DISTRIBUTION SYSTEM RELIABILITY ASSESSMENT CONSIDERING EQUIPMENT AGEING

E. Ghiani, S. Mocci, F. Pilo
Department of Electrical and Electronic Engineering - University of Cagliari - Italy
emilio.ghiani@diee.unica.it

ABSTRACT

In the current distribution system most of existing electrical infrastructure is becoming aged due to the delayed replacement of assets caused by distribution company's budget constraints. Bearing in mind these aspects, the authors have developed a technique for the evaluation of the distribution system reliability based on a Sequential Monte Carlo (SMC) which takes into account the role of equipment ageing. Real-world examples are provided to illustrate the effect of including ageing system failures into system and individual reliability indexes.

INTRODUCTION

In the current distribution system most of existing electrical infrastructure is becoming aged due to the delayed replacement of older components, increased equipment loading and scarce maintenance. In fact, with the liberalization of the electric sector, distribution companies are even more oriented to profit maximization and the reduction of maintenance and refurbishment costs may be a way to raise profits in the short term. The current strategy for distribution networks feeder renewal is based on the statement *use the equipment until it fails* according to the concept of corrective maintenance, whereas predictive maintenance is limited only to protective relays and switchgears, substation automation equipment, and distributed generation. Only recently some distributors adopt the predictive maintenance based on aerial thermography for detecting anomalies in the system and enabling repairs to be initiated before failures occur (e.g. an insulator partially damaged is next to fail and need to be replaced).

On the other side, in many industrialised countries regulators have imposed to distributors severe standards on reliability indexes, and adopted regulatory actions based on incentives and penalties to promote the reliability improvement. For example, in Italy, the Italian Regulator (AEEG), with both the goals of improving the continuity of supply levels and smoothing regional differences, promulgated mandatory national standards on the continuity and quality of supply. The parameters used to measure the quality of the distribution service is the Customer Minute Loss (CML) or SAIDI, a standard measure of network reliability that represents the average number of supply minutes lost per LV customer and the number of non scheduled interruptions for MV customers (SAIFI). CML varies geographically as a function of customer density. Three density levels have been identified: urban areas (more than 50,000 customers), suburban areas (between 5000 and 50,000 customers) and rural areas (less than 5000 customers [1]. For the period 2004-2007 the SAIDI reference standards has been respectively set at 25, 40 and 60 min [2]. In order to respect the AEEG directives distribution planners have undertaken several actions to improve the reliability of the system like the installation of network automation equipment in the MV/LV substations and the installation of Petersen's coils. Anyway, these actions are only temporary solutions because the replacement of aged equipment seems to be, in the long term, unavoidable because many distribution system components are quickly approaching to the end of their lifetime. TSO and DSO planners and engineers are starting to be concerned about such an incoming situation because ageing faults have the potentialities to reduce drastically the positive effects of the investments made. For these reasons, the traditional reliability assessment techniques need to be revised to take into account ageing failures in order to avoid the underestimation of system risk that leads to incorrect conclusions in system planning. Consequently, novel methods and tools to evaluate the reliability of distribution systems are necessary to plan economic sound investments and to find the optimal priorization of the reliability-oriented actions.

Bearing in mind such aspects, the authors have developed a technique for the evaluation of the reliability in distribution networks based on the Sequential Monte Carlo (SMC) algorithm. The SMC allows simulating the reliability of a network during a given year by considering the sequence of events caused by a network fault. The reliability of lines is considered as well as the reliability of Automatic Switching Sectionalizing Devices (ASSDs) and the availability of Distributed Generation (DG) in both on-line and stand-by applications.

The provided real-world examples illustrate the role of ageing in reliability evaluation and its impact in the position of ASSDs. Furthermore, the intentional islanding is also analysed as a countermeasure against the possible rise of sustained interruptions caused by the effect of ageing.

AGEING MODELIZATION

One of the main steps in reliability assessments is the modelization of the failure behaviour of the components that compose the system under study. The failures in distribution systems depend on a number of different parameters such electrical and mechanical stress, weather conditions and geographical location. In the paper, the attention of the Authors is devoted to the modelization of

the behaviour of the network components due to ageing. Generally, many of the elements of the networks (e.g. lines, transformers, switchgears, isolators, etc.) have been in service for more than 30-40 years and they begin to exhibit non-constant failure rates that are typical of ageing.
The correct modelling of ageing is not an easy task. Indeed, the equipment in service in existing distribution networks has been manufactured by different companies and they may have different characteristics (e.g. paper or XLPE-insulated power cables, ceramic or glass insulators in overhead lines, etc.) with different behaviours in term of resistance to fatigue or/and depletion of materials due to operating conditions. A further difficult arising in the correct ageing modelling is due to the lack of data about the existing components failure history in defined configurations and operating modes. The adoption of maintenance database is recent and not completely implemented in many distribution companies. Definitely, in planning studies oriented to predict the reliability of a given network the main complexity is determination of the failure rate after the useful life. In many reliability studies, the failure rate is considered as constant during the useful life whereas it increases with the component age according to the well known bathtub curve. Because different causes of failure could lead to different failure distributions there is not a general consensus about the best way for modelling the wear out period. Several authors use the Weibull probability density function (*pdf*) [3] and some others the Gaussian or the Exponential one [4]. Moreover, there are still further open issues like the definition of the lasting of the wear-out period and/or the end of the useful life, and the chosen of the correct values for the coefficients in the *pdf* adopted. For the aforementioned reasons and according to the practical approach followed in the paper, in the wear out stage a failure rate that is randomly extracted from a population of failure rates having a uniform distribution between a minimum value, equal to the failure rate during the normal operating stage, and a maximum value equal to five times the minimum value. In fact, on average, equipment in service more than 30 - 40 years has typically failure rates 3 to 5 times higher than the equipment within the design life. It should be observed that different fault rate distribution after the normal life may be easily implemented in SMC so that the assumption made does not undermine the general validity of the approach.

MONTE CARLO SIMULATION

Several papers in the Literature have dealt with the reliability assessment of electric power systems. Analytical and simulation techniques have been developed and applied. By considering that the results with simulation and analytical approaches are in very good agreement [9] the SMC is one of the most convenient methods to identify the several chronological aspects concerning power system operation as well time varying loads and generation and, in particular, the equipment ageing process here investigated. In order to overcome the difficulties arising from the

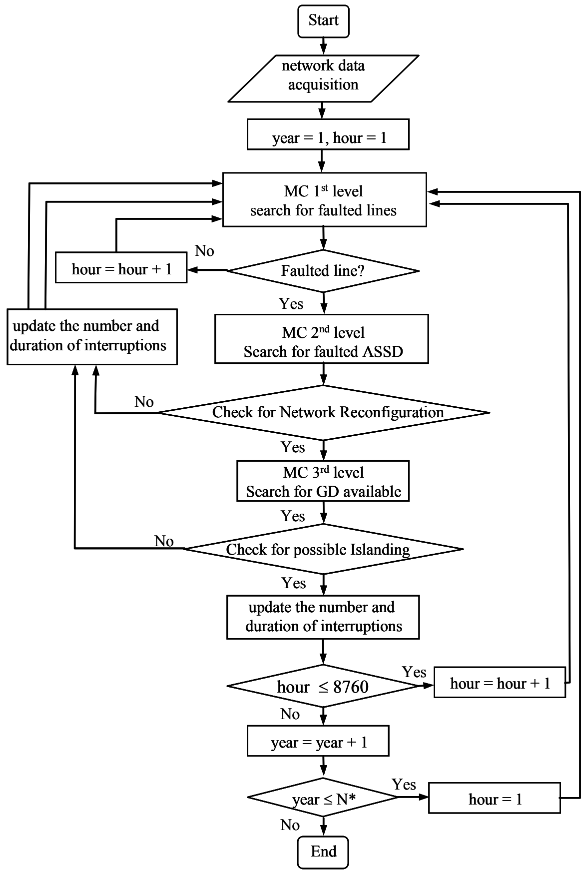

Fig. 1. The flow chart of the sequential MC method

rigorous application of analytical procedures, in this work the authors developed an original SMC method based on numerical simulations and implemented with commercial software and FORTRAN language. The SMC allows simulating the reliability of a network during a given year by considering the sequence of events caused by a network fault. The reliability of lines is considered as well as the reliability of ASSDs and the availability of DG in both on-line and stand-by applications. Thanks to the flexibility of the methodology, adding the reliability models of HV/MV and MV/LV transformers as well as of other components is straightforward.
The procedure is applicable to a network where a number of ASSDs are positioned in optimal location [6] and a defined penetration level of DG is supposed to be installed considering the option of intentional islanding [7,8].
The procedure of reliability evaluation is decomposed into three levels and considers an hourly time varying load and generation according to the flow chart depicted in fig.1. The duration of the simulation is one year. The proposed reliability evaluation procedure includes the following basic steps:

1. Consider the generic hour t^* of the examined year.
2. The analysis of the network determines whether at the time t^* there is a line fault and in which position taking into account the reference (horizon) year and the age of the lines.
3. Whether a fault happens, ASSDs may rapidly isolate

the faulty zone and allow many loads to be fed by controlling emergencies ties and/or DG. The possible unavailability of ASSDs is considered to exactly assess the impact of the fault in the network.

4. Whether a fault happens, DG and intentional islanding are considered. At the time t^* all intentional islands have to comply with the technical constraints (e.g. voltage variations, frequency fluctuations, overloads and short circuit level, etc.) considering the hourly load and generation curve of each node. Also in this case the unavailability of DG is taken into consideration.
5. Whether a fault happens the reliability indexes are updated.

Steps 1-5 are repeated until one year is completely simulated, and then the whole procedure is repeated for a sufficient number of times to provide statistical information. Faults caused by ageing are considered as well as external factors like trees contacts, lightning, animals and human activities. The older are the lines the higher is the likelihood of faults for them. ASSDs may rapidly isolate the faulty zone by reconfiguring the network and help reducing both location and repair stages. The failure of an ASSD can fade these benefits by increasing both the number of affected nodes and the duration of the interruption. The SMC considers the likelihood of ASSDs malfunctions for a more realistic simulation. The existing DG is considered and its capability to feed the loads isolated due to line faults with intentional islands. The power production and the load demand are all hourly calculated, by using the load and generation curve of each node [8].

The application of the procedure described above allows collecting the average number of interruptions and their durations in each MV node. The expected SAIDI and SAIFI can also be assessed to describe the system reliability performance.

CASE STUDY

The proposed methodology has been applied to the portion of Italian 20kV distribution network depicted in Fig. 2. It presents a single open-loop feeder between 2 HV/MV substations with one open branch (emergency tie). The network is radial but the nodes in the main feeder can supplied during faults by isolating the faulted branch thanks to the redundancy of paths achieved with the emergency connections. Customers supplied by laterals can not be supplied during upstream faults if intentional islanding is not allowed. Such network supplies 142 MV/LV nodes, divided in 25 trunk nodes and 117 lateral nodes. Overhead distribution lines and cable feeders are used, for a total length of 69.5 km of power lines. The average amount of electric power delivered to MV nodes is 9.1 MW. In order to assess the network reliability indexes, a fault rate of 0.15 failures/year·km and 0.10 failures/year·km have been assumed for the not aged overhead lines and buried cables respectively. The fault location time has been assumed conventionally equal to an average value of 1 hour in case of a manually operated network and of 10 minutes for a fully automated network. The repair stage mainly depends on the kind of the faulted line. Overhead lines are less reliable than buried cables but they can be repaired easier; in the paper the average fault repair time is equal to 8 hours and 5 hours for buried cables and overhead lines respectively.

The useful life of the equipment is considered to be 30 years for cables and 40 years for overhead lines with a wear out period of 15 years for both. During the first 10 years of the wear out period the fault rate is considered to be up to 3 times the fault rate during normal life and up to 5 times in the remaining period of 5 years. The lateral feeders are assumed to be built in 1970, whereas the main feeder is suppose to be refurbished in 1990 in order to face the growth of the load. Ageing effects are neglected in ASSDs and DG due to their recent installation and/or the predictive maintenance. Anyway, the probability of failure of the automatic switches is assumed to be 0.06% and the distributed generators are considered to be 96% reliable in case of on line operation and 94.8% in case of back-up operation. In order to guarantee the convergence of the SMC the simulation is repeated 50,000 times.

When ageing is not considered in reliability assessment the network presents a SAIDI of 83.4 min/year and a SAIFI of 0.72 with no DG. In order to emphasize the role of ageing different horizon years have been considered. Table I shows the results obtained with the application of the procedure considering the years 2007, 2012 and 2017 as reference year with different levels of network automation (14% and 40% of nodes with ASSDs) and with different DG penetration (26% and 52% of load). Intentional islanding is allowed in both cases with DG. From Tab. I it is quite clear that for the examined network in 2012 the increasing of the automation is not sufficient to face ageing problems.

Even with 40% of ASSDs nodes (see Tab. II) the network will have a SAIDI comparable with the network having only 14% of ASSDs. The resort to DG and intentional

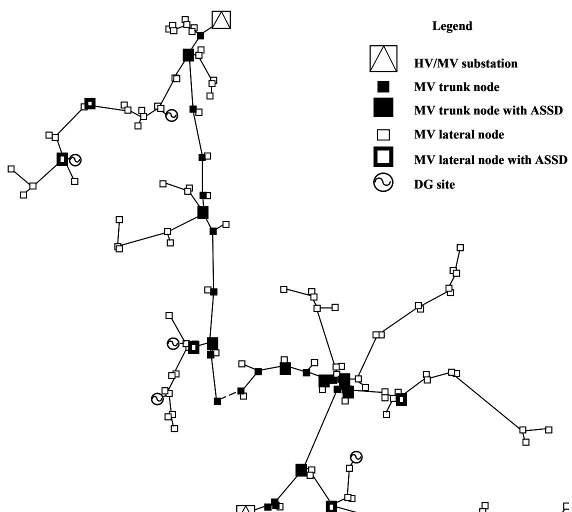

Fig. 2. The test network

islanding can be useful to reduce the effect of ageing in mean time giving DSO the possibility of starting the substitution of the most aged system elements. The general remark is that the mechanism of penalties and incentives established worldwide by many Regulators it has been useful to allow a drastic improvement in reliability performance, but the time horizon considered is often too short. DSO want to have the shortest pay-back time for reliability investments and they have reasonable adopted a number of high profitable solutions with a pay-back time comprise in time horizon imposed by Regulators so that penalties might be reduced or avoided and incentives earned. Network automation is the usual solution to achieve those goals but it is not sufficient when ageing appears. Network automation, smartgrids, and DG are useful to improve efficiency, to allow a direct participation of loads in the energy markets and to improve reliability and security but, as they allow postponing network investments, Regulators should be concerned about ageing that risks to avoid many of the possible benefits.

CONCLUSIONS

In many industrialised countries, Regulators have imposed to distributors a continuous improvement of the quality of service, often measured as continuity of the supply. The majority of investments have aimed at reducing the duration and the frequency interruptions by exploiting automation and communication systems or by reducing the number of faults that require the permanent intervention of the protections. Unfortunately, the incoming ageing of many network components risks to reduce the positive effect of these actions. The paper has presented an SMC method to calculate the reliability indexes with aged lines in real world networks. As discussed in the paper, ageing cannot be faced only with network automation whereas DG can be useful only in the medium term whether intentional islanding were admitted.

REFERENCES

[1] V. Ajodhia, L. Lo Schiavo, R. Malaman, 2006, "Quality regulation of electricity distribution in Italy: an evaluation study", *Energy Policy*, Volume 34, Issue 13, Pages 1451-1708 (Sept. 2006)

[2] Italian Authority for Electricity and Gas - AEEG, Decision 004/04, [http: www.autorità.energia.it].

[3] L. Wenyuan, 2002, "Incorporating aging failures in power system reliability evaluation", *IEEE Transactions on Power System,* Volume 17, Issue 3, Aug., 918 - 923.

[4] B. Retterath, S.S. Venkata, A.A. Chowdhury, 2004, "Impact of time-varying failure rates on distribution reliability" *Proc. of Conference on Probabilistic Methods Applied to Power Systems*, 12-16 Sept., 953 - 958.

[5] R. Billinton, P. Wang, 1998, "Distribution system reliability cost/worth analysis using analytical and sequential simulation techniques", *IEEE Transactions on Power Systems*, vol. 13, Issue: 4, November, 1245 - 1250.

[6] G. Celli, F. Pilo, 1999, "Optimal Sectionalizing Switches Allocation in Distribution Networks", *IEEE Transactions on Power Delivery*, vol. 14, no. 3, July, pp. 1167-1172.

[7] CEI, Prog. C.970, 2006, Regole tecniche di connessione per utenti attivi e passivi alle reti AT ed MT delle imprese distributrici di energia elettrica.

[8] G. Celli, E. Ghiani, S. Mocci, F. Pilo, 2005 "Distributed Generation and Intentional Islanding: Effects on Reliability in Active Networks". *Proc. of CIRED conference*, Turin, Italy, June, Session No. 5.

[9] P. Wang, R. Billinton, 1999, "Time sequential distribution system reliability worth analysis considering time varying load and cost models", *IEEE Transactions on Power Delivery*, vol. 14, Issue: 3, July, 1046-1051.

TABLE I - NETWORK RELIABILITY BY YEAR - AUTOMATION LEVEL 14%

Reference Year		No DG	On-line DG DG% = 26%	Back-up DG DG% = 26%	On-line DG DG% = 52%	Back-up DG DG% = 52%
2007	SAIDI	103.73 min/year	76.59 min/year	77.40 min/year	50.92 min/year	52.25 min/year
	SAIFI	0.81	0.75	0.81	0.71	0.81
2012	SAIDI	180.80 min/year	134.36 min/year	135.89 min/year	83.89 min/year	86.32 min/year
	SAIFI	1.35	1.23	1.35	1.16	1.35
2017	SAIDI	335.20 min/year	248.83 min/year	251.78 min/year	149.43 min/year	154.53 min/year
	SAIFI	2.43	2.19	2.43	2.04	2.43

TABLE II - NETWORK RELIABILITY BY YEAR - AUTOMATION LEVEL 40%

Reference Year		No DG	On-line DG DG% = 26%	Back-up DG DG% = 26%	On-line DG DG% = 52%	Back-up DG DG% = 52%
2007	SAIDI	102.15 min/year	76.54 min/year	77.52 min/year	49.53 min/year	51.20 min/year
	SAIFI	0.54	0.45	0.54	0.39	0.54
2012	SAIDI	179.09 min/year	134.00 min/year	135.32 min/year	82.80 min/year	86.08 min/year
	SAIFI	0.92	0.78	0.92	0.67	0.92
2017	SAIDI	331.58 min/year	251.10 min/year	254.59 min/year	148.71min/year	154.84 min/year
	SAIFI	1.80	1.46	1.80	1.25	1.80