the occurrence of the permanent fault, because of the very low fault current resulting. Some DNO maintain supplying the faulty area (single-phase earth-fault) during a long time (two hours for instance, or more in some cases) in order to improve the reliability and to give time enough at the field crew to locate the fault. Our localization solution is proposed to reduce the time for detection and location.

Elementary faulty area is an important concept for the current EPS and the future EPS. It represents the circuit area which may be isolated by the appropriate equipment (EPS switches), allowing the remaining part of the distribution to be normally supplied. This concept is not so easy to handle: tie branches (normally open emergency switch) connected to an adjacent and separated distribution EPS already exist and allow a certain level of back-up. So the elementary area is often composed of several breakers or switches at its electrical boundaries, and may be composed of numerous branches of conductors.
Clearing a permanent fault takes less than 1s generally, but often a large area is de-energized (larger than the elementary area). That entails specific difficulties and technical solutions for the location after clearing action.

Two main strategies exist to carry out the three steps above mentioned:

- Detection, analysis and action are done in the main substation from local measurements,
- Detection, analysis and action are distributed inside the distribution EPS on several key points.

In France a combination of these two strategies is used, a part of the second strategy being done manually and using a processed visual check. In numerous configurations, a main MV feeder is installed and numerous derivations are then attached to it. The sending-end of these derivations may be key points used for local detection. Some of these local detectors are supervised by the main substation (SCADA) to indicate the passage of a fault current.

As described previously, the memorization of specific information is needed in order to determine the fault elementary area and to try to locate as accurately as possible the exact fault location. For instance in overhead FPI the local memorization and indication of the fault current passage are achieved by a specific signalisation (flashing light, mechanical flag).

The sensors may be of current type, but some specific methods need also voltage sensors. The technical specifications for the measurements depend on the goal:

- Exact localisation from the substation using local measurement needs a precise instantaneous measurement (the bandwidth depends on the exact method used),
- Detection, analysis and action from dedicated equipments inside the EPS distributed on several key points.

Wattmetric homopolar detection
In the case of a compensated neutral distribution EPS, a possible solution for feeder fault detection is to measure the zero sequence current and the zero sequence voltage. Observed from the sending-ends of the feeder, the faulty feeder alone will have an active component (for the zero sequence current or power).
The knowledge of different components for the zero sequence circuit may allow the DNO to evaluate the fault location. A main issue is the precision required for the electrical variables measured and for the various impedance data of the network.

The topology of the MV cells with various configurations and various emergency path leads to define two main levels of cell in MV. This concept is not essential for the first fault occurrence: the network is operated in open loops condition. But when a fault has been cleared and a new configuration has been defined, it is important to update the new conditions for the protection system and the fault localization method.

Figure 3-4 gives a simple view on this concept. The level 1 cell groups all the feeders linked by emergency switches. Various substations may be associated to that cell. The level 2 cell groups all the level 1 cells that may be interlinked by the MV bus bar in the associated substations.
In another way, the boundaries of level 1 cell are not passed through by MV conductors, except at the output of the MV substations bus bars. The boundaries of level 2 cell are not passed through by MV conductors except at the input of the MV substations bus bars.

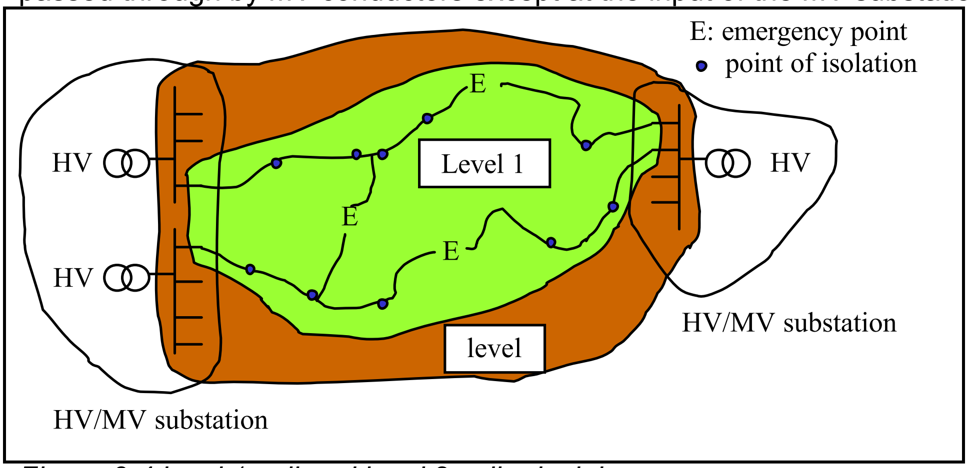


Figure 3-4 level 1 cell and level 2 cell principle

In Figure 3-5 a help to decision tool for fault diagnosis (HTFD) is shown as being associated to a given HV/MV substation. The purpose of this tool is to inform the operator about the location of a permanent fault. It can be seen that the emergency points (E) are the current boundaries for the radial operation inside a level 1 cell.

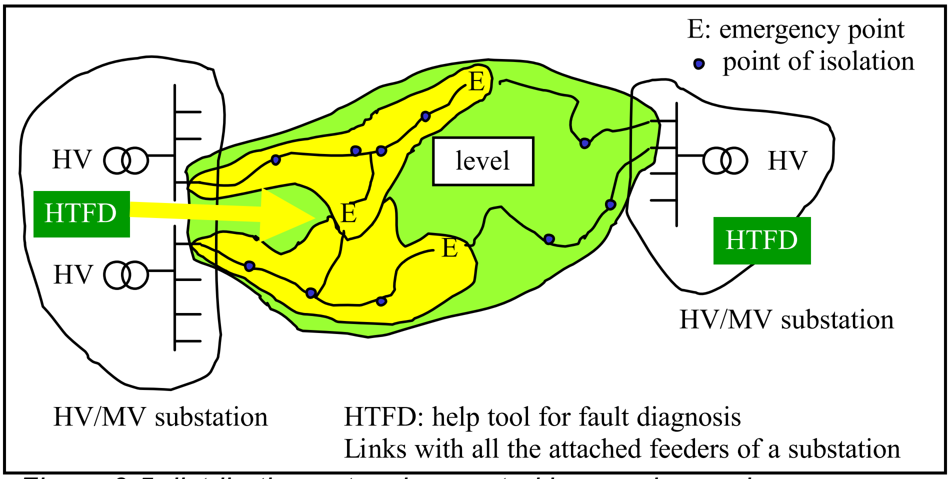


Figure 3-5 distribution network operated in open loop scheme

3.2 Transmission and sub-transmission EPS

The elementary area is a simple line without derivation, two breakers being in the two adjacent substations on each end of the line. When a permanent fault occurs on a conductor, the three phases are opened in the two connected substations in order to clear the fault (a few exceptions exist i.e. a single phase disconnection in case of specific fast re-closing process for a double circuit transmission, but this case is rare). For an important power flow, several circuits may be paralleled: the loss of one circuit is less critical than for a distribution feeder.

Two main protection systems are widely used in transmission and sub-transmission EPS:
- Non-unit protection: installed at one end of line, typical example of the distance protection
- Unit protection: installed at the two ends of the line, typical example of the line differential protection or also of the phase comparator protection

Two main types of communication are used between two substations:
- Exchange of analogical output in order to compare measured values (case of line differential protection),
- Exchange of numerical order (case of distance protection to combine or accelerate actions at the two ends of a line).

The fault being cleared, the transmission substation may have specific equipment installed to evaluate the fault distance. A typical solution for this function is based on the wave propagation property, the line being out of power and disconnected from the remaining EPS. With the upcoming of numerical protection, the numerical distance protection may be equipped now with additional functions, one being fault distance evaluation. The output of this additional function may be the apparent impedance of the line or the fault location expressed in percentage of the line length (in that case the linear impedance of the line must be given to the protection by the operator).

4. Fault localization in distribution without DR

Some general assessments:

- The main breaker of the feeder is activated by an order emitted from a protection relay,
- A relay may have diverse inputs (for instance dedicated measurements of current and voltage),
- A relay includes analysing algorithms and its main output function is to send the right tripping order in the right time to the breaker,
- Miscellaneous functions may be added: communication (for instance information exchange with a remote substation or a distributed equipment) or supervision (for instance evaluation of the fault distance from the substation delivered to an EPS control station),
- A combination of multiple relays may be oriented to the same breaker.

Two methods categories may be considered:

- Active,
- Passive.

The active methods entail more or less some disturbances in the EPS. For instance, it may be an injection of a relative low signal in the conductors, or also reconnecting a circuit, including eventually a fault in order to locate its position.
The passive methods use measurements to detect and locate the fault without generating any electrical constraint on the EPS. The FPI (fault passage indicator) is powerful and low cost equipment for passive methods. It is distributed in general at key points of the distribution EPS (on the main feeder and derivations), being associated in general with the boundaries of the elementary areas. High precision and band-width measurements may be available in the main substation in order to record signals flowing through the main feeder sending-end, and so may be used for a passive method.

The fault location may use a process combining several different input data and the two kinds of methods, active and passive. The principle of trial and error is widely used in distribution EPS, allowing the operator to save money compared with an integral controlled systems. Each operator defines its procedure following its facilities, human resources and economical constraints.

The following tools and evaluation programs are the main technical solutions and data inputs to help an EPS operator to locate a fault in distribution or transmission system.

- Phone calls by customers allow the DNO to locate a terminal fault in the EPS (under fuses, distribution system). A dedicated service analyses and locates the diverse help demands.
- FPI and switches used locally and manually (distribution system)
- FPI and switches remote controlled (distribution system)
- Substation signal analysis and fault feeder identification (1-phase fault, transmission system)
- Substation signal analysis and distance evaluation based on the industrial frequency signals (transmission system)
- Substation signal analysis and distance evaluation based on the transient signals observed during fault detection (transmission system)
- Substation signal analysis and distance evaluation based on the wave propagation property (fixed equipment in transmission system, mobile equipment in distribution

system). The involved circuit is the elementary section and is maintained out of power.
- Evaluation of fault distance by the distance protection (transmission system with new integral numerical protection)

The approach based on substation signal analysis has been on study for several years, but the real application has not yet been achieved. An input data used up to now for that kind of experimental approach in HV/MV substation is the fault recorder (disturbograph).

4.1 Phone calls by customers

This general method is used worldwide. It concerns all the types of unintentional circuit opening caused by fault or not: over-current blowing a fuse, fault blowing a fuse, line or cable sectioned by storm or human activity.
From the calls location and knowing the EPS configuration in use, the maintenance team is able to locate roughly the location of the EPS problem. Then a technical and local move by a technician is needed to locate exactly the problem, to observe and to solve if possible.
If the trouble indicated by phone calls comes from a more general issue (main feeder out of power, substation out of power), people calling are informed that the technical problem has been observed and is being treated (the operator is already informed).

This method is largely used in France in the LV public distribution EPS. For a permanent fault occurring in the high voltage public distribution EPS, the operator is informed by the main feeder protection quickly.

In the USA, fuses are largely used in the LV public distribution EPS (short lines or cables) but also in the single phase derivations, in combination with re-closers. So the phone calls system is widely used there.

If the fault origin is apparent (e.g. fall on the ground of a conductor), the maintenance team could repair and re-energize this EPS area again. In other case the maintenance team may use specific equipment or use a trial and error method to reduce the fault investigated area.
The investigation may be done out of power with an appropriate detection equipment. It could take hours of work depending on the equipments available to open derivations and disconnect loads.

4.2 Trial and error

When the fault is detected but not clearly located by selective protection devices, the main solution consists in opening and closing elementary circuits in order to locate the fault. The main drawback is inconvenience and low power quality for the customers inside the researched area: power is successively on and off for numerous customers because of the fault need to be cleared by the appropriate circuit breaker (located at the sending-end of the main feeder in general).

4.3 Fault Passage Indicator

The first function is to detect a permanent fault current passing through its sensors. The second function is to memorize and indicate this state. So a non indication by FPI gives a piece of information: the fault is located between the last enlightened FPI and the following ones which are not enlightened. This gives the basic functions and usage of the non-directional FPI at the moment as indicated on the following figure.

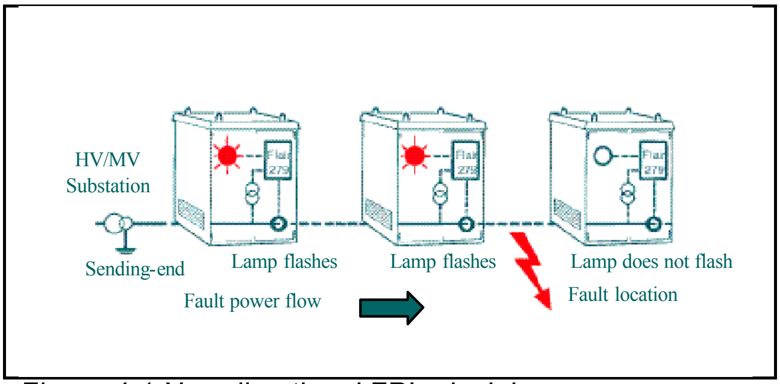


Figure 4-1 Non-directional FPI principle

Different devices have been developed to be adapted to overhead lines or underground cables, and to be adapted to the diverse existing neutral grounding systems.

The non-directional FPI uses a simple current sensor. The permanent fault is detected if an appropriate threshold has been reached. The resulting sensor output value is compared to the threshold periodically. When the over-current occurs, a timing process is initiated in order to decide for the activation of the indicator (taking into account the characteristics of non permanent fault clearing systems).
This system is set to indicate the previous passage of a permanent fault. When fault current disappeared (caused by a tripping inside a private installation or following a non permanent fault) through the FPI and normal voltage is recovered, after a defined delay the FPI system is reset.

It's a low cost solution (compared with a breaker and its protection system associated).
Compared with fuses, the associated FPI and switches allow the operator to detect and to sectionalize the EPS without the drawback of a short tripping time (drawback in term of selectivity). It's a high advantage in rural and overhead EPS when 80% of faults are fugitive, and are fast cleared by the automatic re-closing system.

The different switches distributed on the public EPS may be associated or not with a FPI. When a switch associated to a FPI is remote controlled, the FPI output is also remote supervised.

This equipment is used in the French distribution EPS, associated or not the switches distributed along the main distribution feeder and derivations: its indication allows the operator to reduce the investigation time, several trial and error sequences are then used to reduce the out-of-power area.

These existing fault detectors are divided into two types:

- Fault detectors based on a simple current criterion (for single-phase faults with impedance grounded neutral and for multi-phase faults).
- Fault detectors based on a directional criterion (for single-phase faults with compensated neutral).

The signals emitted by the fault detectors can be supplied:

- In a local way in the detector itself or with the help of a local system that record the events.

- Sent to a centralised point by ICT systems

The main advantage of this method is a right compromise between the cost of the supply failure (load shed) and the cost of this equipment.

4.4 Method based on substation measurements and analysis

There is no a current use of this kind of method in the distribution EPS. These approaches have been followed and experimented by some manufacturers and some utilities in the last years, but have not yet resulted in an industrial product.
These approaches give a trend for an expected future solution of the fault localization, with or without DR.

4.5 Possible combination of methods

4.5.1 Trial and error method and FPI

This method is widely used: the fault location search is boosted by FPI using logical and priority sequences.
An efficient process to locate the fault is defined by:
1/ reducing first the impacted zone on the main feeder
2/ reducing then the derivations around the reduced faulty area
…using iteratively

- controlled switch equipped with FPI,
- controlled switch without FPI (blind test, the main breaker could be closed on fault)
- manual switch equipped with FPI
- manual switch without FPI (blind test, the main breaker could be closed on fault)

Today the networks are much more equipped with manual switches than controlled switches (supervised and controlled from an operation control room). These manual switches require time and dedicated field crew to check locally the FPI and then operate them.

Depending on the fault location inside the public distribution EPS, the investigation for finding the elementary fault area lasts:

- A few min if the fault is located between two or under one remote controlled switch with FPI or without FPI,
- A few 10min if a maintenance worker must drive to the faulted area, observe the FPI and switch manually numerous switches,

Finally, this method gives only the fault elementary area: another investigation is initiated to find the exact fault location, the fault cause and fast repair if possible. This step may last hours, especially for fault inside an underground cable.

The LV distribution EPS is mainly protected by fuses on the public area:
The cause for a blown fuse being undetermined, a maintenance worker may try with a new fuse without any reconfiguration (the adjacent customers in the same LV EPS may suffer voltage dips). If it blows again, the origin of the fault or of the over-current must be found by iterative trial and error, the derivations being opened and closed following a defined or not defined process.
So the same type of method is used in the LV public distribution EPS.

4.5.2 Fault distance evaluation and FPI

During the CRISP project, a combination of FPI results and distance evaluation is proposed. This principle is already interesting for the existing distribution EPS, and is expected to be convenient also for a future situation with DG.
The following figure gives the principle: the design of the network and the accuracy and reliability of the distance evaluation influence the number and the locations of the needed FPI.
In fact the distance evaluation results from an iterative process analysis section by section of conductors. Then the multiple possible locations found are as an electrical distance unit. This solution is developed to be tested in a CRISP project experiment.

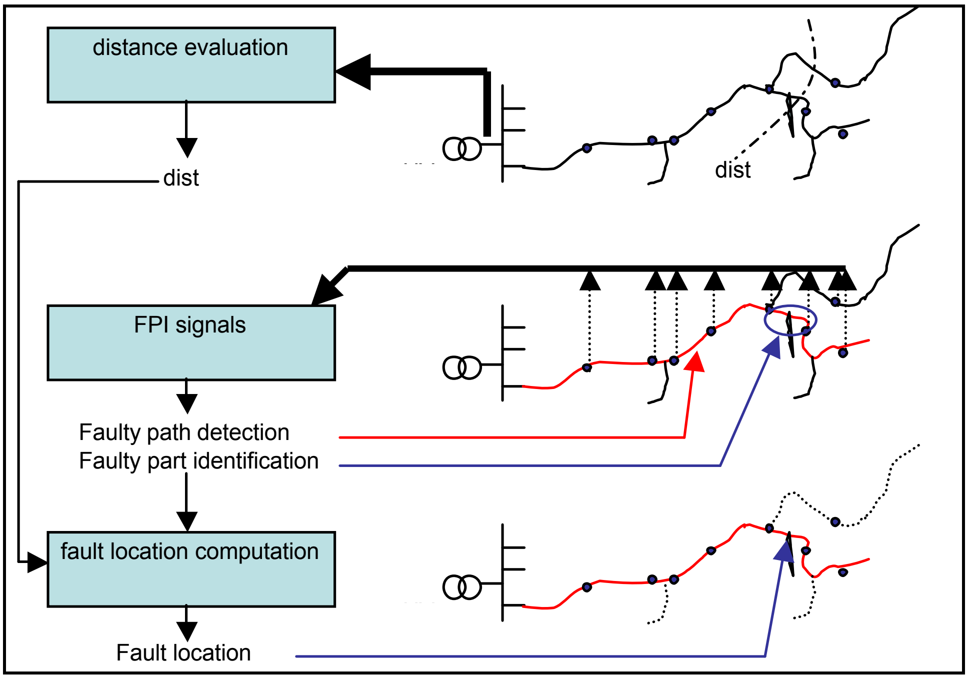


Figure 4-2 Principle for the combination of FPI and distance evaluation

5. Expected DR fault contribution, protection and localization issues

A fault contribution of DR may induce problems in the case of a high level of local production. The possible local rise of the fault current amplitude may disturb the fault protection system and associated location system.

5.1 Grounding

The neutral connection to the ground is an important feature for the single-phase fault current amplitude and so for the security and safety aspects. This question is relative to the DNO technical rules in association with the European and national regulations. The existing grounding systems in the HV/MV substation and in the MV/LV substations are quite different in the European countries today.

In a general manner, inside the producer and consumer installations the neutral points of the machines are disconnected from the local ground: they do not contribute to the single-phase fault current. If the requirement of DNO is met, any type of DR does not contribute to the single-phase fault current on the distribution EPS.

In the case of production by an inverter, in single-phase or in three phases with neutral connection (low voltage EPS), the single-phase fault may be supplied by the DR. A general principle is that the current resulting from the inverter under such a single-phase fault is very fast controlled and limited.

5.2 Distributed Resource type

Three kinds of interface between the generating unit and the EPS are considered: synchronous machine, induction machine and inverter.

The induction machine needs voltage to maintain its magnetizing energy. During the fault, the deep fall of voltage has a fast action on the induction machine: the contribution to the fault current decreases to a low level in a few cycles. So the consequences for the protection installed inside the public EPS may be neglected for this kind of generation.

The inverter in PWM mode (pulse width modulation) is very fast controlled (for instance the PWM frequency may be around 10kHz). The fault situation is detected (slope of current variation) and the current may be limited and maintained during a given time in order to avoid any nuisance tripping.

The synchronous machine may supply a fault with a relative important transient current, relative to its nominal power. During a few cycles, if the excitation during the normal situation is maintained, the current may be around 6 times as the nominal current delivered by the unit and then is progressively reduced up to a value close to its nominal current if the short-circuit is maintained. In fact the machine manufacturers provide regulators that control the excitation in order to obtain specific fault characteristics. For instance a value of fault current of three times the nominal value may be maintained during 10s, and then reduced to a half-nominal value (waiting for the action of the protection system).

So the risk of an increase in the fault current in the distribution may come from the DR based on synchronous machines. In general these machines connected to a MV voltage are high power units (>500kW and <10MVA) and are equipped with specific regulators as indicated before (current limitation to 3In by unit).

The short-circuit power on the MV distribution due to the interconnected EPS (supply from the very high voltage) depends on the nominal power of HV/MV transformer and its defined series impedance. For typical French substations, a value is nearly 200MVA for a 36MVA transformer and nearly 70MVA for a 10MVA transformer. Similar values are expected in the distribution EPS of the other European countries. So the main contribution to the fault current is expected to come from the interconnected network, even if a high rate of DR is connected to a given Feeder.

5.3 Protection and localization issues

5.3.1 Issues for the public EPS protection

A possible risk is nuisance tripping or disturbances among the previous automatic systems developed to clear non permanent faults. Two levels of question should be taken into account:
1/ are the existing protection scheme with existing settings convenient for the expected DR installation?
2/ are the existing protection scheme with adapted settings convenient for the expected DR installation?
If the answer to these two questions is no, new kinds of protection are required.
The answer depends highly on the amount of the local production and the configuration of the network.

5.3.2 Issues for the DR installation protection

In the current situation the loss of a distribution feeder must disconnect the producers distributed in that feeder. The device used for this function is named disconnecting protection, and is based on minimal and maximal thresholds of voltage (frequency and magnitude of the voltage).
The operation of protection during a fault may disconnect more DR installations that needed. The resulting local lack of produced power may be a drawback for the associated distribution. One solution adopted up to now is to introduce several levels of delayed operation of these devices, depending on the level of power produced.

5.3.3 Issues for the fault location

The main problem expected is to have not enough information from the non directional FPI: the fault contribution of DR could involve fault indication in any location of the network. In this case the indication of the direction of fault becomes necessary. A specific device sensing the direction of the flowing power is needed, enabling to determine clearly the direction of the fault when detected by the FPI.

6. Fault localization tools and methods with DR

6.1 Automatic outage indication in LV EPS

With the micro-grids and ICT development, the low voltage distribution may be more and more supervised, enabling to detect quickly and automatically a no-powered LV area.
The disconnecting protection associated with any DR has the function to detect an abnormal condition for voltage (frequency and magnitude), so it could exchange a part of this information with the associated controllers to inform a dedicated control room about a change on the local voltage (for instance to a virtual power plant).
The abnormal condition observed on voltage may be centralized and analysed to locate the point of failure or of isolation.

6.2 Method based on trial and error

The principle of this method is general and will be certainly maintained in the future as a main method or an emergency method. The reason to avoid its use is due to the constraints imposed on the electrical system by the multiple closing on fault.
The problem of indication of fault by DR has been presented as a potential problem. Another problem in intentional islanding will be in the future the non indication of fault due to a too low contribution on faulty current by the associated DR. In that case, the trial and error method will remain a solution to clear the smallest faulty area. The real achievement will be also more complex: the supply is delivered by the distributed DR, and no more by a well defined unique path (the sending-end of a feeder).

6.3 Method based on FPI

Two main types of FPI are in use: non-directional or directional FPI. The existing directional FPI deals with the zero sequence components what is not the main interest in the case of the contribution of DR units for a fault current. New kinds of devices must be developed in the future to find the fault direction for multi-phase faults. This development should not be a problem for FPI manufacturers which have already developed a solution of ground directional FPI.

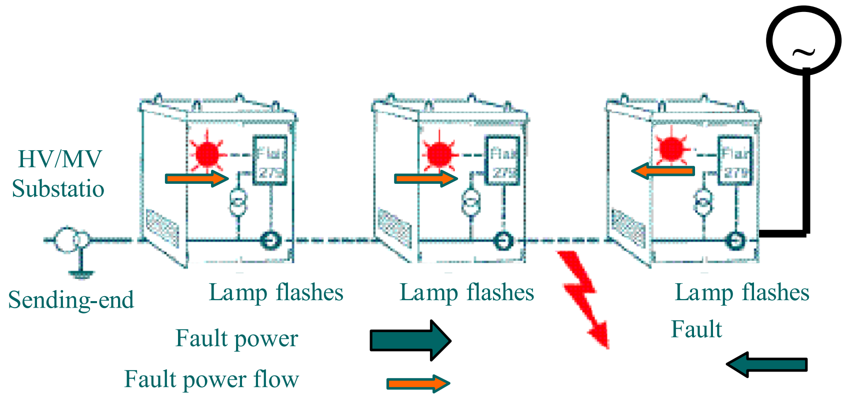


Figure 6-1 Phase directional FPI in a high DR in distribution EPS

Since the FPI may be enlightened by DR or by high capacitive currents, it is useful to detect the direction of power flow. The directional type uses additional information on voltage to evaluate the orientation of power flux. So the fault direction relative to the FPI may be found. This kind of indicator is expected to be efficient with DR introduction.

If the current caused by fault and supplied by the DR is high enough to make the indicators enlightened, the direction of power allows the operator to know the right direction for the fault location investigation.

In a long term analysis, working under intentional islanding will cause some troubles with the FPI current thresholds settings. The low level of short-circuit current will need a real time adaptation of the local protections settings.

6.4 Method based on substation measurements and analysis

A main principle is based on the equivalent impedance evaluation. The voltage and the current have to be measured in magnitude and in phase at a given point of the network: the sending-end of a feeder in general. The impedance by length unit of conductors is known and used to find the location of fault.

The collection of the needed transient data is done by equipment dedicated to fault diagnosis: fault recorder. The results may be transmitted to specific programs by mean of specific and standardized data files. A typical example is COMTRADE (communication transient data exchange) which is widely used in the field of power systems.

In general, the fault is recorded with a window giving electrical variables before and after the detection of the fault. The use of this kind of fault recorder is highly recommended for the fault localization since the time to collect data is short (between fault appearance and fault clearance) and the information of previous fault state may be of importance.

Several pieces of information are available in the current resulting signals, in the low frequency range (industrial frequency) but also in the high frequency range.
In the high frequency range, a phenomenon of resonance may be used to evaluate the fault distance. In transmission system, a transient signal may be injected to evaluate the fault distance by the return time of the propagating wave.

Some of these methods are based on measurements of the electric parameters at the fundamental frequency. The single-phase fault distance evaluation is difficult to achieve because of the various bifurcations and distributed loads, and the multiple existing grounding systems. In general the application of these methods is relatively easy with multi-phase faults, the current being high and depending mainly on the impedance of the direct path to the substation.

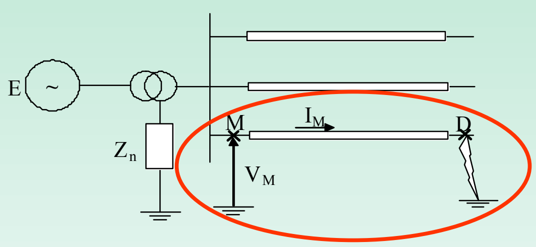
Hereafter is given a short list of fault localization methods:

- Impedance computation method, called “the one-end algorithm” because it takes into account the electric parameters measured at the end of the branch, these measures are synchronized and nowadays, it is employed in the majority of the distance relays. The advantage is the simplicity and the low cost because it doesn’t need telecommunication equipment. The disadvantage is the loss of precision if the system is complex and if the fault resistances are huge.
- Computation, measurement and comparison of the short-circuit reactance. It’s a method used by OKA in Austria and by several operators in Germany and it was thought for the poly-phases faults. It consists of the computation of the short-circuit reactance with the information given by all the relays disposed in the network. This

reactance is sent to the SCADA system (Supervisor Control and Data Acquisition). If a fault appears, the short circuit reactance measured is transferred to an algorithm and the result is the line where the fault is located.

- Computation, measurement and comparison of the short circuit current. This method is mainly used in Finland and it is known as FI-model. It uses the Distribution Management System (DMS), the SCADA system and the protection relays. A fault current measured is compared with a computed value, resulting on an evaluation of the fault distance. The computation is carried out with the assumption that the network topology has not changed by the effect of the fault.
  This method use three main sources of information: the fault passage indices, the statistics of the different faults in the areas and the fault distance computation (the protection relays give the information regarding the faults: current, type of fault, phase involved in the fault…then, this information is sent to the SCADA which includes the state of the network and its topology, the whole information is given to the DMS and this last one computes the fault current and compares it to the measured current values.
- The two-end algorithm. It was designed to the fault location in transmission networks, this method uses the phasor measure of voltage and current, that is the Fourier transformation obtained from temporal values at the main harmonic frequency. This measure is done by a Phasor Measurement Unit (PMU). In order to improve the efficiency the measures are synchronized by GPS.
- Analysis of the neutral voltage variation to compute the fault impedance.
- Analysis of the residual current variation. It is leaded to the location of ground resistant faults in the distribution networks. The residual current methods use the variation of the neutral voltage and the residual currents. The residual current of the feeder non-affected by the fault is zero and it is equal to a 1/3 of the fault current. The combination of the computation of the fault current from the analysis of the neutral voltage variation and the knowledge of the residual current are inputs of an algorithm that computes the impedance of the fault loop.

Loop impedance evaluation at 50Hz



Loop = Bcle

$$d = \frac{\mathrm{Im}\left(\overline{Z_{Bcle}}\right)}{2.l_{moy.d} + l_{moy.o}}$$

Figure 6-2 Loop impedance used for fault distance evaluation

The method proposed to be taken into account in the CRISP project consists of the computation of the fault distance from the MV substation. As indicated in Figure 6-2, it determines the reactance in the fault loop and from the knowledge of conductors characteristics, it gives the expected fault points in the EPS. Because of the multiple derivations in a distribution network, several points may be found. The measurements needed to evaluate the fault distance may be done with equipment used for fault diagnosis. The cost of a lot of FPI in the distribution is high, so a combination of these devices with the fault location program may result in a better compromise. The configuration may change at any time caused by faults or other reason (maintenance for instance). So it is necessary to know in real time the topology of the network in order to be able to initiate properly the tool for fault localization. This information of the network configuration should be exchanged between the operation centres that drive the same MV level 1 cells.

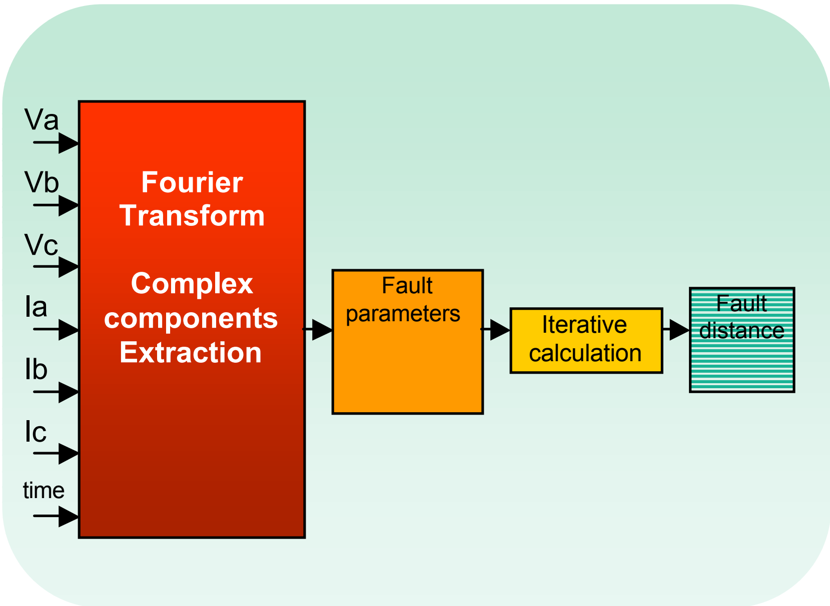


Figure 6-3 Fault distance evaluation principle

The limits of this method are a consequence of the quality in the computation of the fault distance. This computation depends on the knowledge of the networks (topology, physical and electric parameters), the fault resistance (for single-phase faults) and the quality of the recorded electric data.

In order to boost the process, a local and previous analysis near the fault recorder may prepare and select the essential data needed for the fault evaluation distance program located in the control room: this combination of local conversion and analysis with fast communication to another computation system emphasises the use of ICT.

6.5 Method based on dedicated equipment for fault location

Since the previous equipment used to locate accurately the fault is working out of power, the elementary faulty area will be kept in the same condition. Any generating unit connected to this section will have to wait for the appropriate reparation and re-energization.

6.6 Possible combination of methods

6.6.1 Trial and error method and FPI

The method described without DR may be used in a high DR rate in the network with the following adaptation:

- FPI are directional,
- The disconnecting protection must disconnect all the generating units included in the investigated area, and maintain them disconnected during the trial and error process.

Even if another method is developed in the future to improve the fault localization, this method will stay a basic and reliable method to investigate in case of failure of the future ones.

Today the networks do not include a high rate of DR, the utility keep using the non directional FPI and fast disconnecting protection for the dispersed generators.

6.6.2 Fault distance evaluation and FPI

During the CRISP project, a combination of FPI results and distance evaluation has been proposed. The combination proposed has to comply with a high DR penetration in the distribution systems: directional FPI are used and an adapted fault distance evaluation is studied.

The principles of the fault location system are described by the following figures. The ICT takes an important place in that approach in order to boost the analysis and transmission of the data.

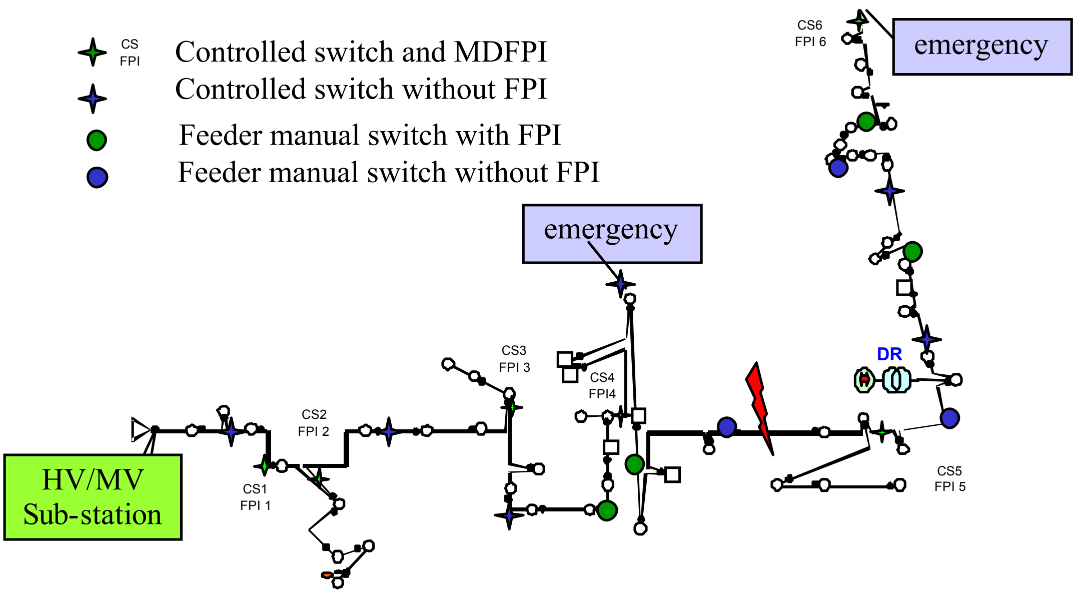


Figure 6-4 Fault localization principles step 1: a fault occurs

When the permanent fault is detected (the reclosing sequences are not sufficient to eliminate the fault), the main circuit breaker is opened and an alarm is sent to the operator to inform him about the existing feeder no more supplied.
The whole feeder has been interrupted, and during a while ICT components send information to a dedicated tool. This tool use the information collected and its predefined

data (as for instance the knowledge of the topology of the network) to give a or several expected fault location.
In the example given in the figure 6.5, a unique point is indicated.

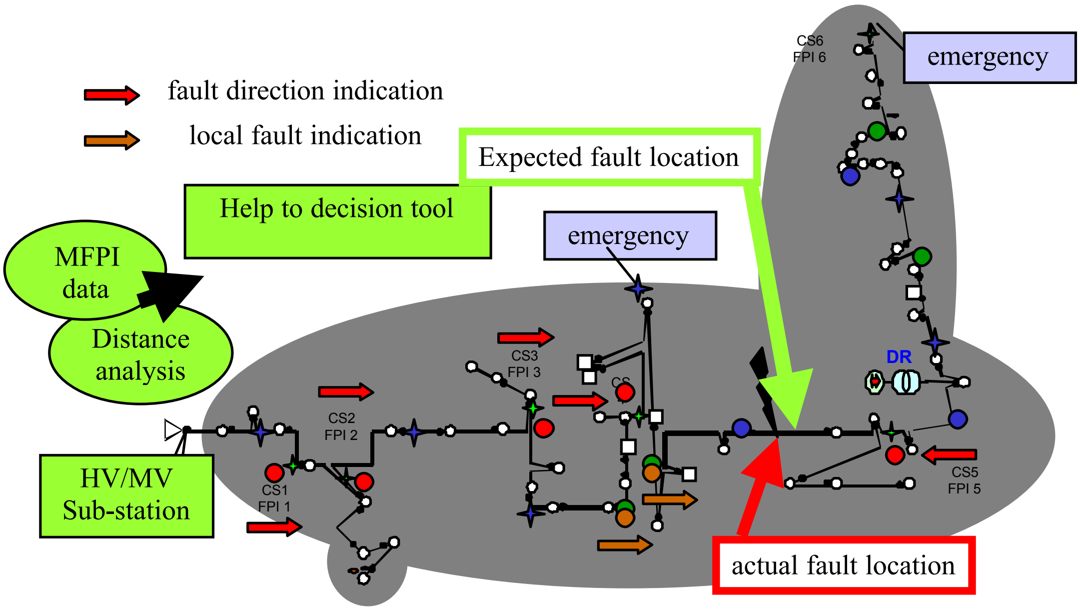


Figure 6-5 Fault localization principles step 2: the fault is cleared and investigated

The operator may use remote controlled EPS interrupters to change the configuration of the network. So a main part may be supplied as indicated by the figure 6-5. Even if the location is defined by the tool, the network showed in the example is equipped with manual interrupters that have to be switched locally.

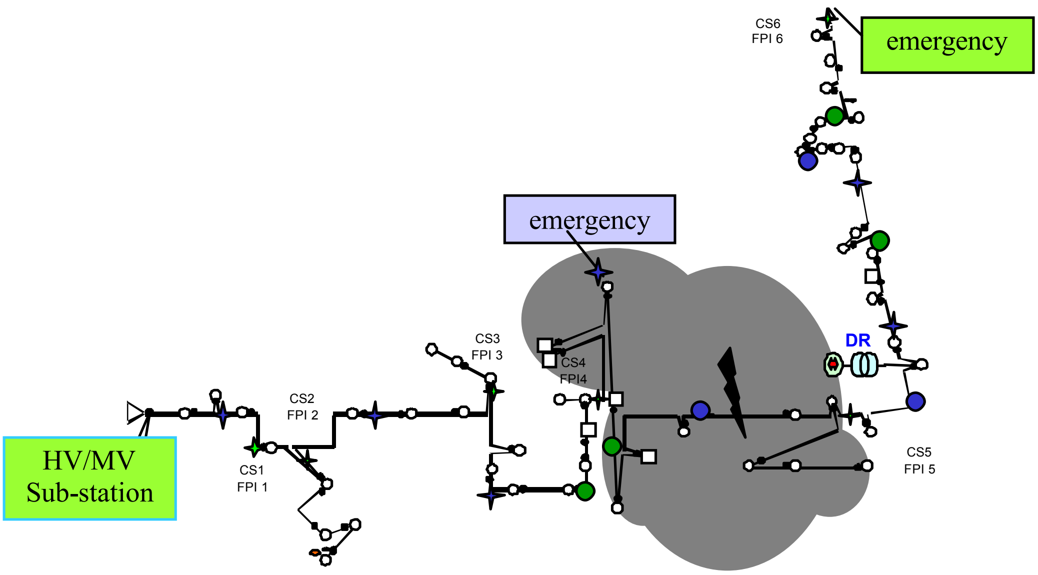


Figure 6-6 Fault localization principles step 3: faulty area reduced by remote control

A field team is sent to finalize the reduction of the unsupplied area, and to try to find the cause and to repair the permanent fault.

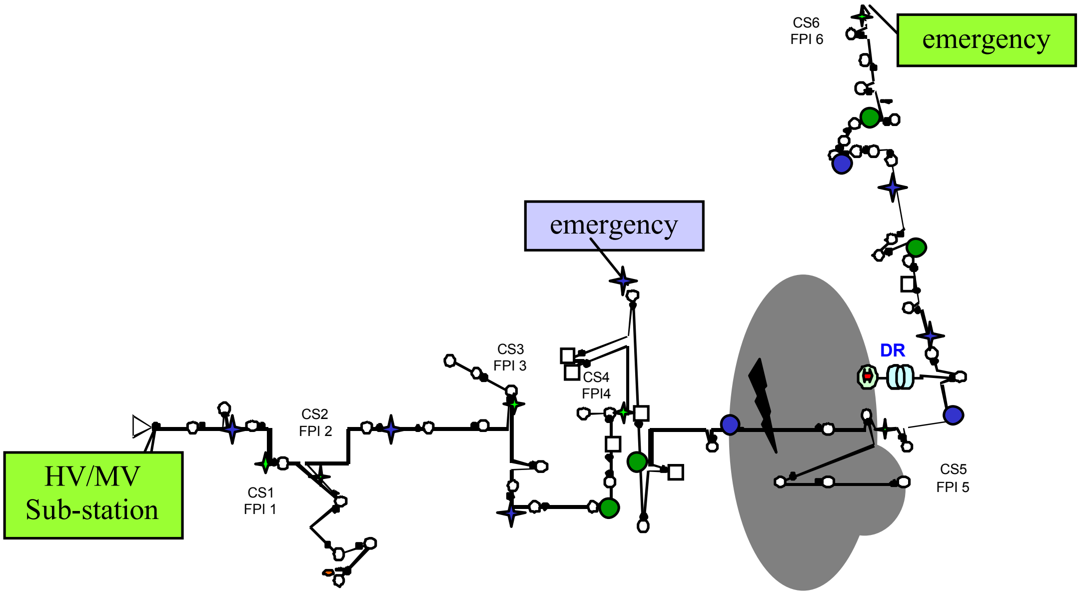


Figure 6-7 Fault localization principles step 4: elementary faulty area isolated manually

7. Computation methods for analysis and decision

Various computation methods have been applied to electric networks systems in order to improve the response time or the precision for data acquisition, calculation, and equipment control.

Some of these methods include mathematical approaches that allow the programs to boost the calculation convergence or to give correct results windows (taking into account accumulated knowledge and experiences).

Some of these mathematical approaches are:

- Probabilistic methods (point probability method, overall probability method)
- Genetic algorithms
- Neural networks
- Fuzzy logic

They may be used for planning design purpose (no high time constraints during simulation in general), or for real time operation purpose (high level of time constraint).

In the case of the localization process, it appears that different levels of analysis may be defined, enabling to share the evaluation (calculation) effort in a distributed way, enabling to limit drastically the information to collect or to send and so enabling to boost the information useful for the operator and the system.

For the fault localization purpose during operation of the EPS, direct and simple calculations are required. The main complexity analysis depends on the description of the network topology and all the technical data required, and on updating conveniently this topology in a real time. Specific kinds of algorithms need to be defined to manage the topology in a flexible manner, making easy the configuration changes in a future EPS.

Depending on the time process, the decision of the operator will be manual or automated. Nevertheless, for computation aspects, the strategy and axes of decision of the operator will be described in a same manner of the ICT components. If a future step consists in making automatic the decision of the operator, this description will be useful to define the requirements for the associated dedicated ICT component.

8. Equipment needed and location

As indicated in this document, a lot of equipment and systems already exist for dealing with faults. A practical way to improve the existing solutions and to adapt the system for the high DG penetration is to keep the modularity and the separation between the main functions in the system.

The place of the ICT components in the chain will vary in the future, depending on its abilities to integrate progressively the existing power system functions: sensors acquisition, conversion of signals to identified situations, managing warning and information signals… A goal of the CRISP project is to reach an evaluation of its ability to analyse data and to transmit securely and quickly the information.

At the moment four types of ICT components seem basically involved by the proposed fault location help tool: distributed interface with FPI, distributed interface with EPS controlled switches, interface to fault recorder inside a substation, centralized tool combining topology data and information from the interfaces. The associated ICT have different requirements because of the great difference on the information kept and transmitted.

The number of distributed interfaces depends on the number of controlled switches and FPI distributed in the network. In the future this number will depend at the same time on the cost of the elementary package (ICT component associated to a FPI or ICT component associated to a EPS switch) and on the local density of energy produced and consumed (the topology is generally more complex to deal with near high density consumption because of multiple derivations and emergency possible re-connections). Automation is expected to be more intensive in term of number of distributed interfaces near urban area than near rural area.

The requirement for the ICT components for the proposed application is under study inside the CRISP project. This application will be experimented with a real time simulation tool representing the electrical power system, the main goal being to evaluate the abilities of the dedicated ICT components developed in this project.

9. Information and communication technology

The ideal solution for fault localization may be a result of the help tool in less than 10s. It may allow the operator to integrate this localization in the fault protection sequence, avoiding a large amount of disconnection of local consumption and local production: the EPS switch may be controlled during a phase of slow disconnection of the feeder for instance.

Nevertheless a great improvement is possible today to boost the time between the permanent fault detection and the reduction of the power break to the elementary faulty area. A rough figure is nearly one or two hours, depending on the availability of detection equipment, of isolation equipment and field crew. Another possible improvement is to reduce the number of interruptions for customers during the investigation phase.

The current approach is to find a structured way to reduce as low as possible the investigation time with an ICT solution, with a realistic evaluation on the costs and on the accuracy of the results induced by the solutions. It means that the adequate requirements are needed in order to keep these three aspects as the main leading constraints: accuracy, time, and cost.

The approach in that purpose in the CRISP project should allows us to find and characterize the future weak points in the fault location help tools, the analysis and communication parts being expected to change drastically (speed increase and cost reduction) in the future.

Communication technology is already used in the system and different international protocols are defined for EPS substations. We keep our mind open to the current advances on information network platforms (keeping in mind the standard being developed) and try to reach an optimized application using information analysis abilities: as the production may be decentralized, a great part of calculation may be decentralized to keep the system as flexible as possible. This type of way means an integration of the electrical and information network in a common development strategy for a specific function.

10. Conclusion

The fault detection, fault clearing and fault localization are important functions of an EPS (transmission, sub-transmission or distribution). These functions may be improved by means of a better use of ICT components in the future. This improvement should become necessary in distribution EPS with a high introduction of DR, because of the possible multiple ways of supply. The transmission and sub-transmission protection systems are already installed in order to manage power flow in all directions, so the DR issue is less critical for this part of the power system in terms of fault clearing and diagnosis. The distribution power system faced to a permanent fault has to achieve two main actions: a system allowing the operator to identify the faulted elementary EPS area quickly and a system allowing the exploitation field crew to locate and repair the fault as soon as possible.
A solution proposed is to use a help tool to lead the two actions thanks to an accurate fault localization system.

The introduction of DR in distribution EPS involves some changes in fault location methods or equipment. The different existing neutral grounding systems make it difficult the achievement of a general method relevant for any distribution EPS. Solutions are studied in the CRISP project in order to improve the current state of fault diagnosis (investigation time and solution cost involved with a dedicated use of ICT) and make this power system function adequate with the future high DR situation expected.

The approach followed to improve the fault diagnosis inside the MV distribution involves new consideration and understanding about the control of MV cells. The document has described the concept of MV level one cell, which will be important for the future fault location tools. The improved flexibility and coordination between feeders will have links with the other expected functions needed to make the distribution EPS more autonomous or intelligent.