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TOOLS FOR OPTIMAL OPERATION AND PLANNING OF URBAN DISTRIBUTION SYSTEMS

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SUMMARY

This paper reports on the results of the implementation of a set of software tools for the comprehensive analysis and optimisation of distribution systems, developed jointly by Azienda Energetica Metropolitana (AEM) Torino S.p.A. and Dipartimento di Ingegneria Elettrica Industriale - Politecnico di Torino. The software tools cover several aspects of distribution system analysis, fault current calculation, reliability assessment, total operating cost evaluation, optimal reconfiguration, optimal planning and service restoration (Table 1). The tools have been applied to study the present AEM-Torino distribution systems: 27 kV network (240 nodes), 22 kV network (518 nodes) and part (943 nodes, about 35%) of the 6.3 kV network.

RELIABILITY ASSESSMENT

The system reliability is represented by a set of *local* indices, including frequency and duration of the interruptions, power and energy not supplied to every load point, and average duration of the interruption, and of *global indices*, including the classical *SAIDI*, *SAIFI* and *CAIDI* and two further indices, the Total Power Not Supplied and the Total Energy Not Supplied. Results are presented to show the global indices for different fault types and the distribution of the interruption frequency and duration for the Low Voltage customers.

OPTIMAL RECONFIGURATION

The *optimal reconfiguration* tool determines the state of the switches to reach an optimal configuration with a given objective function (Table 1), by maintaining the radial structure and by verifying a set of constraints (minimum and maximum node voltage, maximum earth-fault current, maximum three-phase short-circuit current, maximum current for each branch, maximum

number of switching operations to reach the final configuration from the initial one, and independence of supplies for customers with a second delivery point). The optimal choice of the supplied terminal of the open branches, which impacts on all the reliability indices and on the earth-fault current, is also incorporated. Results of the loss minimisation by using the iterative improvement and simulated annealing-based methods are presented. The *SAIDI* and *SAIFI* indices at the near-optimal configuration are reported to show that the loss reduction is not in conflict with the service continuity.

OPTIMAL PLANNING

The *Distribution system planning* program deals with a set of interventions (installation of remote-controlled switches, construction of new lines, removal of existing lines, substitution of lines) that could be carried out to improve the system performances, both from the economical and reliability point of view. The program automatically selects the most convenient actions in order to minimise the sum of the annual operating and investment costs, keeping into account the same constraints described for the optimal reconfiguration. Results showing the impact of the installation of remote-controlled switches on the reliability indices and the choice of the number of switches to be installed on the basis of economical considerations are presented.

SERVICE RESTORATION

The *Service restoration* tool determines the network configuration after a branch (line or transformer) outage in order to minimise the violations of the operating constraints. Two strategies have been defined, respectively operating at *constant load* and at *variable loads*, both implemented with iterative improvement and simulated annealing-based algorithms.

TABLE 1 – Overview of the tools implemented

<i>Analysis</i>	<i>Electrical and reliability calculations</i>	<i>Optimal reconfiguration</i>	<i>Optimal planning</i>	<i>Service restoration</i>
<i>Objective function</i>	---	Min total losses, Min operating cost, Optimal reliability indices, Min earth-fault current.	Min total cost.	Min weighted sum of the limit violations.
<i>Method*</i>	---	IT, SA and GA	IT, SA and GA	IT and SA
<i>Results</i>	Power flow, reliability indices, fault currents.	Optimal network configuration, losses, cost, reliability indices, states of the terminals of the open lines.	Optimal network configuration, total cost, reliability indices.	Operations for the service restoration with fixed or variable loads.

*Methods: IT (iterative improvement), SA (simulated annealing), GA (genetic algorithms).

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ABSTRACT

This paper reports on the results of the implementation of a set of software tools for the comprehensive analysis and optimisation of distribution systems, developed jointly by Azienda Energetica Metropolitana (AEM) Torino S.p.A. and Dipartimento di Ingegneria Elettrica Industriale - Politecnico di Torino. The software tools cover several aspects of distribution system analysis, fault current calculation, reliability assessment, total operating cost evaluation, optimal reconfiguration, optimal planning and service restoration.

1. INTRODUCTION

A set of software tools have been developed to assist the distribution system restructuring at AEM-Torino. The present distribution system consists of three voltage levels (27, 22 and 6.3 kV), that will be standardised to a unique voltage level (22 kV). Meanwhile, the present AEM distribution network will be merged with the one of the ENEL distribution company, according to the rules stated by the Italian Government for the electricity market restructuring.

The software tools developed, summarised in Table 1, are used for the analysis of the present urban distribution system in Torino and for planning the future distribution system.

Results of the application of the tools to various aspects of reliability analysis, optimal operation and optimal planning of the distribution system are presented for three large urban MV distribution systems, respectively called *System A*, *System B* and *System C*, whose data are shown in the Appendix.

2. RELIABILITY ANALYSIS

After the recent restructuring of the Italian electricity market, the reliability evaluation of the MV distribution networks is becoming even more relevant. According to the rules recently issued by the Italian Authority, the electricity distribution companies must guarantee minimum standards of service continuity, otherwise they must refund their customers.

The reliability analysis [1-4] has been implemented by assuming a negligible probability of occurrence of simultaneous faults. Three types of faults have been considered:

1. faults at the supply nodes, with a unique repair stage;
2. temporary faults in the distribution system, with trip of the circuit breaker, successful re-closure and final normal operation, with a unique repair stage;
3. permanent faults, requiring three different repair stages after the trip of the circuit breaker:
 - 3a) remote-controlled operations, driven from the control centre, to isolate the fault and restore the operation in the non-faulted part of the system;
 - 3b) additional manual operations, performed by the maintenance operators to isolate the fault and restore the operation in the non-faulted part of the system;
 - 3c) on-site fault repair and final service restoration.

The normal operation and each repair stage are assumed as states of the system to set up a Markov process describing the system restoration after a fault [5].

The system reliability is evaluated by using a set of *local* and *global* indices.

TABLE 1 – Overview of the tools implemented

<i>Analysis</i>	<i>Electrical and reliability calculations</i>	<i>Optimal reconfiguration</i>	<i>Optimal planning</i>	<i>Service restoration</i>
<i>Objective function</i>	---	<ul style="list-style-type: none"> • Min total losses, • Min operating cost, • Optimal reliability indices • Min earth-fault current 	<ul style="list-style-type: none"> • Min total cost 	<ul style="list-style-type: none"> • Min weighted sum of the limit violations
<i>Method*</i>	---	<ul style="list-style-type: none"> • IT • SA • GA 	<ul style="list-style-type: none"> • IT • SA • GA 	<ul style="list-style-type: none"> • IT • SA
<i>Results</i>	<ul style="list-style-type: none"> • Power flow • Reliability indices • Fault currents 	<ul style="list-style-type: none"> • Optimal network configuration • Losses, cost, reliability indices • States (closed/open) of the terminals of the open lines 	<ul style="list-style-type: none"> • Optimal network configuration • Total cost, reliability indices 	<ul style="list-style-type: none"> • Operations for the service restoration with fixed or variable loads

*Methods: IT (iterative improvement), SA (simulated annealing), GA (genetic algorithms).

The *local indices* of the load point n are computed by considering the frequency and duration of the states in which the load point n is not supplied. Assuming the power P_n to be delivered at the load point $n = 1, \dots, N$ during the normal operation, the following *local indices* are defined:

- f_n frequency of the interruptions;
- d_n duration of the interruption (equal to the probability of interruption);
- $P_n^{NS} = f_n P_n$ power not supplied;
- $E_n^{NS} = d_n P_n$ energy not supplied;
- $d_n^{AV} = d_n / f_n$ average duration of the interruptions.

The *global indices* represent the overall reliability of the system. The three most common global indices are:

1. System Average Interruption Frequency Index:

$$SAIFI = \frac{1}{N} \sum_{n=1}^N f_n \quad (1)$$

2. System Average Interruption Duration Index:

$$SAIDI = \frac{1}{N} \sum_{n=1}^N d_n \quad (2)$$

3. Customer Average Interruption Duration Index, representing the average duration of an interruption:

$$CAIDI = \frac{SAIDI}{SAIFI} \quad (3)$$

Two further indices have been defined in order to compute the total operating cost (Section 4.2):

4. Total Power Not Supplied:

$$PNS = \sum_{n=1}^N P_n^{NS} = \sum_{n=1}^N f_n P_n \quad (4)$$

5. Total Energy Not Supplied:

$$ENS = \sum_{n=1}^N E_n^{NS} = \sum_{n=1}^N d_n P_n \quad (5)$$

The reliability indices are used to quantify the cost of the interruptions according to the rules of the Italian Authority. Comprehensive testing has been carried out on MV and LV customers of the various distribution systems. Some results of the reliability analysis are presented in Table 2 and Table 3 by distinguishing the types of faults for the LV customers belonging to *System B* and *System C*.

For the supply point faults, the *SAIFI* and *SAIDI* indices for *System C*, in which the effects of the faults in *System A* (which supplies the *System C*) are included, are higher than the ones for *System B*, where only the faults of the HV/MV transformation are considered. The temporary faults contribute significantly to the *SAIFI* (31% for *System B* and 16% for *System C*), while their impact on the *SAIDI* is negligible due to the low repair time. The contribution to the *SAIFI* of the permanent faults is almost the same in the two systems (0.32 vs. 0.39 interr/year), the higher line length of *System B* being compensated by a lower fault rate per unit length. The contribution to *SAIDI* is quite different (6.9 vs. 27.1 min/year) because of the higher level of automation (remote-controlled substations) of *System B*.

The distributions of frequency and duration of the interruptions are shown in Fig.1 and Fig.2, where the results for the LV customers of *System B* and *System C* are compared. The interruption frequency and duration for *System B* are particularly low.

TABLE 2 – Global indices for LV customers of System B

Fault type	SAIFI [interr/year]	SAIDI [min/year]	CAIDI [min/interr]
Supply point	0.36 (37%)	1.96 (20%)	5.4
Temporary	0.31 (31%)	0.92 (9%)	3.0
Permanent	0.32 (32%)	6.90 (71%)	21.9
TOTAL	0.98 (100%)	9.78 (100%)	9.9

TABLE 3 – Global indices for LV customers of System C

Fault type	SAIFI [interr/year]	SAIDI [min/year]	CAIDI [min/interr]
Supply point	0.90 (59%)	4.09 (13%)	4.6
Temporary	0.24 (16%)	0.73 (2%)	3.0
Permanent	0.39 (25%)	27.06 (85%)	69.3
TOTAL	1.53 (100%)	31.90 (100%)	20.8

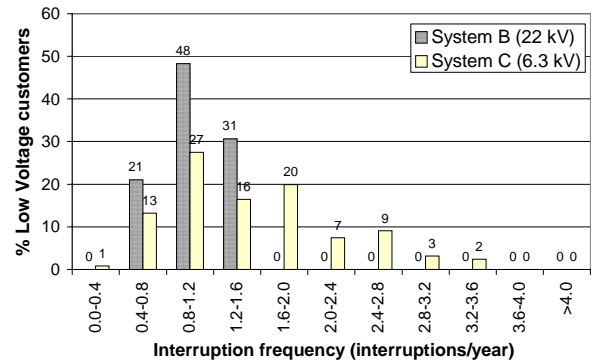


Fig.1 – Distribution of the interruption frequency for the LV customers of *System B* and *System C*.

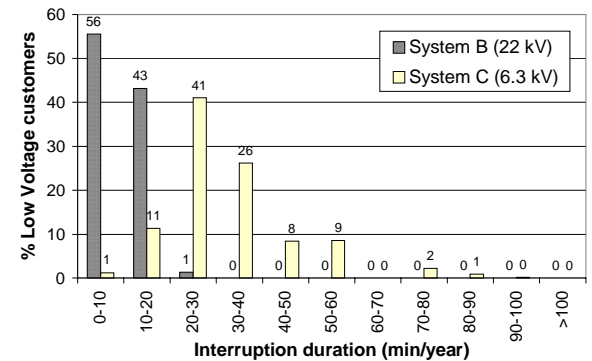


Fig.2 – Distribution of the interruption duration for the LV customers of *System B* and *System C*.

3. OPTIMAL RECONFIGURATION

3.1. Objective function and constraints

The MV urban distribution networks of the AEM are supplied by multiple HV/MV substations and MV/MV substations and have a meshed structure with radial

operation. Most of the lines are underground cables. Part of the substations are remote-controlled, and some of them can have complex busbar schemes. Different radial operating configurations may be created by opening and closing the switches at the terminal of each branch. The *optimal reconfiguration* tool determines the state of the switches to reach an optimal configuration for a given objective function, by maintaining the radial structure and by verifying a set of constraints. Typical objective functions are total losses, reliability indices (interruption frequency and/or duration), and total operating cost taking the cost of losses and the cost of interruptions into account (Section 4.2). The operating and structural constraints considered are:

- maximum branch current;
- minimum and maximum node voltage;
- maximum three-phase short-circuit current;
- maximum earth-fault current;
- maximum number of switching operations required to reach the final configuration from the initial one;
- independence of supplies for customer with a second delivery point.

For the open branches, which are supplied at one side for diagnosis purposes, the choice of the supplied terminal impacts on all the reliability indices and on the earth-fault current. The optimal choice of the supplied terminal of the open branches is incorporated in the optimal reconfiguration.

3.2. Algorithms

The distribution system optimal reconfiguration leads to a combinatorial problem, solved by heuristic techniques using both a deterministic approach (iterative improvement, IT) and modern stochastic algorithms (based on the simulated annealing, SA [6-7]). Different versions of deterministic and stochastic algorithms [8-12], both based on the branch-exchange mechanism [13] which includes the choice of the supplied terminal of the open branches, have been implemented and tested.

In the IT method, a new radial configuration is accepted only if the objective function is improved and if all the constraints are satisfied. The limitation in the number of switching operations required to reach the final configuration from the initial one is obtained by using a minimum threshold for the improvement of the objective function.

In the SA-based method, a penalty factor is introduced for each constraint, including the number of switching operations to reach the final configuration from the initial one, thus defining a penalised objective function.

3.3. Example of optimal reconfiguration of System A

A comparison between the results obtained by using the IT and the SA-based methods is shown in Fig.3. The number of switching operations to be performed to reach the optimal configuration starting from the initial one is imposed as a constraint. The best results in terms of the reduction in the total losses have been obtained by running the SA-based algorithm several times, with a

time-consuming process, because extensive testing has shown that a single run or a few runs of the algorithm cannot guarantee a satisfactory result.

The *SAIDI* and *SAIFI* reliability indices corresponding to the solutions obtained with the IT method are shown in Fig.4. These indices, not included in the objective function, exhibit a small variation in all the cases tested. Hence, the loss reduction objective is not in conflict with the service continuity.

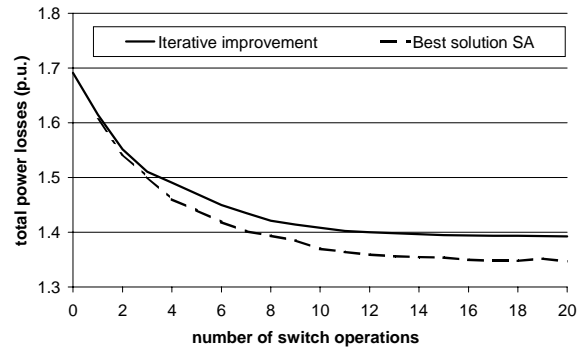


Fig.3 - Minimum power losses computed with the IT and the SA-based algorithms.

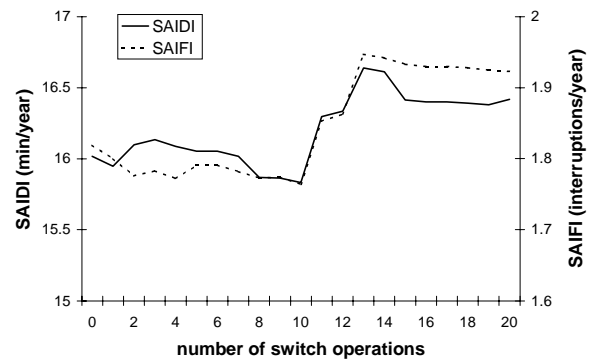


Fig.4 - Reliability indicators for the solutions of the minimum losses reconfiguration with the IT method.

4. OPTIMAL PLANNING

4.1. Planning actions and objective functions

The *Distribution system planning* program deals with a set of interventions that could be carried out to improve the system performances, both from the economical and the reliability point of view [14-15]. Some types of planning actions have been specifically chosen for the AEM planning needs, including installation of remote-controlled switches (RCS's), construction of new lines, removal of existing lines and substitution of lines. The program automatically selects the best actions to minimise the sum of the operating cost (losses, interruptions, fault repair) and investment costs over a year, with the same constraints described for the optimal reconfiguration. For planning actions which modify the operating radial configuration (e.g., installation of new lines and removal of existing lines), a simple reconfiguration algorithm has been implemented, since the full optimal reconfiguration of Section 3 requires an excessive computational burden.

4.2. Total annual cost

For the computation of the total annual cost, the following components are considered:

- cost of losses: $C_{LOSS} = \chi^{EN} E^{LY}$
- costs of reliability: $C_{REL} = \chi^{ENS} E^{NS} + \chi^{PNS} P^{NS}$
- costs of fault repair: $C_{REP} = \lambda^{PERM} \chi^{REP}$
- investment costs: $C_{INV} = \frac{C_{INV}^{TOT}}{\sum_{k=1}^{K_y} \frac{1}{(1+\tau)^k}}$ (5)

where:

E^{LY} is the energy lost in one year, χ^{EN} is the cost of energy, χ^{PNS} and χ^{ENS} are the costs of the power and energy not supplied, χ^{REP} is the cost of the fault repair, λ^{PERM} is the total fault rate for permanent faults, C_{INV}^{TOT} is the total investment cost, K_y is the number of periods in one year of investment and τ is the rate of interest. For the purpose of the cost minimisation, it is sufficient to include in the objective function the variations of the costs with respect to the ones occurring in the reference configuration.

4.3. Algorithms

The approaches used for the optimal distribution system planning are both deterministic (iterative improvement) and stochastic (genetic algorithms and simulated annealing), with several dedicated methods. The constraints are included in the penalised objective function. In the methods of the stochastic approach, it is possible to add a constraint on the limitation of the investment cost. With the iterative improvement algorithm, it is only possible to limit the number of interventions by using the acceptance threshold in the same way as indicated for the optimal reconfiguration.

4.4. Examples

Two examples related to the installation of remote-controlled switches RCS's in the AEM 6.3-kV network (the *System C* in the Appendix) are presented in the sequel.

4.4.1. Impact of the installation of RCS's on the reliability indices. The installation of RCS's is an effective way for reducing the duration of the interruptions to satisfy the requirements of the Authority. The number of RCS's installed in *System C* may be largely increased for improving the level of automation. In Fig.4, the *SAIDI* and *CAIDI* reliability indices are plotted vs. the number of additional substations equipped with RCS's. The computations have been carried out with the iterative improvement technique. The results clearly indicate that the improvement of the reliability indices is mainly obtained by adding a few RCS's, while it becomes less significant when adding the successive RCS's. The program allows the user to identify the most convenient locations for the installation of the additional RCS's.

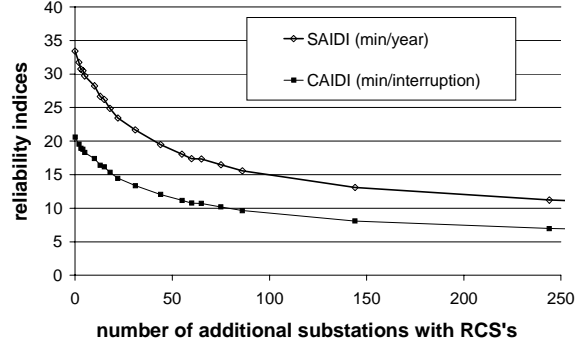


Fig.4 – Effects of the installation of RCS's on the *SAIDI* and *CAIDI* reliability indices.

4.4.2. Cost evaluation for improving the distribution automation. The choice of the number of RCS's to be installed in the network clearly depends on economic considerations. Fig.5 shows the variation of the investment costs for the RCS's acquisition (by assuming 2.6 kEuro/year for each substation), of the costs due to the Energy Not Supplied (by using $\chi^{ENS} = 7.75$ Euro/kWh) and of the total costs, which exhibit an almost flat curve in the range from 35 to 60 remote-controlled substations.

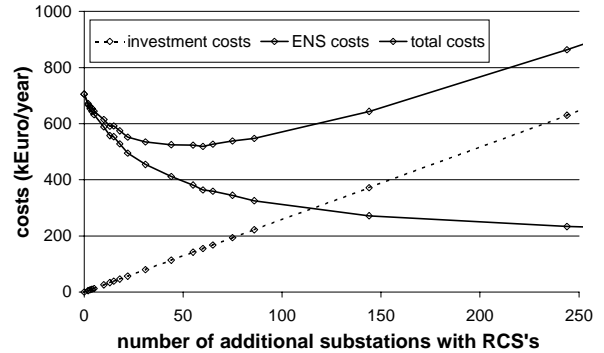


Fig.5 – Additional costs for the installation of new RCS's.

5. SERVICE RESTORATION

The *Service restoration* tool determines the network configuration after a branch (line or transformer) outage in order to minimise violations of the operating constraints. Two strategies have been defined to endeavour the best configuration. The first strategy operates at *constant load*, by choosing the radial configuration in such a way to restore the service for all the loads, using as objective function the sum of the square deviations of the constraint violations. The second strategy operates at *variable loads*, by restoring the service for part of the loads not supplied after the outage. In this case, the weighted contribution of the part of the loads not supplied after the service restoration is added in the objective function to the sum of the square deviations of the constraint violations. Both deterministic (iterative improvement) and stochastic (simulated annealing) algorithms are used.

CONCLUSIONS

Some examples of application of a dedicated program including a set of tools for the distribution system analysis and planning have been presented.

Further work is in progress in order to:

- implement composite planning interventions, such as the creation of a new substation between two existing nodes by partially using the existing lines;
- include the reliability indices as constraints rather than as objective functions, in order to compute solutions which do not exceed the reliability requirements fixed by the Authority;
- extend the possibilities offered by the tools to the management of various aspects of concern in merging two large urban distribution networks.

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APPENDIX

Distribution systems characteristics

The main characteristics of the AEM distribution networks used in this paper are summarised in Table A1 (27 kV network), Table A2 (22 kV network) and Table A3 (a portion of the total the 6.3 kV network corresponding to around 35% of the total number of nodes). The layout of the 22 kV network is shown in Fig.A1.

TABLE A1 - 27 kV distribution network (System A)

Number of supply points	7
Number of load points	94
Number of nodes	240
Number of branches	360
Total length of the lines	255 km
Total power supplied	370 MW

TABLE A2 - 22 kV distribution network (System B)

Number of supply points	3
Number of load points	450
Number of nodes	518
Number of branches	537
Total length of the lines	207 km
Total power supplied	136 MW

TABLE A3 - 6.3 kV distribution network (System C)

Number of supply points	14
Number of load points	657
Number of nodes	943
Number of branches	1115
Total length of the lines	330 km
Total power supplied	172 MW

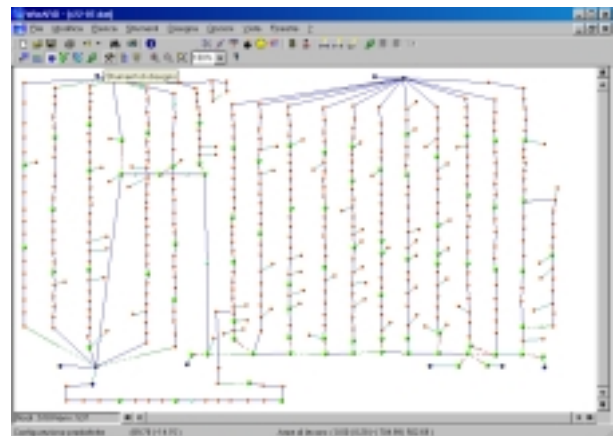


Fig. A1 - One-line representation of the 22 kV AEM distribution network (System B).