ABSTRACT

This paper presents the method used by Enel Distribuzione to find the optimal location and number of automation devices in the MV network, taking into account technical and economical constraints. With this method, it is possible to optimize a single feeder or the entire distribution network with low computational effort. In order to avoid the exponential rise of the calculations due to the increase of the studied network, the optimization procedure uses a specific decomposition of the electrical network in elementary parts. This method has been used for one year by Enel planners and contributed to the effectiveness of automation of the entire MV distribution network.

INTRODUCTION

The Italian Regulator for electricity market (AEEG) asked the distribution companies to improve the quality of service, reducing the number and the time duration of interruptions. For this reason, Enel Distribuzione (ED) developed a Network Automation System (NAS) capable of automatically detecting and isolating faulty sections, thanks to automation devices (ADs) installed along the MV feeders. Moreover, ED started a program to ensure the propagation of the automation to the entire MV distribution network. In this context a software tool, described in [1], has been created to assist the planners and to permit the management of all the involved processes. The core of this software is a procedure, that establishes the optimal number and location of AD in the network.

The problem of finding the location and the number of AD in a radial distribution network is a combinatorial optimization problem, that takes into account various operational and equipment limits and requires high computational efforts. Some methods have been proposed to reduce the computational efforts and contemporaneously to maintain certain levels of accuracy [2-5]. Most of them are based on a general optimization method (simulated annealing [2], Bellmann’s optimality principle [3], immune algorithm [4], quantum evolution algorithm [5]). Enel method adopts an algorithm oriented to this specific application. In fact, it is based on a decomposition of the network in elementary parts and each part is determined analysing the route of every possible fault current. The purpose of this paper is to describe the adopted solution and to show some real applications.

NETWORK AUTOMATION SYSTEM

The Enel MV distribution network is made by feeders departing from different primary substations (HV/MV). The feeders have a meshed structure, but they are radially operated; open switches define the boundaries of each line, therefore each feeder has a single supply point. The MV nodes are secondary substations, pole switches, pole transformers or joints.

In order to lower the earth currents and, at the same time, to reduce the number and the average duration of outages, in a lot of primary substations the neutral conductors has been connected to the earth through a special impedance (Petersen coil plus resistor). NAS works in synergy with telecontrol and the grounding system; it is based on motorized switches, directional fault detectors and a group of automatons resident in the memory of the same RTU used for remote control.

The NAS philosophy (called FNC) works differently according to the type of the fault that is detected by the fault detectors:

− a short circuit is isolated after several trips of the circuit breaker;
− an earth fault is isolated without any tripping of the circuit breaker.

More information about the Enel telecontrol and automation system can be found in [6].

As far as the duration of interruption, the classical classification is adopted:

− long interruption, t > 180";
− short interruption, 1" < t ≤ 180";
− transient interruption, t ≤ 1".

The impact of automation in the reduction of the duration of the interruptions is significant. In case of a short circuit, the customers in the healthy sections located upstream the faulty are not affected by a long interruption. In case of earth fault, the customers in the healthy sections located upstream the faulty one are not affected by any interruption. In fact, in this last case, only the switch located immediately upstream the faulty section is opened if the earth fault persists for a programmed time.

Moreover, the followings has to be taken into account:

− thanks to the grounding system an earth fault can be maintained for several seconds (theoretically there is no need at all to open the feeder, but, for thermal
problems, the earth current into the grounding impedance doesn’t have to exceed 40°); 
− statistically only two lines belonging to the same MV bar can be affected by an earth fault at the same time; 
− on the average, a single switch completes its operation (opening or closing) in 4".
Because of these operational times, no more than 3 switches in series along a line can be automated.
In the next future faster switches will be available and consequently:
− the total number of ADs in series will be more than 3;
− even in the case of a short circuit, the customers in the healthy sections located upstream the faulty will not be affected by any interruption.

OPTIMAL ADs ALLOCATION

The scope of the automation is to increase the continuity of supply according to the request of the AEEG.
The purpose of the optimization problem is to find the positions and the number of the ADs in a radial network, considering an assigned search space.

Constraints and search space

The constraints are the following:
− a threshold in the continuity of service improvement (the automation gain must be more than a stated value);
− economical limit, due to the cost of installation activities;
− technical limit due to the number of ADs in series

Theoretically, the standard search space is made by all the points of the network that permit the introduction of ADs. However, the physical introduction of ADs could require the creation of a new node (pole switch or secondary substation); with high installation costs. In order to suggest a viable solutions, the following restrictions of the search space have been done:
− only the existing nodes are considered;
− there is an option to include/exclude some kind of nodes (include/exclude joint, substation, pole switch);
− there is an option to consider only the nodes already equipped with ADs (only a software reconfiguration is needed).
The standard starting point of the optimization process is the network without any ADs; however, it is also possible to start from an existing configuration of ADs (for example, made in a previous project).

Objective functions

The improvements of the continuity of service can be obtained limiting the number of the customers affected by a long interruption and reducing the average number of short interruptions for the customers.
Since in Italy the MV customers are regulated differently from the LV ones, a simple algorithm is applied, to convert each MV customer (with a specific contractual power) into an equivalent number of LV customers.
In this context it is possible to choose two different objective functions:
− reduction of the costs of the interruptions;
− maximize the global benefits of the automation.

Reduction of the costs of the interruptions

Without automation any fault causes a long interruption for all the customers in the feeder (the remote control actions are not fast enough).
With automation, the feeder is divided in some areas; each area has as boundaries two or more ADs. Thanks to the automation, the customers in the healthy areas upstream the faulty one are not affected by any interruption at all (earth fault) or not affected by short interruptions (short circuit).
For each area (Aᵢ) it is possible to calculate the reliability (number of the faults in one year) through the following formula:

\[ Gaᵢ = \sum_j l_j^{se} \cdot t_j^{se} + \sum_{z=1}^{m} \sum_{y=1}^{n} \sum_{x=1}^{p} \]  

where \( l_j^{se} \) is the length of the branch \( j \) in the area \( Aᵢ \), \( t_j^{se} \) is the fault rate (number of faults in one year per km) of the branch \( j \) and \( t_z^{cy} \) is the fault rate (number of faults in one year for the type \( y \) component) of the network component \( z \) in the area \( Aᵢ \).

For a feeder with \( m \) areas and \( cl^{eq} \) customers, it is possible to evaluate the number of customers that suffer a long interruption in a year through the following formula:

\[ n_a^{c0} = \sum_{i=0}^{m} cl^{eq} \cdot Gaᵢ \]  

where \( cl^{eq} \) is the number of the customers (LV and “LV equivalents”) that suffer a long interruption in case of a fault in the area \( Aᵢ \).

With reference to the short interruptions, in case of short circuit, a long interruption is transformed in some short interruptions (their number depend on the position of the faulty area in the feeder) for the customers in the healthy areas upstream the faulty area; the following formula has been adopted:

\[ n_a^{c0} = \sum_{i=0}^{m} p_i \left( cl^{eq} - cl^{eq} \right) Gaᵢ \]  

where \( p_i \) is the number of the short interruptions in case of a fault in the area \( Aᵢ \).
The benefit for the distributor (reduction of the costs of the interruptions) due to automation is calculated through the following formula:
\[ B = \left(n_0^l - n_0^u\right) \left(T \cdot c^u + c^w\right) - n_u^w \cdot c^w \]  

(4)

where \( n_0^l \) is the number of customer that suffer a long interruption in a year without automation, \( T \) is the average duration of a long interruption in the feeder, \( c^h \) is the cost per time unit of the long interruption, \( c^w \) is the fixed unitary cost connected to the number of interruptions (short or long).

**Maximize the Global benefit of the automation**

The global benefit of the automation take into account the costs \( C \) of the activities needed to realize and activate the system:

\[ G = B - C \]  

(5)

The objective is to maximize this value.

**Optimization algorithm**

In order to find the optimal locations and number of automation devices to be placed in the MV network, the following procedure is applied for each feeder:

- calculation of the routes of fault currents (RC);
- calculation of the primary routes (PR);
- optimization of AD placement in each PR;
- calculation of the optimal configuration.

**Calculation of the routes of fault currents**

For every possible location of the fault, the route of fault current (RC) is calculated. All the components of the network (branches, busbars, etc.) are possible locations, however the faults due to customers (MV customers or MV/LV transformers) are considered as busbar faults into the feeding Enel substation. Both kinds of fault are considered: earth faults and short circuits.

**Calculation of the primary routes**

All the RCs, that are not entirely included in others, are defined primary routes (PR). In the Figure 1 all the PRs are showed for a simple feeder.

**Optimization of AD placement in each PR**

A PR includes some network elements; practically, it is like a straight linear feeder that starts in the primary substation (or in other supply point) and ends in one boundary point of the MV line. Each PR has the same number of customers of the original feeder (Figure 2).

A full search (all the possible configuration are tested) is performed to find the best placement of ADs in each PR.

**Calculation of the optimal configuration**

The ADs placed in each PR are inserted also in all the other PRs that contain the relevant locations; in fact a PR can share some part of the network with the other ones. Since in any PR the number of ADs can overcome the technical upper limit, a trade off procedure is used to solve this controversy. The complexity of this algorithm grows linearly with the number of the ADs contained in each PR. This feature guarantees a viable computational effort.

**APPLICATIONS**

As an example, the procedure is applied to the feeder Saliceto, located in Piemonte. The total number of system nodes is 114. The total length (sum of the length of all the branches) is 57.4 km (32.8 km of aerial, 22.1 km of overhead cable and 2.5 km of aerial cable). The only supply point is a primary substation named Ceva. In the Figure 3 the network with the ADs placement is showed, highlighting the position of the customers (only the nodes that contains customers has been labelled).

In this example the costs related to the number of interruptions is not taken into account \( \left( c^w = 0 \right) \).

<table>
<thead>
<tr>
<th>Table I: Results for the feeder Saliceto</th>
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<tbody>
<tr>
<td><strong>Obj. Fun.</strong></td>
</tr>
<tr>
<td>Costs Reduction</td>
</tr>
<tr>
<td>Global Benefit</td>
</tr>
<tr>
<td>Only exist. ADs</td>
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</tbody>
</table>

In case of objective function \( \text{Reduction of costs of interruption} \) many ADs have been placed, the reduction of impact on long interruption was very high, but the installation costs are not viable. The reduction remains relevant also choosing as objective function the \( \text{Global benefits} \), but in this case the costs are lower, because the algorithm found a very good trade off.
If only the existing ADs in the field are considered the installation costs are zero and there is not difference between the application of the two objective functions.

Table II contains another example regarding the MV feeder Dolianova, located in Sardinia. The total number of system nodes is 170. The total length (sum of the length of all the branches) is 83.2 km (61.7 km of aerial and 21.5 km of overhead cable). The supply point is the primary substation named Sestu.

In the feeder Dolianova the situation without automation is critical ($n_{\text{li}} = 74575$), because the feeder is long and the customers are very dispersed; moreover some line sections are very old, but the algorithm found a good trade off.

Table II: Results for the feeder Dolianova

<table>
<thead>
<tr>
<th></th>
<th>$n_{\text{li}}^0$</th>
<th>$n_{\text{li}}^0 / n_{\text{li}}^0$</th>
<th>$C$ [k€]</th>
<th>$N^* \text{ AD}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs Reduction</td>
<td>11475</td>
<td>0.1539</td>
<td>227.4</td>
<td>51</td>
</tr>
<tr>
<td>Global Benefit</td>
<td>16903</td>
<td>0.2267</td>
<td>9</td>
<td>16</td>
</tr>
<tr>
<td>Only exist. ADs</td>
<td>35735</td>
<td>0.4997</td>
<td>0</td>
<td>6</td>
</tr>
</tbody>
</table>

To obtain the same result by means of network restructuring or modernization, higher costs would be necessary. In this case, the reconfiguration of the existing automation is not able to provide enough advantages.

**CONCLUSIONS AND FUTURE WORKS**

The validity of this method has been demonstrated by more than one year of practical application. In all the network studied so far, the software implementing the algorithm runs very fast (less of 50" with Pentium IV processor 2.4GHz) and provides very good solutions.

In the future meshed and active networks will be tested, according to the evolutions of the network into smart grids.

**REFERENCES**


