Reliability-Centered Maintenance Task Planning for Overhead Electric Power Distribution Networks

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Abstract

In this paper, it is presented an approach to match technically and economically the reliability of electricity distribution networks through an optimization methodology consisting of the mathematical model and metaheuristic solution technique to obtain an optimized plan for efficient management of maintenance tasks. The problem of maintenance tasks is formulated as a mixed dynamic nonlinear multi-objective optimization model, in which costs to perform maintenance tasks on equipment and/or components that make up the electric distribution network are minimized, while they have their reliability maximized. The constraints of this model are the individual and group electricity supply interruption duration and frequency indices, and availability of financial and human resources. The solution of this problem is obtained through a specialized non-dominated sorting genetic algorithm multi-objective metaheuristic, which provides a set of non-dominated solutions very close to the optimal Pareto frontier. Each solution at this frontier represents a maintenance plan able to assist the making decision of the operators in distribution companies for managing the maintenance crews.

Keywords NSGA-II · Metaheuristic · Multi-objective programming · Reliability · Maintenance tasks · Distribution systems

List of symbols

Sets

Ns	Number of consumers connected to the sth feeder section
ph	Planning horizon
E	Equipment installed in the system
S	Number of feeder sections in the system

Parameters

$\mathrm{Cost}\left[x_{(e,m)}^{t}\right]$	Cost of maintenance task of level m at the equipment e in the time t
$\mathrm{TMP}[x_{(e,m)}^{t}]$	Average preparation time to a maintenance task of level m at the equipment e in the time t
$\mathrm{TMD}_{e}[x_{(e,m)}^{t}]$	Average travel time of the field crew to perform the maintenance task of level m, at the equipment e in the time t
$\mathrm{TME}[x_{(e,m)}^{t}]$	Average time to perform the maintenance task of level m at the equipment e in the time t
T_{fact}	Available time to the maintenance crew (minutes)
t	Time interval into planning horizon (months)
e	Type of equipment installed in the system
r	Interest rate
TMAE	Average time to the emergency attending by utility field crews (hours)
DIC	System interruption duration per consumption unit
FIC	System interruption frequency per consumption unit
M_e	Number of maintenance tasks allowed per equipment e
C_s	Reliability of the sth feeder section
P_s	Active power in the sth feeder section

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Cs_{consi}	Reliability for attending the consumer i of the sth feeder section
δ_e^m	Multiplier parameter of failure rate of the equipment e to the maintenance task m
λ_{eq}^t	Equivalent failure rate in the time t
λ_e^t	Failure rate of the equipment e in the time t
λ_{exter}^t	Failure rate due to external features in the time t
λ_{disc}^t	Failure rate due to energy power losses in the main substation
λ_{main}^s	Failure rate of the sth feeder section in the main branch
λ_{tri}^s	Failure rate of the transformer installed in the sth feeder section
Tv_e	Life cycle of the equipment e (years)
T_e	Updated use time of the equipment e (years)
ρ_{imut}	Initial mutation rate
ρ_{fmut}	Final mutation rate
B	Damping constant of crossover and mutation rates
Ng	Total number of generators
$Iter$	Number of iterations
ρ_{icros}	Initial crossover rate
ρ_{fcros}	Final crossover rate

Variables

$x_{(e,m)}^t$	Integer decision variable that defines the maintenance level of equipment e in time t

1 Introduction

The execution of maintenance tasks in distribution networks by the power utilities is an important action for managing its assets to enhance the reliability and availability indices of the power energy supply. In the determination of maintenance plans of an equipment, must be taken into account the most suitable maintenance task and the past time since its last performed repair more its physical and operational condition and life cycle (State Grid 2011). The maintenance plan must be determined by considering the status of all equipment in the distribution network because the maintenance plan that is determined by the set of the best individual plans for each equipment cannot be optimum. An efficient maintenance plan to distribution systems is achieved using the coordinated maintenance over all the equipment and their physical and operational conditions for optimally allocating available financial resources.

Distribution networks are vulnerable to different types of failures, which can be internal failures at equipment itself, or failures due to external threats dependent on weather condi-

tions such as wind, lightning and thunderstorms. External-caused failures reduce the equipment life cycle by increasing the frequency of maintenance tasks that result in growth of costs to power distribution utilities.

The realization of preventive maintenance tasks can be used to attenuate the impacts of nature actions and/or equipment aging with the objective to improve the service availability of power energy supply. However, the global cost of this countermeasure can raise the price of this service to values that are unfeasible without the guarantees of uninterrupted power energy supply. Furthermore, the demand for high-quality services (with low interruption indices), which are supervised by regulating agencies, requires that power distribution utilities invest in maintenance programs to preserve the reliability of their networks. In this way, utilities always looking for feasible solutions, technically and economically, able to improve power network reliability. The planning of centered reliability maintenance tasks, which is employed by general electricity industries, is an emerging technique to create feasible maintenance plans able to preserve operational availability of devices and equipment in power energy distribution system (PEDS) by minimizing costs of maintenance tasks and enhancing reliability indices.

Mathematical models and solution techniques for determining centered reliability maintenance plans of equipment in distribution system have been proposed in specialized literature. In Huang et al. (2004), it is proposed a mathematical model to schedule maintenance tasks of distribution network equipment using an objective function to minimize the maintenance costs and financial losses due to energy supply interruptions. In the maintenance optimization model proposed by Li and Brown (2004), the objective function minimizes the average value weighted by the distribution system reliability index. In Yeddanapudi et al. (2008), it is defined the entire risk of the distribution system interruption and development of a coordination model of maintenance resources as an objective function to maximize the risk reduction after the realization of maintenance tasks.

In Piasson et al. (2016), it is proposed a multi-objective optimization model to schedule-centered reliability maintenance tasks in distribution systems. The objective functions model mathematically the costs related with the different maintenance levels of the distribution system equipment and network reliability in analyzed planning horizon. The model constraints are: (a) expected values of availability indices like the system average interruption frequency index (SAIFI) and system average interruption duration index (SAIDI) for each set of consumers; (b) available time in hour for maintenance crews; (c) number of maintenance tasks specified to every type of network equipment and device. The multi-objective genetic algorithm, non-dominated sorting genetic algorithm (NSGA-II), is proposed in the solution of the mathematical model. A binary optimization model to determine the opti-

mum plan of maintenance tasks for each distribution system equipment is proposed in Sittithumwat et al. (2004). The objective is the minimization of the SAIFI index in the main feeder branch. The model constraints are the amount of financial and human resources available to perform maintenance tasks in analyzed planning horizon. In tests with a generic feeder, it is taken into account a constant failure rate and variable failure rate over maintenance tasks for every system equipment that are modeled as fuzzy sets.

A multi-objective optimization model to determine the maintenance plan in distribution system is proposed in Hilber et al. (2007). This model considers annual expected costs of energy supply interruption to consumers and maintenance costs in distribution network (preventive and corrective maintenances). These two objective functions are combined through weighting technique to yield a single-objective function. Availability indices of the energy supply service are not considered in the model that is assumed static, i.e., it is not extended to analysis of failure behavior along time under performed maintenance tasks. The failure rates of equipment are dealt as constant. The relation between system equipment and their reliabilities is examined through an index that matches to expected total interruption costs to consumer in a time interval of one year. Three maintenance task levels are taken into account. The effects of each maintenance task over reliability of network equipment are not totally analyzed. The proposed model is tested under a test system with 178 equipment including circuit breakers, cables, transformers, bus and fuses. The employed solution technique is a particle swarm optimization (PSO) metaheuristic. In Usberti et al. (2015), it is proposed a mathematical bi-objective optimization model that considers costs of maintenance activities and the maximum value for a system average interruption frequency index in planning period. This multi-objective problem, named maintenance resources allocation problem (MRAP), is to define the best compromise of maintenance policies for the network at local and global levels for a given period. The MRAP problems are solved using the concept of ε-constraint by a hybrid genetic algorithm. The solution of these problems provides local solutions and associated trade-off curve. These solutions are optimally combined to solve a global-level multiple criteria optimization problem, revealing the local efficient solutions and associated trade-off curves for a group of networks, providing information to assess the decision on maintenance activities in the network management. Results are presented to one illustrative example and a real-life case study.

The heuristic procedure to specify strategies of maintenance tasks in distribution systems, which satisfy the predefined objectives of availability and reliability indices of power supply service, is proposed in Dehghanian et al. (2013). The strategies of maintenance tasks are ranked based

on trade-off between costs and benefits and on exploration of system operator and specialist knowledge.

In this work, it is proposed a generic mathematical model of multi-objective optimization and to solve it, the NSGA-II that provides the plans of centered reliability maintenance task for different equipment of distribution network in different time of the planning horizon. The achieved results allow for distribution utility planning sector to make decisions in order to optimize the use of human and financial resources by indicating which equipment and feeder sections should undergo to different types of maintenance tasks and which maintenance crews should be dispatched to each scheduled task. The mathematical model is comprised by two objective functions: one for modeling the costs of maintenance tasks and another for modeling the system unreliability (unreliability is defined as being the reliability complement), relating their reliability indices per performed maintenance task. The model constraints are system interruption duration and frequency (DIC and FIC) indices per consumption unit, assets' devaluation of equipment comprising the system and available time of maintenance crews.

The contribution of this work is as follows: (1) A multi-objective model is proposed to schedule maintenance tasks in overhead and radial distribution networks that provides a set of non-dominated solutions aiding the decision making according to requirements and conditions of financial resources of power distribution utilities; (2) the constraints, which take into account the availability indices, are needed to power distribution utilities avoid the fine payment and preserve its image to the consumers; (3) the proposed model requires a reduced database and deals with the failure indices due to the use condition of equipment and devices in distribution network; (4) unlike many literature works, failure external factors related to the adverse weather conditions are taken into account to obtain the reliability in each feeder section, making easy the integration of proposed model with the geographic information system present in modern PEDS; (5) the consideration of the failure rate per component, which is updated over the planning horizon, makes the model constraints simplified, reducing its computational complexity. In comparison with Piasson et al. (2016), the coding of the solutions to the problem has been restructured to reduce the memory capacity required for its storage and to give speed and robustness to the algorithm. In this version of the NSGA-II algorithm, variable recombination and mutation rates are used during their generational cycle.

This paper is organized as follows: Sect. 1 presents the introduction conception about centered reliability maintenance task and literature review; Sect. 2 presents the definition of reliability and failure rates of equipment installed in the distribution network and hypothesis needed to propose a generic multi-objective optimization model for solving the problem of centered reliability maintenance task plan-

ning; Sect. 3 presents the proposed methodology to solve the multi-objective optimization model, i.e., the NSGA-II metaheuristic; Sect. 4 presents the achieved results in tests with the computational implementation of proposed methodology in a generic power system to show the robustness and efficiency of proposed solution technique; and Sect. 5 presents the conclusions about achieved results and the proposed methodology.

2 Methodology

In maintenance task planning is taken into account the following network equipment: capacitor banks (BC), sectionalizing switches (CHM), protection switches (CHP) like circuit breakers, fuses and automatic reclosers, distribution transformers (TR), voltage regulators (RT) and primary cable (LN), which includes the feeder and branch conductors, crosspieces and isolators of poles in every section of the primary network. Every equipment can have different types of failure that affect the power system in different ways. This work always deals with the worst scenario to the power system with the failure occurrence over its equipment, i.e., it takes into account a partial, or full, interruption of power energy supply after a failure event (Horton et al. 1990). This approach aims to establish the interruption maximum cost which permits a better analysis of trade-off between costs and benefits of established maintenance plans. For example, if a scenario is expected due to event failure of equipment but other more favorable scenario happens, then the benefits of maintenance task planning are maximized because the trade-off between cost and benefit of established maintenance plan is available to the worst scenario. On the other side, if a favorable scenario is expected but another worst scenario happens, then the cost should raise in comparison with benefits of maintenance plan what can make its execution unfeasible.

In this way, every network equipment can undergo to four levels of maintenance task. These levels are defined as: m_1 to the absence of maintenance tasks; m_2 as minimum maintenance; m_3 as full maintenance; and m_4 to the equipment replacement. The m_4 maintenance task most severely affects the reliability of equipment and distribution network. The full maintenance task, m_3, can recover the reliability of equipment as much as the maintenance task of m_4 level, but at a lower cost. Despite the cost, the maintenance task of level m_4 still is better because equipment can be out of their economic life cycle and, hence, the replacement by new equipment must be most feasible in a general perspective of the cost–benefit ratio.

Table 1 Typical values of failure rate for equipment of overhead power distribution system

Equipment	Failure rate (failure/year)
Protection switch (CHP)	0.0144
Sectionalizing switch (CHM)	0.000775
Voltage regulator (RT)	0.000614
Transformer (TR)	0.000614
Capacitor bank (BC)	0.085
Primary cable (LN)	0.0198[a]

[a]Per miles of conductor

2.1 Reliability General Concepts

The most important variable to determine the equipment reliability is the failure rate. In this work, it is assumed that degradation of PEDS equipment is monthly and modeled through parameters that are named as failure rate multipliers. These multipliers determine the expected variations of the equipment failure rate in a certain time period according to programmed maintenance tasks and to their values in previous period. In this way, it is needed to take into account the initial value of failure rate to compute the equipment failure rate in planning horizon of maintenance optimization model. In Horton et al. (1990), the typical values of failure rate for each type of equipment in underground urban network of PEDS are estimated. In Table 1, it is presented the typical values of annual failure rates for transformers, reclosers, fuses and urban feeder cables.

In the determination of initial failure rates of distribution network equipment ($\lambda_e^{t_{\mathrm{initial}}}$), it is used the typical values of failure rate ($\lambda_e^{\mathrm{typical}}$), as is presented in Table 1, through (1):

$$\lambda_e^{t_{\mathrm{initial}}} = \delta_e^m \lambda_e^{\mathrm{typical}} \tag{1}$$

The equipment in real-world distribution networks is in different stages of degradation depending on their age or number of maintenance task preformed, Sittithumwat et al. (2004), IEEE Std. 493-1997 (1998), Usberti et al. (2015) and State Grid (2011). Through (1), it is generated the initial values of failure rates to simulate the possible states of conservation for each equipment of the PEDS. In this way, failure rates are updated where the typical failure rate of an equipment is updated by multiplying the lowest level failure rate (no maintenance) by the time in which the equipment remains without maintenance tasks (*tsm*). This procedure simulates the degradation that happens in equipment of the PEDS in a certain time interval.

2.2 Mathematical Model

The objective functions of mathematical model are the total costs of maintenance tasks (2) and system unreliability (3). The f_2 value is arithmetic mean of unreliability partial index obtained for each time interval, t, of the planning horizon, ph. This value is the average of fault probabilities for each feeder section, weighted by active power loads P_s in the sth feeder section. The lower the value, the better the expected system reliability. In computation of f_1, the cost of each maintenance activity, $\text{Cos}t\left[x_{(e,m)}^t\right]$, for each piece of analyzed equipment, $e \in E$, is updated through the interest rate r because of inflationary expectations:

Min:

$$f_1 = \sum_{t=1}^{ph}\sum_{e=1}^{E}\text{Cos}t\left[x_{(e,m)}^t\right]\left(\frac{1}{1+r}\right)^t \tag{2}$$

$$f_2 = \frac{1}{ph}\sum_{t=1}^{ph}\left[\frac{\sum_{s=1}^{S}(1-C_s(t))P_s}{\sum_{s=1}^{S}P_s}\right] \tag{3}$$

Subject to:

$$\text{DIC}_{\text{month}}(t) \leq \text{DIC}_{\text{month}}^{\min} \tag{4}$$

$$\text{DIC}_{\text{quarter}}(t) \leq \text{DIC}_{\text{quarter}}^{\min} \tag{5}$$

$$\text{DIC}_{\text{year}}(t) \leq \text{DIC}_{\text{year}}^{\min} \tag{6}$$

$$\text{FIC}_{\text{month}}(t) \leq \text{FIC}_{\text{month}}^{\min} \tag{7}$$

$$\text{FIC}_{\text{quarter}}(t) \leq \text{FIC}_{\text{quarter}}^{\min} \tag{8}$$

$$FIC_{year}(t) \leq FIC_{year}^{\min} \tag{9}$$

$$\sum_{e=1}^{E}\text{TMP}\left[x_{(e,m)}^t\right] + \text{TMD}_e\left[x_{(e,m)}^t\right] + \text{TME}\left[x_{(e,m)}^t\right] \leq T_{\text{fact}} \tag{10}$$

$$T_e + t - Tv_e \geq 0 \tag{11}$$

$$\sum_{t=1}^{ph}x_{(e,m)}^t \leq M_e \tag{12}$$

where

$$\text{DIC}_{\text{month}}(t) \leq \text{TME}\left[x_{(e,m)}^t\right] + [1-C_s]\text{TMAE} \tag{13}$$

$$\text{FIC}_{\text{month}}(t) \leq x_{(e,m)}^t + [1-C_s] \tag{14}$$

$$\text{DIC}_{\text{quarter}}(t) \approx \frac{1}{k_{\text{quarter}}\text{DIC}}\sum_{t=1+3(q-1)}^{3q}\text{DIC}_{\text{month}}(t) \tag{15}$$

$$\text{FIC}_{\text{quarter}}(t) \approx \frac{1}{k_{\text{quarter}}\text{FIC}}\sum_{t=1+3(q-1)}^{3q}\text{FIC}_{\text{month}}(t) \tag{16}$$

$$\text{DIC}_{\text{year}}(t) \approx \frac{1}{k_{\text{year}}\text{DIC}}\sum_{t=1+12(y-1)}^{12y}\text{DIC}_{\text{month}}(t) \tag{17}$$

$$\text{FIC}_{\text{year}}(t) \approx \frac{1}{k_{\text{year}}\text{FIC}}\sum_{t=1+12(y-1)}^{12y}\text{FIC}_{\text{month}}(t) \tag{18}$$

$$C_s = \prod_{i=1}^{Ns}Cs_{\text{consi}} \tag{19}$$

$$Cs_{\text{consi}}(t) = e^{-(\lambda_{\text{consi}}^s)} \tag{20}$$

$$\lambda_{\text{consi}}^s = \lambda_{\text{main}}^s + \lambda_{\text{quarter}}^s \tag{21}$$

$$\lambda_{\text{main}}^s = \sum_{e \neq \text{main}}^{E_s}\lambda_e \tag{22}$$

$$\lambda_{\text{external}}^t = \lambda_{\text{tree}}^t + \lambda_{\text{wind}}^t + \lambda_{\text{thunderbolt}}^t + \lambda_{\text{lightning}}^t \tag{23}$$

$$\lambda_{\text{eq}}^t = \lambda_e^t + \lambda_{\text{external}}^t + \lambda_{\text{disc}}^t \tag{24}$$

$$\lambda_{\text{eq}}^{t+1} = \delta_e^m\lambda_{\text{eq}}^t \tag{25}$$

The constraints' sets shape the acceptable limits of reliability indices that are established by regulating agencies. In the Brazil, these indices are the monthly, quarterly and annual DIC and FIC as is, respectively, given by (4), (5), (6), (7), (8) and (9); monthly average time available to the utility maintenance crews (10); system equipment, or asset, devaluation (11); and maximum number of maintenance tasks that are allowed for each system equipment (12).

In the calculation of monthly indices, such as DIC and FIC, are considered, respectively, the average time spent by maintenance crews in the execution of a maintenance task that provokes the power energy supply interruption to consumer groups and possible interruptions from fault external in the feeder section and main branch, as in (13) and (14). The calculation of quarterly and annual availability indices is an approximated value from monthly indices in concordance with (15), (16), (17) and (18).

The reliability of any sth feeder section that is limited by protection, or sectionalizing switches, depends upon of reliability index of all consumers' groups that are connected in this feeder section (19), from the lateral branches and the main feeder branch. The reliability of ith consumer is calculated through a probability density function of Poisson (20),
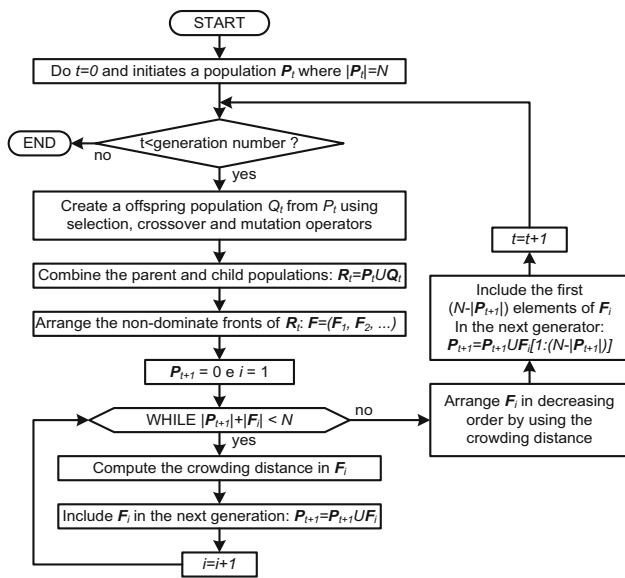
Fig. 1 Flowchart of the implemented NSGA-II algorithm

Fig. 2 Chromosome coding

which is the reliability function for distribution transformers, oil switchgears and main feeder branch (21), where the main branch is comprised by all equipment with exception of transformers (22).

The failure rate of a feeder section is comprised by failure rates due to action of external threats (fault rate due to contact of vegetation in the network, wind, thunderstorms and lightning) (23) and by power energy supply loss in substation achieving; thus, the total failure rate as in (24) provides a more realistic behavior of reliability level for equipment installed in PEDS.

3 Solution Technique

The problem model (2)–(12) has a complex nature and is hard to be solved through classical optimization techniques. Among solution techniques found in the literature to solve this type of problem, the NSGA-II has been highlighted as a standard approach to solve multi-objective optimization problem that is very well known due to two important mechanisms of selection operation: fast non-dominated sorting and the crowding distance (Deb et al. 2002). In Fig. 1, it is presented the flowchart of implemented algorithm. The next subsections depict the computational implementation details of some particular stages of this algorithm to solve the proposed mathematical model as given in (2)–(25).

3.1 Coding of the Decision Variables

The chromosome, or representation to a solution of determined maintenance planning, is displayed in Fig. 2. To a

given set of equipment E and assuming that for each equipment e of this set there is a set of Me feasible maintenance tasks in the time period $t \in ph$, then every decision making can be modeled by an integer variable representing the set of feasible maintenance tasks, as is given in (26) where "1" means the lowest level (no maintenance) and "3" the highest level (full maintenance), while "4" is the replacement of equipment by new one:

$$x^t_{(e,m)} = \{m | m = 1, 2, 3 \vee 4\} \qquad (26)$$

3.2 Selection Operator

In NSGA-II, the selection operator uses two specialized mechanisms: fast non-dominated sorting and crowding distance. The fast non-dominated sorting comprises random selection of two, or more, non-dominated solutions located in the Pareto front. The crowding distance operator is applied in estimation of density at solution set that are near to a particular solution of a population in the same Pareto front. To determine this distance, it is computed the smallest distance among analyzed solution, r_i, and solutions that belong to set of solution of its neighborhood, for each objective of mathematical model. This distance works as a size estimative of the largest cuboid that includes the solution r_i without the inclusion of any solution of population. A solution r_i, which is the multi-objective optimization problem solution, overtakes other solution r_j whenever:

- The solution r_i is located in a Pareto front below of solution r_j; then, $r_i < r_j$;
- Both solutions belong to same Pareto front, but the solution r_i has larger crowding distance than r_j and, hence, $d_i > d_j$.

3.3 Genetic Operators

The mutation and crossover rates are variables during the generational cycle of NSGA-II, according to (27) and (28). The initial (ρ_i) and final (ρ_f) mutation and crossover rates are previously specified as well as the iteration number (iter),

Table 2 Cost of maintenance tasks by equipment class (US$)

Equipment	m_1	m_2	m_3	m_4
CHP	0	50	50	100
CHM	0	50	50	100
LN	0	50	150	1000
BC	0	50	150	800
TR	0	100	600	4000
RT	0	100	450	3000

Table 3 Equipment multiplier parameters of failure rates

Equipment	δ_1	δ_2	δ_3	δ_4
CHP	1.01	0.98	0.98	0.01
CHM	1.01	0.98	0.98	0.01
LN	1.04	0.98	0.3	0.01
BC	1.02	0.95	0.4	0.01
TR	1.02	0.95	0.42	0.01
RT	1.02	0.95	0.41	0.01

total number of generations (ng) and value of damping coefficient (β):

$$\rho_{\mathrm{mut}} = \rho_{\mathrm{i,mut}} + \rho_{\mathrm{f,mut}} e^{\frac{-\mathrm{iter}}{\beta \mathrm{ng}}} \tag{27}$$

$$\rho_{\mathrm{cros}} = \rho_{\mathrm{i,cros}} + \rho_{\mathrm{f,cros}} e^{\frac{-\mathrm{iter}}{\beta \mathrm{ng}}} \tag{28}$$

Table 4 Parameters of the NSGA-II

Parameter	Value
ρ_{imut}	0.09
ρ_{fmut}	0.21
ρ_{icros}	0.9
ρ_{fcros}	0.2
β	18%
ng	4000
Pop	800

4 Test and Results

The NSGA-II is implemented in general-purpose programming language C++ . The evaluation of proposed mathematical model and solution technique is performed by analyzing the performance of maintenance plans that are achieved under a distribution test system with 154 equipment.

4.1 Test System

The test system is a feeder with 58 transformers, two voltage regulators, one capacitor bank, one sectionalizing switch, nine fuses, two maneuver switches, 80 cables and one circuit breaker. In "Appendix," Table 6 shows the data of test system. The topology of the test feeder is shown in Fig. 6. All equipment can be subjected to four maintenance levels, and the planning horizon has 2 years.

4.2 Parameters of the Mathematical Model and NSGA-II

The costs of equipment maintenance tasks are presented in Table 2. These values are mean costs for each type of equipment since, in general, the maintenance costs of every equipment depend on its particular features like manufacturer, nominal power, etc.

The failure rate multipliers are equivalent to impacts of maintenance tasks in the equipment reliability. For each equipment are defined four failure rate multipliers, as is given in Table 3, in which the first multiplier (δ_1) characterizes the degradation due to the absence of maintenance tasks, while the fourth (δ_4) is equivalent to the replacement of the equipment by new one. The failure rate multipliers to protection

and maneuver switches are the same because defects in mechanisms of these equipment affect the network reliability in a similar way and their maintenance tasks comprise basically the visual inspection, components replacement or replacement by new equipment at the end of cycle life, according to ANEEL (2000).

In Table 4, it is presented the parameters that are used in the execution of NSGA-II and they were adjusted through exhaustive experiments.

4.3 Test Conditions

The network equipment is grouped in feeder sections that allow for isolating the permanent faults in one, or many, simultaneous sections reducing, thus, the number of consumers affected by a fault. This distribution network grouping in feeder section is based on location of protection, and/or maneuver switches that are operated in restoration of the power energy supply to consumers in feeder sections adjacent to a section under fault.

4.4 Achieved Results

The obtained result is presented in Fig. 3 in which the optimum problem solution of maintenance task planning in power distribution network is the set of non-dominated solutions in the first Pareto front (rank1). This front is comprised by the set of non-dominated solutions by initialing in zero cost, without the realization of any maintenance task in distribution network, and by ending in cost needed to replace the most part of network equipment. In a detailed analysis of
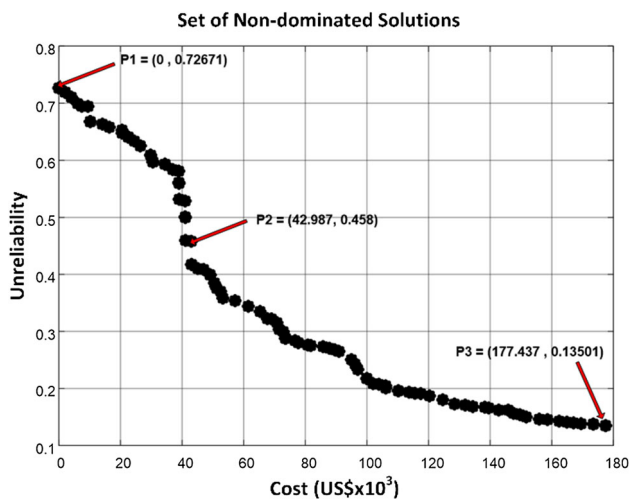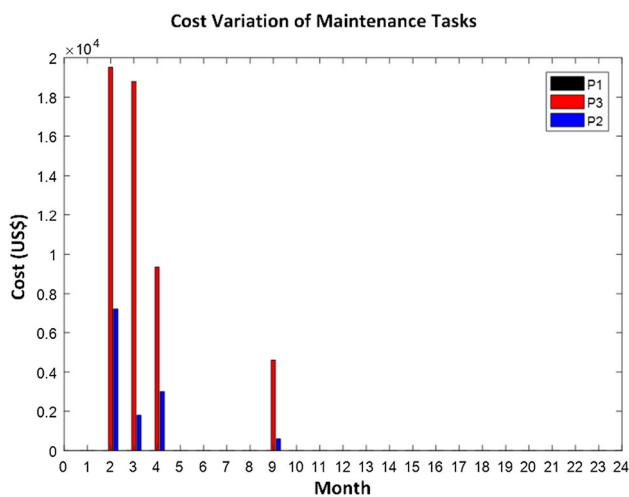
Fig. 3 Pareto front

Fig. 4 Monthly cost variation of maintenance tasks that refers to selected solutions in the Pareto front

Fig. 5 Variation of reliability indices due to realization of maintenance tasks provided by solutions P1, P2 and P3

these results, it is assessed the following set of solutions: "P1" indicates the absence of investment in maintenance tasks; "P3" reveals the maximum investment in maintenance tasks; and "P2" provides the intermediary point. In each one of these solutions, it is verified the progression of the monthly cost of maintenance task (Fig. 4) and the monthly variation of system reliability (Fig. 5).

In Fig. 5, it is verified that in initial period the distribution network has a very low reliability index, around 0.34, indicating the distribution network vulnerability against interruption events what requires effective countermeasures of maintenance to improve the reliability. Consequently, a large amount of financial resources is needed and must be available in the first months to perform the maintenance tasks (Fig. 4).
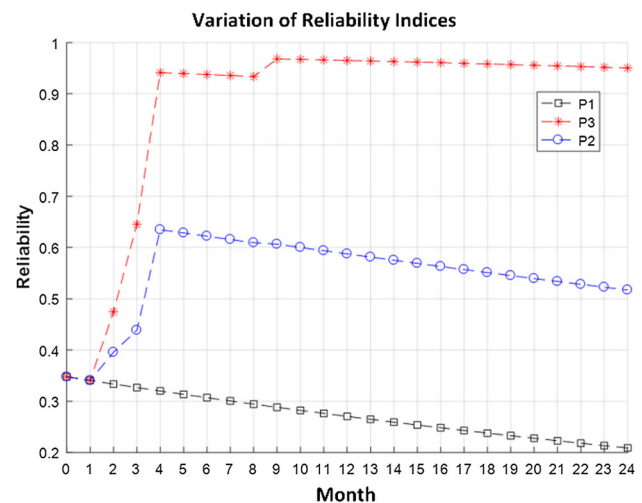
The planning of maintenance tasks necessary for each equipment of distribution network in planning horizon for solution "P2" requires a total of 88 maintenance tasks that are divided into three levels: 54 maintenance tasks of level two; 24 of level three; and 11 of level four.

In every feeder section with an amount of consumer groups, one fault in anyone of their equipment activates the protection switches causing the power energy supply interruption to all their consumers. By assuming, the distribution network is comprised by a main feeder branch that provides energy to lateral branches. The fault incidence in a feeder section of the main branch causes the action of its protection devices opening the switches, and, thus, most part of the distribution network remains without power energy supply. Then, it is important to prioritize the feeder sections that comprise the main branch of overhead radial distribution network in the execution of maintenance tasks.

In Fig. 6, the test system is divided into 13 feeder sections limited by protection and maneuver switches where section #1 and section #7 comprise the network main branch and the others are lateral branches. In Table 5, the plans of maintenance tasks to the section #1 referent to the solution "P2" of the Pareto front are presented, while Fig. 6 displays the equipment where must be performed scheduled maintenance tasks according to Table 5. The red colored cycles correspond to the execution of maintenance tasks in branches (LN, CHP, RT, CHM), and blue colored cycles comprise the execution of maintenance tasks in load nodes (TR, BC).

The computational cost to achieve results with good quality to this test system with 154 equipment is obtained by spending 1,826 s of computational processing or approximating 30 min. The computer-implemented algorithm is processed using a personal computer with Intel Core i7 processor and 8 GB of RAM.
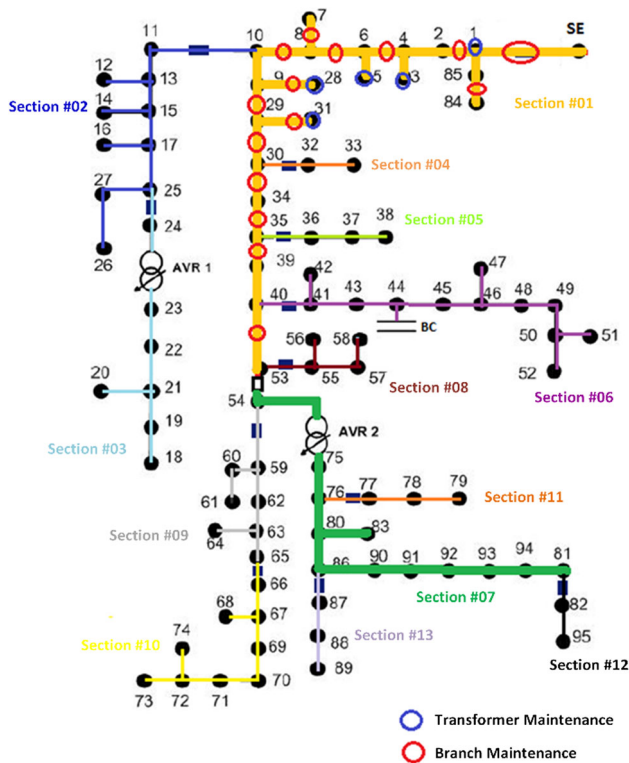
Fig. 6 Scheduling of maintenance tasks for the test system

Table 5 Maintenance tasks in the equipment of section #1

Equipment	Month	Level	Equipment	Month	Level
CHP1	1	2	LN13	1	2
LN1	1	2	LN15	1	2
LN3	1	2	LN18	1	3
LN4	1	2	LN19	1	2
LN5	1	3	LN20	1	3
LN7	1	2	TR1	1	2
LN8	1	2	TR3	1	3
LN9	1	2	TR4	1	3
LN10	1	4	TR6	1	3
LN11	1	4	TR7	1	2

5 Concluding Remarks

In the proposed formulation, the objective functions are modeled by taking into account the full topology of the distribution network and focusing on achievement of maximum reliability with lower investment cost. In this way, the interruption time of consumers is reduced and reliability and availability indices of power energy supply service are improved. The proposed methodology obtains a set of optimized solutions which allow for developing, with safety and economy, the planning of maintenance tasks in overhead power distribution networks. The achieved solutions provide network reliability diagnostic over its life cycle that is favorable to do better decision making.

The integer coding system, the selection operators by dominance level, the crowding distance and the adaptive operators of crossover and mutation guaranty the efficient performance and convergence of the implemented NSGA-II algorithm for obtaining the optimized Pareto convex curve to planning of maintenance tasks with suitable reliability levels.

Appendix

In Table 6, it is presented the data of test system where the header of columns describes, respectively, origin bus, b_o, type of equipment in branch, **LE**, end bus, b_e, and type of equipment in the end bus with active power in kW, **BE**$[P(b_e)]$.

Table 6 Data of test system

b_o	LE	b_e	BE[$P(b_e)$]	b_o	LE	b_e	BE[$P(b_e)$]
SE	CHP1	1	TR1[30]	48	LN43	49	TR31[12]
1	LN1	2	TR2[18]	49	LN44	50	–
2	LN2	4	–	50	LN45	51	TR30[34]
4	LN16	3	TR3[30]	50	LN46	52	TR29[32]
4	LN3	6	–	40	LN13	53	
6	LN17	5	TR4[20]	53	CHP7	55	TR38[12]
6	LN4	8	–	55	LN51	56	TR37[54]
8	LN18	7	TR5[25]	55	LN49	57	TR36[23]
8	LN5	10	–	57	LN50	58	TR35[24]
10	CHP2	11	–	53	CHM1	54	–
11	LN21	13	TR16[56]	54	CHP8	59	–
13	LN34	12	TR11[89]	59	LN64	60	TR42[42]
13	LN22	15	TR17[56]	60	LN65	61	TR41[23]
15	LN33	14	TR12[60]	59	LN52	62	TR40[13]
15	LN23	17	TR18[64]	62	LN53	63	–
17	LN32	16	TR13[24]	63	LN63	64	TR39[14]
17	LN24	25	–	63	LN54	65	–
25	LN30	27	TR15[24]	65	CHP9	66	–
27	LN31	26	TR14[67]	66	LN55	67	–
25	CHP3	24	–	67	LN62	68	–
24	RT1	23	–	67	LN56	69	TR47[13]
23	LN25	22	TR23[32]	69	LN57	70	TR46[16]
22	LN26	21	TR22[34]	70	LN58	71	TR45[15]
21	LN29	20	TR19[34]	71	LN59	72	-
21	LN27	19	TR21[53]	72	LN61	74	TR44[23]
19	LN28	18	TR20[36]	72	LN60	73	TR43[53]
10	LN6	9	–	54	RT2	75	–
9	LN19	28	TR6[56]	75	LN66	76	–
9	LN7	29	–	76	CHP10	77	–
29	LN20	31	TR7[36]	77	LN76	78	TR49[34]
29	LN8	30	–	78	LN77	79	TR48[34]
30	CHP4	32	TR25[36]	76	LN67	80	–
32	LN35	33	TR24[23]	80	LN78	83	TR55[32]
30	LN9	34	TR10[25]	80	LN68	86	–
34	LN10	35	–	86	LN69	90	TR54[67]
35	CHP5	36	TR28[36]	90	LN70	91	TR53[24]
36	LN36	37	TR27[23]	91	LN71	92	TR52[24]
37	LN37	38	TR26[15]	92	LN72	93	TR51[64]
35	LN11	39	–	93	LN73	94	TR50[60]
39	LN12	40	–	94	LN74	81	TR49[56]
40	CHP6	41	–	81	CHP11	82	–
41	LN47	42	TR34[16]	82	LN75	95	TR58[89]
41	LN38	43	TR33[46]	86	CHP12	87	–
43	LN39	44	CB[90]	87	LN79	88	TR57[56]
44	LN40	45	TR34[23]	88	LN80	89	TR56[25]
45	LN41	46	–	1	LN14	85	TR8[20]
46	LN48	47	TR33[64]	85	LN15	84	TR9[30]
46	LN42	48	TR32[32]				

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