OPTIMISING THE INVESTMENTS ON DISTRIBUTION NETWORKS TO MEET THE RULES FOR CONTINUITY OF SUPPLY: A NOVEL PLANNING AND OPERATIONAL TOOL

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SUMMARY

The paper summarises the methodology and the results regarding the implementation of a tool dedicated to the definition of the optimal type and sequence of investments in the framework of the new rules for continuity of supply in distribution networks. After a brief description of the approach for the calculation of the continuity of supply indexes, the attention is focused on the estimation and the final tuning of the parameters adopted by the tool, and on the methodologies for the research of the optimal type and sequence of investments to improve the continuity of supply.

INTRODUCTION

In the past MV distribution networks have been planned mainly to meet consumption needs and the principal index adopted to assess the continuity of supply was the economical value associated with the Energy Not Supplied (ENS). The new regulation criteria for reliability, based on customer indexes, have extended the target of the MV distribution networks planning to a careful reliability analysis in order to optimally manage the increase of investments allocated by distribution companies for continuity of supply improvement. In this context it is fundamental for distribution companies developing methodologies and software tools to deeply analyse the global customer indexes of MV networks and their variation in correspondence of new interventions. Moreover, a method to automatically identify the optimal type and sequence of investments to reach the target customer indexes is required by the dimensions of the MV networks under analysis (thousands of MV busbars).

CONTINUITY OF SUPPLY ASSESSMENT

In electrical distribution systems, fault management is the principal way to reduce outage times. Technical and organisational solutions for fault management are different in dependence to the network structure and protection philosophy. The methodology proposed in this paper refers to MV networks realised with feeders in radial configuration from the HV/MV substation to the MV loads and to the MV/LV transformers. The protection scheme is typically composed by a single circuit breaker at the beginning of the MV feeder, while along the MV feeder can be installed two typologies of disconnectors:

• remotely controlled switching disconnectors (RCD) controlled by Distribution Control Centres (DCC)
• manually controlled switching disconnectors (MCD), manually tripped and reclosed by the maintenance staff

Even if each feeder is radially operated, MV networks have usually a meshed structure and the feeder-ends are generally connected with other feeders, or sometimes with busbars of the same feeder, by means of normally open emergency tie-switches (see Figure 2).

In order to analyse the different steps needed for the service restoration after a fault on a MV network, it can be useful to divide each feeder into zones and subzones:

• the zones are portions of the feeder bounded by two or more remotely controlled switching disconnectors
• the subzones are portions of the feeder bounded by two or more manual or remotely controlled switching disconnectors

Figure 1. Example of MV feeder subdivision in zones and subzones.

In case of permanent faults, several steps are needed to insulate the faulty feeder section and to re-energise the remaining sections. The principal steps implemented in the tool are:

• alert time $T_{a}$: it is the time necessary to distinguish between a temporary fault and a permanent fault. In this period of time some reclosing actions can be attempted by means of the circuit breaker at the head of MV feeder. All the customers connected to the feeder are not supplied during this time.
• research of the faulty zone time $T_{r}$: the control actions carried out by the DCC on the remotely controlled switching disconnectors allow the insulation of the faulty zone and the re-energization of the sound zones, by closing the circuit-breaker located at the head of the feeder or by closing the tie-switches in the feeder-ends. All the customers connected to the feeder are not supplied during this time. The duration of $T_{r}$ is proportional to the average number of control actions carried out by the DCC and to the time of a single control action ($T_{u}$).
• logistics time $T_{l}$: it is the period of time needed by the maintenance staff to reach the faulty zone. All the customers connected to the faulty zone (and to the downstream zones not provided with emergency tie-switches) are not supplied during this time.
• research of the faulty subzone time $T_{r,s}$: the research of the faulty subzone is carried out by the maintenance staff operating the manual switching disconnectors under the control of the DCC. The duration of $T_{r,s}$ is proportional to the average number of manual switching operations needed
and to the time of a single manual switching operation ($T_r$). At the end of the process, the service is restored in the sound upstream subzones and in the sound downstream subzones if provided with tie-switches.

- research and repairing of the faulty component: after the identification of the faulty subzone, the maintenance staff researches the faulty component inside the subzone ($T_{rr}$) and starts the repairing of the component ($T_{rp}$). These periods of time, not negligible in rural overhead MV networks, usually affect very few customers in metropolitan networks because each MV busbar is normally connected with a turn in - turn out scheme realised with manual switching disconnectors and every feeder-end is provided with emergency tie-switches.

Considering the above mentioned modelling of the restoration process and the components outage rates, all the local and global indexes for duration and number of interruptions can be calculated. The analysis can be performed examining the restoration time of every busbar for every possible position of the faulty component and weighting the restoration times with the correspondent outage probability. In the restoration time analysis attention has to be paid to the different typologies of emergency tie-switches, Figure 2 shows that, if the feeder-ends are connected with busbars of the same feeder, the fault in position A causes the outage of the downstream substations and the repairing of the component is needed to restore the service for the connected customers. If the fault is in position B the service restoration can be carried out without the repairing.

![Figure 2. Typologies of emergency tie-switches.](image)

Besides allowing a fast calculation of the continuity of supply indices, the described approach to the reliability calculation enables an on-line evaluation of the impact on the indexes due to the insertion of new remotely or manually controlled disconnectors and new emergency tie-switches on the feeder ends. In order to assist the reliability planning, the calculation of two further feeder indexes, named Feeder Structural Criticality Index (FSCI) and Feeder Average Interruption Duration Index (FAIDI), has been introduced in the tool. The Feeder Structural Criticality Index represents the average interruption duration suffered by the LV customers belonging to the feeder and caused by a permanent fault in the MV feeder. The FSCI for the $f^{th}$-feeder is given by:

$$FSCI_f = \frac{\sum (d_i \cdot C_{LV}^i)}{\sum C_{LV}^i}$$

(1)

where $d_i$ is the average annual interruption duration for LV customer belonging to the $i^{th}$-subzone in case of permanent interruption suffered by the feeder and $C_{LV}^i$ is the total number of LV customers supplied by the distribution company in the $i^{th}$-subzone of the feeder.

The Feeder Average Interruption Duration Index reflects the average annual interruption duration for LV customers belonging to the feeder caused by faults on the MV feeders. It can be calculated by means of the following equation:

$$FAIDI_f = FSCI_f \cdot N_f$$

(2)

where $N_f$ represents the yearly number of permanent interruptions of the feeder.

The extension of the FAIDI index to the MV network under examination represents the portion of the system average interruption duration index due to faults on MV feeders (MVSAIDI):

$$MVSAIDI= \frac{\sum FAIDI_f \cdot C_{LV}^f}{\sum C_{LV}^f}$$

(3)

The total duration of interruption index for LV customers can be obtained by adding to the MVSAIDI the duration of the interruptions due to outages on LV and HV systems and on HV/MV substations.

The FSCI represents the component of the average interruption duration due to the structure of the feeder and due to the presence, along the feeder, of manually or remote controlled disconnectors or emergency tie-switches. For this reason the FSCI is independent of the number and typology of faults. The adoption of this index, together with the FAIDI Index, allows the operator to quickly recognise the effectiveness of structural or maintenance interventions for each feeder. As a matter of fact, the value of $FSCI_f$ reflects the capability of the $f^{th}$-feeder to clear a permanent fault, while the value of $FAIDI_f$ reflects also the fault rate of the feeder. Consequently, feeders with an high value of FSCI need structural improvements while feeders with an high value of FAIDI and a low value of FSCI need timely maintenance interventions for reducing their outage rates.

![Figure 3. Representation of the feeders in the FAIDI-FSCI plane.](image)

In Figure 3 are presented the calculations of FAIDI and FSCI indexes carried out on 165 feeders of a MV cable metropolitan network (around 400,000 LV customers). The representation of the results on the FAIDI-FSCI plane allows the planner a preliminary identification of the most critical feeders and typologies of critical states.
TUNING OF THE PARAMETERS

Because of the difficulty in modelling the real system restoration process, a careful assessment of the different repair steps duration and an up-to-date definition of the fault rates for the components of the MV network is requested. For this reason two activities are necessary:

- the preliminary definition of the above mentioned parameters \( T_0, T_s, T_l, T_a, T_{rs} \) and \( T_{rp} \) on the basis of the distribution company experience;
- the final tuning of these parameters based on the results furnished by the tool and on the value of the well-known overall indexes for continuity of supply related to the previous years.

The average value of the parameters \( T_0, T_s, T_l, T_a, T_{rs} \) and \( T_{rp} \) depends on many aspects: kind of area (urban, suburban or country area), type of MV network (overhead lines or underground cables), protection and automation philosophy, position and number of the maintenance teams in the area, size of the area, etc. For this reason it is possible to estimate the value of \( T_0, T_s, T_l, T_a, T_{rs} \) but it is usually difficult to assign a very accurate value. On the contrary, the outage rates of the MV network components can be estimated on the basis of the values assumed in the previous years, which are normally well known by the distribution companies. Consequently, the final tuning of the parameters for an homogeneous portion of MV network can be carried out calculating, by means of the tool, the overall indexes for a few previous years and comparing them with the real overall indexes measured by the distribution company.

The tuning is essential to obtain a good estimation of the overall indexes for years to come and is consequently necessary to define the number and the typology of interventions to reach the target values for continuity of supply indexes fixed by the Regulator.

Typical values of the time parameters for a cable metropolitan network can be the following:

- the alert time \( T_0 \) can vary between 2 and 3 minutes but it is strictly correlated to the protection and automation philosophy
- the research of the faulty zone time depends on the time for a single control action \( T_a \) carried out by the DDC. \( T_a \) can be assumed about 2-3 minutes but can be reduced if an automatic control system for faulty zone research is installed
- the logistics time \( T_l \) is quite variable because the time needed by the maintenance staff to reach the faulty zone depends on a great number of factors. A reasonable value can be 20-30 minutes
- the research of the faulty subzone time depends on the time \( T_s \) needed for a single manual switching operation and \( T_s \) can be assumed 6-9 minutes
- the research of the faulty component in the subzone time \( T_{rs} \) can be usually assumed equal to 90-150 minutes for underground cable lines while \( T_{rp} \) for the repairing can vary between 12 and 36 hours. \( T_{rp} \) generally affects a low number of customers in metropolitan networks. However distribution companies can exploit, for feeders without emergency tie-switches, the installation of backup generators, the meshed structure of the LV network or the installation of temporary LV cables. Consequently a reasonable value for \( T_{rs} + T_{rp} \) could be 250 – 450 minutes.

The sensitivity analysis for the MVSAIDI variation with the parameters can be useful to clarify which are the most influential parameters and which are the results of the tuning actions.

![Figure 4. Variation of MVSAIDI with the time parameters \( T_0, T_s, T_l \) and with the cables outage rate (test network: metropolitan area, \( U_0 = 23 \text{kV}, 165 \text{feeders, 2760 MV busbars, no RCD installed})

![Figure 5. Variation of MVSAIDI with the time parameter \( T_{rs} + T_{rp} \) (test network: metropolitan area, \( U_0 = 23 \text{kV}, 165 \text{feeders, 2760 MV busbars, no RCD installed})

In Figure 4 and Figure 5 are reported the results of the sensitivity analysis carried out on the test network (with no RCDs installed) for \( T_0, T_l, T_s, (T_{rs} + T_{rp}) \) and for the underground cable outage rate \( R_{UC} \).

The influence of \( T_l \) and \( T_s \) on MVSAIDI index is very high, respectively 0,35 (min/year)/min and 1,2 (min/year)/min, because they represent the most significant components of the restoration time. On the contrary the influence of \( (T_{rs} + T_{rp}) \) is low because the network is almost meshed.

The sensitivity analysis can also be useful to perform a cost/benefit analysis of the actions for the parameters improvement. For example, if actions for cables outage rate reduction are carried out and the reduction is 1 fault/100 km/year, the reduction of MVSAIDI is 4,2 min/year. This information allows the distribution company to appraise the avoided penalties and to compare them with cost for \( R_{UC} \) reduction.

OPTIMIZATION OF THE INTERVENTIONS FOR CONTINUITY OF SUPPLY IMPROVEMENT

In an already meshed metropolitan network, one of the most effective ways for reducing the duration of the interruptions is the installation of RCDs.

Even if the tool allows the operator the graphical insertion of all the typologies of new investments and the on-line
evaluation of the correspondent improvement of the reliability indexes, the complexity of a real MV distribution network requires an automatic research of the optimal type and sequence of interventions. The planner can adopt exclusively his experience in case of very small grids or for particular feeders, but this approach for wide networks can lead to technically acceptable solutions that are not optimal from the economical point of view.

The methodology implemented in the tool for the definition of the optimal type and sequence of RCDs and MCDs installation is based on a two-steps heuristic approach. In the first step the optimisation of the interventions is performed on each feeder. The low time consumption of the reliability calculation methodology adopted allows to directly evaluate all the positions of one or more RCDs and MCDs.

The research of the optimal position and sequence of installation of RCDs is based on the minimisation of an economical index named Specific Cost for FAIDI Reduction (SCFR):

\[
SCFR(j,i) = \frac{c(j,i)}{\Delta FAIDI(j,i)}
\]

(4)

where \(c(j,i)\) is the total cost of the \(i\)-th intervention on the \(j\)-th feeder under examination and \(\Delta FAIDI\) is the correspondent FAIDI reduction.

For each feeder belonging to the area under examination it is possible to define the vector of the costs associated with each solution examined and the respective \(\Delta FAIDI\) vector:

\[
c(j) = [c(j,1), c(j,2), \ldots, c(j,M)]
\]

(5)

\[
\Delta FAIDI(j) = [\Delta FAIDI(j,1), \Delta FAIDI(j,2), \ldots, \Delta FAIDI(j,M)]
\]

(6)

where \(M\) is the number of solutions examined for the feeder. The SCFR vector can be directly calculated by applying (4):

\[
SCFR(j) = [SCFR(j,1), SCFR(j,2), \ldots, SCFR(j,M)]
\]

(7)

The best investment corresponds to the solution with the lowest SCFR:

\[
SCFR(j)_{\text{best}} = \min_{i=1,2} \{SCFR(j,i)\}
\]

(8)

In the second step the optimisation is extended to all the feeders of the system under examination with the aim of researching the optimal type and sequence of investments and reaching in the area the target value of interruption duration index fixed by the Regulator.

As in the MVSAIDI index calculation the FAIDI index of each feeder is weighted with the corresponding LV customers number (see equation 2), the research of the best combination of investments in the system can be based on the minimisation of the economical index Specific Cost for MVSAIDI Reduction (SCSR), defined as:

\[
SCSR(j,i) = \frac{c(j,i)}{\Delta MVSAIDI(j,i)} = \frac{c(j,i)}{\Delta FAIDI(j,i) \cdot C_{LV}}
\]

(9)

Since \(\Delta C_{LV}\) is a constant, SCSR is proportional to SCFR weighted with the feeder LV customers numbers \(C_{LV}^j\):

\[
SCSR(j,i) \propto \frac{c(j,i)}{\Delta FAIDI(j,i) \cdot C_{LV}^j} = \frac{SCFR(j,i)}{C_{LV}^j}
\]

(10)

The optimal intervention for each feeder \(SCFR(j)_{\text{best}}\) is calculated in the first step of the optimisation process (see equation 8) and consequently the optimal type and sequence of investments in the system can be identified by creating an investments list and by ordering the investments list according to the SCSR index in order to obtain \(SCSR_{\text{best}}\):

\[
SCSR_{\text{best}} = \min_{j \in \text{system}} \left\{ \frac{SCFR(j)_{\text{best}}}{C_{LV}^j} \right\}
\]

(11)

The above mentioned investments list is dynamically updated, because, when the best intervention is applied to the \(z\)-th feeder, it is necessary to calculate the new \(SCFR(z)_{\text{best}}\) and to introduce it in the investments list before choosing the next action.

**TEST CASE**

In Figure 6, Figure 7 and Figure 8 are shown the results regarding the application of the tool to a wide test network (metropolitan area, \(U_e = 23\) kV, 165 feeders, 2760 MV busbars, around 400.000 LV customers). The research of the optimal type and sequence of investments requires about 2-4 minutes, depending on the target value of FAIDI. The results of RCDs installation on the MVSAIDI index are shown in Figure 6. It is possible to recognize a saturation effect when the number of RCDs installed is higher than the number of feeders because the installation of the first RCD on the feeder is usually more efficient than the installation of the following RCDs.

![Figure 6. Results of RCDs optimised installation on MVSAIDI index (test network: metropolitan area, \(U_e = 23\) kV, 165 feeders, 2760 MV busbars)](image)

In Figure 7 the test feeders without RCDs are represented in the FAIDI-FSCI plane and the dimension of each circle is proportional to the feeder LV customers number. In Figure 8 the test feeders are represented after the installation of 185 RCDs (see Case A in Figure 6). The group of feeders named \(\alpha\) type feeders is not involved in the installation of RCDs because they have a low value of FAIDI and a low number of LV customers. The group of feeders named \(\beta\) type feeders is characterised by structural problems because the FSCI index is very high and the installation of RCDs is not much effective. For this reason the \(\beta\) type feeders need a detailed analysis to define the optimal intervention for the FAIDI improvement because in this case the structural problems are usually due to the absence of a meshed structure and the
absence of emergency tie-switches on some feeder-ends. Consequently new lines are requested to realize a completely meshed structure.

![Figure 7: Representation of the test feeders in the FAIDI-FSCI plane. The dimension of the circles is proportional to the feeder LV customers number. No RCD is installed.](image)

**CONCLUSIONS**

The new customer indexes for continuity of supply introduced by the Regulators oblige distribution companies in defining optimal strategies to manage the reliability of MV networks. A new tool dedicated to the continuity of supply evaluation and optimisation has been developed and tested on extended portions of MV metropolitan network pointing out the following aspects:

- the adoption of structural criticality indexes together with classical duration of interruption indexes for the feeders can be an useful instrument to identify critical feeders and timely interventions
- the tuning of the reliability parameters is one of the main problems to obtain reliable results
- the sensitivity analysis of the reliability parameters can be useful for the tuning activity and allows to perform a cost/benefits analysis of the parameters improvement
- the methodology adopted for the reliability assessment is low time consuming and allows to explore the high number of solutions needed by the euiric optimisation of the type and sequence of investments

**REFERENCES**


