Article

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Decision management on optimal multi-objective maintenance of electrical distribution equipment

Toma de decisiones en el mantenimiento óptimo multi-objetivo a equipos eléctricos de distribución

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Abstract

Maintenance objective in a power distribution equipment is to perform adequately its function, to guarantee the power energy supply in a reliable and security way. Companies have for its equipment overhaul interval maintenance scheduled, no matters its arrival times to failure. This article presents a proposal to help make optimal maintenance decisions, which must be given to a distribution equipment for its correct operation to guarantee its reliability. Based on its actually overhaul interval maintenance scheduled and the statistical arrival failure time of a distribution power equipment, the NSGA-II heuristic model is used to obtain a Pareto front, and help to make the best maintenance decision. Two objective functions are considered, minimize maintenance cost while maximize the reliability of a equipment.

Optimal, Reliability, Minimize, Maximize, Statistical

Resumen

El objetivo del mantenimiento en los equipos eléctricos, es que estos se desempeñen adecuadamente y así, garantizar de manera confiable el suministro de la energía eléctrica. Muchas compañías eléctricas tienen mantenimientos programados para sus equipos, sin tomar en cuenta su historial de fallas. Éste artículo, presenta una propuesta para ayudar en la toma de decisiones sobre el mantenimiento que se le tiene que dar a un equipo eléctrico de distribución para su correcto funcionamiento, y garantizar así su confiabilidad. Basado en un mantenimiento programado y el historial de fallas de un equipo eléctrico de distribución, se utiliza el modelo heurístico NSGA-II, para la obtención de un frente de Pareto, y ayudar así a tomar la mejor decisión sobre el mantenimiento. Se toman en consideración dos funciones objetivos, minimizar los costos del mantenimiento mientras que se maximiza la confiabilidad del equipo.

Óptimo, Confiabilidad, Minimizar, Maximizar, Estadística

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Introduction

The purpose of maintenance is to extend the lifetime of any equipment, or at least to extend the average time to the next failure. In addition, it is hoped that maintenance can reduce the frequency of power service interruptions. However, equipment maintenance is a function of the budget allocated by utilities. In this sense, utilities seek to optimise maintenance for their equipment, i.e. maximise the availability and serviceability of their existing equipment at the lowest cost used for maintenance. Reliability and cost are two important aspects considered by the power system operator in many deregulated power systems (J.E., 2016). Maintenance in electricity systems is divided according to the three entities that comprise it: Generation companies (GENCOs); Transmission companies (TRANSCOs) and Distribution companies (DISCOs) [1]. Force (2011) presents the results obtained from the strategies used for maintenance in the electric power industry. Reliability Centred Maintenance (RCM) is increasingly used; Maintenance based on probabilistic models; Mathematical models; Markov Chains; Statistical distribution; Stochastic processes; etc.

In Yssaad B. (2014) they use the RCM and the program called: failure types and criticality of their effects (FMECA). The two tools (RCM and FMECA) are used to plan future maintenance based on the available failure information from an Algerian power company. The data used by the FMECA are from the equipment of: 1) Power line, 2) Circuit breaker, 3) Bus bar, 4) Power transformer and, 5) Sectionaliser. The reliability, availability and maintenance distribution are based on the estimated failure rate reported by the equipment. The two-parameter Weibull distribution is the distribution used to represent the equipment failures. The costs used for optimal maintenance effectiveness are: material, device location, parts in stock, unavailability, personnel, technical data and outage time. The two-parameter Weibull function is again used in A. (2018) to represent the failure rate, and obtain the optimal maintenance of a piece of equipment. To determine the maintenance, a minimisation of the expected total maintenance cost function is performed.

The cost function used takes into account the costs of: Replacement, Minimum imperfect maintenance, Minimum repair, Operational cost and Cost per failure. Because electrical equipment is subject to different deterioration factors (covariates), maintenance optimisation for GENCOs and TRANSCOs with covariates is presented in Wang Y. (2016). Two covariates are used for generators and transmission lines. To simulate the random failures in the power system, the Monte Carlo technique applied to power systems is used. To describe the degradation process in the equipment, the two-parameter Weibull distribution is used and the Exponential function is used to quantify the effects of the covariates.

The mathematical model used for maintenance optimisation is based on four main causes: 1) minimisation of maintenance costs of generators, transmission lines and their operating costs; 2) time constraints on maintenance in generation units; 3) time constraints on maintenance in transmission lines; 4) security constraints, which include: limits on generation capacity, cost of starting and stopping a generation unit, limit on/off time of generation units, balance in the power system, limit on transmission power flows. These main causes are optimised by a Lagrangian relaxation. In Shayesteh E. (2018) the use of RCM in the generators and transmission lines of the IEEE 14-bus test power system is presented. In this article, electric power generation using renewable sources is included. For the application of RCM, the Severity Risk Index (SRI) proposed by the North American Electric Reliability Corporation (NERC) is used to select the most critical components within an electrical system. Three percentages are proposed as maintenance strategies (according to the desired level): 100%, 50%, 50% and 0% for fully maintained, half-maintained and maintenance-free equipment, respectively. Seven different costs are taken into consideration for each maintenance strategy. Within these costs, there is the environmental cost for the different types of generators, which evaluates their power output, heat generated, amount of CO_2 emission and social cost of CO_2. Optimal power flows are used to determine the impact of maintenance strategies through the expected energy not supplied (EENS) of the system.

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In Carnero M.C. (2017), a maintenance selection strategy for electrical distribution devices in hospital facilities is proposed. This strategy is mainly based on the incorporation of a model that takes into account the maintenance of facilities; maintenance of medical equipment; health and safety; environment; admission programme and medical areas. Maintenance is based on the methodology of Markov chains and on a programme called: Measuring Attractiveness through Category Based Evaluation (MACBETH). A group of specialists is included for each department incorporated into the model, to analyse the different devices of the hospital under study, through MACBETH. In L., L., & Z. (2018) a deterministic piecewise Markov process is presented, an interval methodology is used to model maintenance based on the condition of the equipment. This methodology is used to model the different parameters faced by the equipment such as: temperature, pressure, wear and tear, etc. A multi-objective algorithm called differential evolution of non-dominated classification is used for the optimisation of maintenance costs. The proposed methodology is applied to a centrifugal pump and a pneumatic valve in series of a nuclear power plant. For the determination of the failure rate of the elements, the technique of failure types and effects analysis (FMEA) is used.

Zhang S. (2019) presents the optimisation of maintenance in a nuclear power plant. Three objectives are presented to be considered which are: 1) a reactor is considered as a multi-component system, i.e. between multiple reactors there are structural dependencies, dependencies between internal and external units; 2) Optimisation from multi-component to multi-system; 3) Fuel minimisation. Minimisation is done to a valve system supplying water to two different reactors. The failure rate used in this paper is the exponential distribution, and the non-dominated sorting multi-objective genetic algorithm (NSGA-II) is used for the minimisation of the three objectives. NSGA-II is again used in Ayoobian N. (2016), three objectives are used to minimise: 1) Unavailability; 2) Costs and 3) Exposure time. The third objective is very important due to the existence of radioactive material in nuclear plants. Optimal maintenance is done to a high pressure water injection system. To take the best solution on the Pareto front, the help of an index of sensitivities is taken. The use of RCM and NSGA-II for maintenance scheduling in an electrical distribution system is presented in Piasson D. (2016). The objectives are twofold: to minimise preventive maintenance costs while maximising the reliability of the whole system. The equipment considered are: distribution transformers; voltage regulators; circuit breakers; capacitor banks; switchgear, protection and primary cables. Eleven years of historical fault data were used to model the reliability indices of the equipment. Su C. (2019) presents the use of NSGA-II for the optimisation of the maintenance of an electromechanical part of a wind turbine: the gearbox. The objectives to be optimised are availability and a cost function. The cost function includes the costs of: repair, inspection, failure and replacement. The failure rate used for the gearbox was made using historical data and the two-parameter Weibull distribution function is used, in addition, two adjustment factors are used for the distribution function: age reduction factor and failure rate increase factor.

The present research work has its fundamental basis in César L. Melchor-Hernández (2015), where historical failure data of an electrical equipment is used to determine the optimal maintenance that should be given to this equipment. Through the two-parameter Weibull distribution function, and the assumption of scheduled maintenance by the electric company (TBASE), the minimisation is made to a cost function to determine the optimal maintenance. However, in (César L. Melchor-Hernández, 2015) only one objective (minimisation of the cost function) is taken into account to determine the time (T) and the number of times (N) that the equipment should be maintained. In this research work it is proposed to use a multi-objective genetic algorithm to add another function, the reliability of the equipment.

By minimising the cost function and maximising the reliability of the equipment, a Pareto front is obtained, the objective of which is to help in maintenance decision making, to ensure that the resources allocated are used in the best way possible, without affecting the reliability of the electrical equipment under study.

Model

The distribution function (equation 1) is used to represent the behaviour of the equipment, according to its statistical failures [13].

$$\lambda(t,T)=\left(\frac{T}{T_{BASE}}\right)^{\beta}\frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} \tag{1}$$

Where:

t = statistical time of failure.

T = Optimal maintenance.

TBASE = Company scheduled maintenance.

β = Shape parameter.

α = Scale parameter.

The model used is based on a policy of imperfect maintenance with minimum repairs at each statistical failure. The total expected cost, includes the costs of: minimum repair; scheduled maintenance and; equipment replacement cost (equation 2), where the replacement cost will always be greater than or equal to scheduled maintenance (César L. Melchor-Hernández., 2015), (Nakagawa., 2005):

$$C(N,T)=\frac{1}{NT}\left[C_1\sum_{j=0}^{N-1}\int_0^{NT}\lambda(t,T)dt+(N-1)C_2+C_3\right] \tag{2}$$

Where:

C1 = Cost of minimum repair.

C2 = Cost of scheduled maintenance.

C3 = Cost of equipment replacement.

N = Number of optimal maintenance.

T = Optimal maintenance period.

Doing:

$$\frac{\partial C(N,T)}{\partial N}=0$$
$$\frac{\partial C(N,T)}{\partial T}=0 \tag{3}$$

Is obtained [13]:

$$C(N_k,T_k)_k=\left(\frac{C_2(N_k-1)+C_3}{(2\beta-1)C_1}\right)^{1-\frac{1}{2\beta}}\frac{2\beta C_1}{\sqrt{N_k\alpha T_{BASE}}} \tag{4}$$

However, this model only minimises the cost function, without taking into account the reliability of the electrical equipment. The maintenance of electrical equipment must consider two fundamental aspects: minimising maintenance costs while maximising reliability. When you want to maximise and minimise the objectives, you cannot demerit any of them, i.e., there cannot be a solution that optimises all the objectives. For this reason, multi-objective evolutionary algorithms are used, as they have the ability to find multiple solutions in a single iteration, the results of which are known as the Pareto front. The multiple solutions are of great help in decision making for maintenance budgeting and reliability of electrical equipment.

The use of the NSGA-II model in the electrical industry has been considered on many occasions. The model presented in this paper aims to use the basic data of any electrical distribution company and the use of the NSGA-II heuristic model to maximise equipment reliability while minimising maintenance costs. Equipment reliability is the probability that a piece of equipment will perform its function properly over a period of time under normal operating conditions.

For this work, equipment reliability will be based on equipment failures, depending on the maintenance costs used. Therefore, equipment failures will be determined by:

$$\int\lambda(t,T)dt \tag{5}$$

However, to ensure the optimisation of the maintenance, the following restrictions will be taken into account:

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The number of failures obtained by NSGA-II will be:

$$\sum_{j=0}^{N-1}\int_{0}^{NT}\lambda(t,T)dt \geq 0 \tag{6}$$

To ensure that N and T are within the range of statistical failures (t), the average life of the equipment is taken as the maximum allowable:

$$0 < NT < \alpha\Gamma\left(1+\frac{1}{\beta}\right) \tag{7}$$

Case studies

In Stillman (2003) the failure history of a 33kV insulator, which is part of an urban feeder, is presented. The statistical failure times of the electrical distribution equipment under study are as follows:

No.	Failure (Month)	No.	Failure (Month)	No.	Failure (Month)
1	90	11	145	21	191
2	100	12	160	22	193
3	104	13	165	23	193
4	109	14	170	24	195
5	111	15	175	25	195
6	113	16	178	26	198
7	124	17	180	27	199
8	130	18	181	28	200
9	133	19	186	-	-
10	138	20	190	-	-

Table 1 Failure times of the electrical equipment

To carry out the sensitivity analysis of the model, we will use the data of: C1 = 1000; C2/ C1 = 3; C3/ C1 = 3, 10, 20, 50, 100 and a TBASE = 12 months; from (César L. Melchor-Hernández., 2015). We will start with case 1. Figure 1 shows the reliability of the equipment with the proposed failure rate (1); the failure rate of the two-parameter Weibull distribution and the statistical failures of the equipment. If the costs for case 1 and its current 12-month maintenance are analysed, it can be verified that the equipment replacement cost is equal to the cost of the scheduled maintenance. Therefore, in Figure 1, the proposed reliability function -red colour- is shown. The function indicates that this equipment has no improvement with annual maintenance, and should not be maintained at all. The best option is to replace it, when it fails, as its costs (maintenance and replacement) are equal.

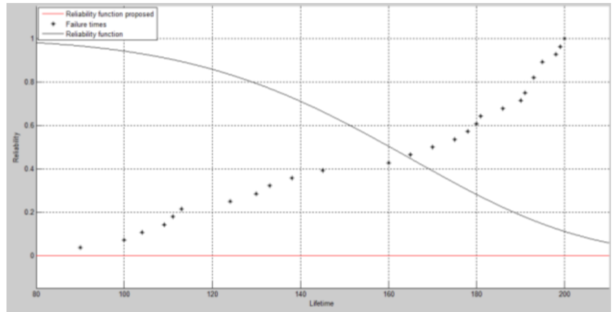

Figure 1 Reliability of the equipment with case 1 parameters

Table 2 shows the results obtained by NSGA-II. 150 generations are used, with a mutation and outcrossing rate of 0.8. For practicality, we put the most outstanding results, of which we can describe the following. If we have semi-annual maintenance, the costs are between 468.75 and 434.78; however, the number of failures is less than zero, constraint (6) is not satisfied, therefore, it is not plotted on the Pareto front. If we have annual maintenance, the costs will be 245.90, again constraint (6) is not met. After the annual maintenance, we have maintenance that indicates that maintenance can be given at 2 and 3 years, without affecting the number of failures of the equipment. This is because instead of maintenance, it is better to replace the equipment with a new one when it fails (due to the costs involved).

N	T (months)	Cost	Number of failures
1	6.4	468.75	1.25E-09
1	6.6	454.545455	1.73E-09
1	6.9	434.782609	2.75E-09
1	12.2	245.901727	1.07E-06
1	24	125.052587	0.001262076
1	35	87.5796397	0.065287388
1	37.2	83.9654946	0.1235164
1	40.1	81.5668227	0.270829589

Table 2 Results obtained with NSGA-II, for case 1

Figure 2 shows the Pareto front for this case. NSGA-II cannot find a balance between the costs and the expected number of failures, the main reason being the costs used, as the replacement cost of the equipment is equal to the cost of the scheduled maintenance. Therefore, the proposed reliability function shows that this equipment should not be maintained at all and wait for the failure of the equipment to be replaced by a new one.

The Pareto front shows costs between 81.5 and 83.96 for the optimisation of the two objective functions under study, complying with constraint (6).

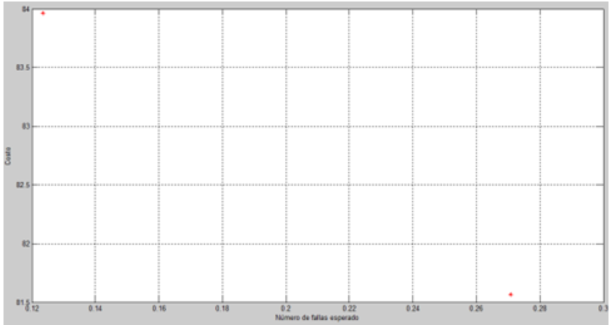

Figure 2 Pareto front with NSGA-II, for case 1

For case 2, the costs used show that the cost of replacement is approximately three times higher than the cost of scheduled maintenance, therefore, NSGA-II starts to find a balance between reliability and maintenance costs.

César L. Melchor-Hernández (2015) shows that the minimum cost for case 2 is a value of 213.79. In Figure 3 it can be seen that a value lower than 215 results in more than one equipment failure. In this case, the reliability of the equipment can be improved by assigning a budget greater than 215, which ensures less than one failure in the average life of the equipment (7).

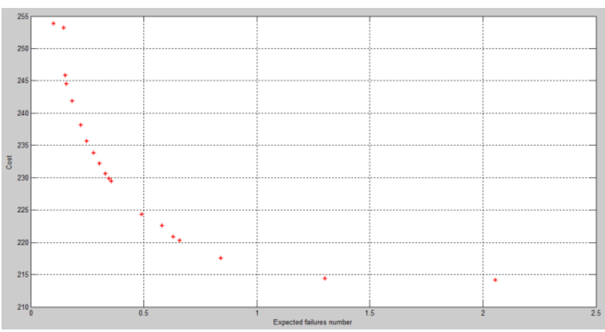

Figure 3 Pareto front with NSGA-II, for case 2

When the cost of replacing a piece of equipment is six times more than the cost of scheduled maintenance, case 3, NSGA-II starts to find more balancing options between the two objective functions, as shown in Figure 4. Figure 4 shows that, if we address a budget between 320 and 400, we could obtain less than one equipment failure, i.e., maintain the equipment every 15 or 20 months, and 6 or 5 times, respectively; however, the cost increases with an approximate value of eighty-three more, compared to the minimum (306.5982).

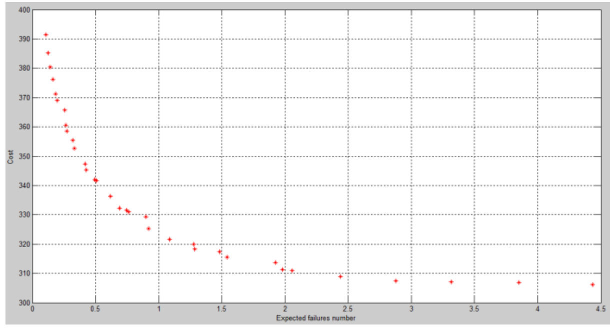

Figure 4 Pareto front with NSGA-II, for case 3.

Table 3 shows the most important results for case 3. The minimisation of this case, coincides with César L. Melchor-Hernández (2015), in which we have an N of 7 and a T of 19, however, with these values we have almost five failures in the equipment. With a higher budget, for example 328,4749, the equipment can be serviced 5 times every 20 months and less than one failure would be obtained in the average life of the equipment.

N	T (months)	Cost	Number of failures
6	15	390.0946	0.1085
7	14	388.96	0.1180
4	19	383.6092	0.1543
6	18	330.8382	0.7305
5	20	328.4749	0.8474
7	18	314.5697	1.6357
6	21	306.8480	3.6628
7	19	306.5982	4.9237

Table 3 Results obtained with NSGA-II, for case 3

For case 4, the cost of replacing the equipment is approximately 16 times more than the cost of scheduled maintenance. Table 4 shows that with a budget of 526.52, there would be only one failure during the average life, restriction (7), of the equipment, so reliability would be guaranteed for this equipment. With a lower budget, 461.70, and with a maintenance period of 13.1 months, there will be approximately 11 failures in the equipment. By means of a risk matrix of the configuration of the system under study, it can be determined which is the best budget that would be assigned to this equipment.

N	T (months)	Cost	Number of failures
1	1	50000	4.63E-18
7	7.7	1261.59	2.27E-04
8	12.2	728.03	0.05
16	11.4	526.52	1.03
20	10.9	500.40	2.08
17	12.4	481.19	3.43
19	12.2	471.03	5.18
19	13.1	461.70	10.91

Table 4 Results obtained with the NSGA-II, for case 4

Figure 5 shows the Pareto front for case 4. The dispersion of NSGA-II works well, due to the costs used for this case. A balance between the two objective functions is observed, which allows us to have a wide number of solutions, for the best management of the allocation of financial resources to the maintenance to be given to the equipment under study.

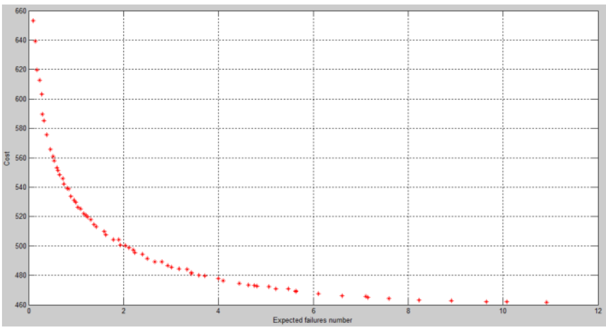

Figure 5 Pareto front with the NSGA-II, for the case 4

For case 5, we have that the cost of replacement is approximately 33 times more than the cost of scheduled maintenance; therefore, maintenance should have a short periodicity, in order to prolong the life of the equipment. Table 5 shows an optimal period of 9.6; however, the number of failures would be approximately 23. By allocating six-monthly maintenance, the reliability of the equipment can be guaranteed, without failures, during the average life of the equipment, however, the budget would increase by more than two hundred and forty, compared to 9.6 months.

N	T (months)	Cost	Number of failures
1	1	100000	4.63E-18
32	2.7	2233.79	1.12E-05
43	6.1	862.61	0.26
32	9.4	658.85	5.18
36	9.4	634.14	9.59
41	9.1	625.81	13.49
33	10.3	623.23	15.83
41	9.6	618.91	23.60

Table 5 Results obtained with NSGA-II, for case 5

Figure 6 shows the reliability function of the equipment, with the different maintenance periods of Table 5. If the equipment is located in a risky place, e.g., hospitals, laboratories, banks, etc., a budget of 862.61 can be allocated to ensure reliability in this area of the electrical network.

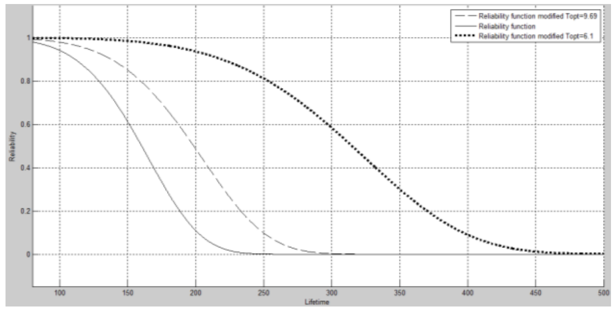

Figure 6 Reliability function of the equipment with the parameters of case 5 and Table 5

Figure 7 shows the Pareto front for case 5. It can be seen that there are several budget options, depending on the required reliability of the equipment.

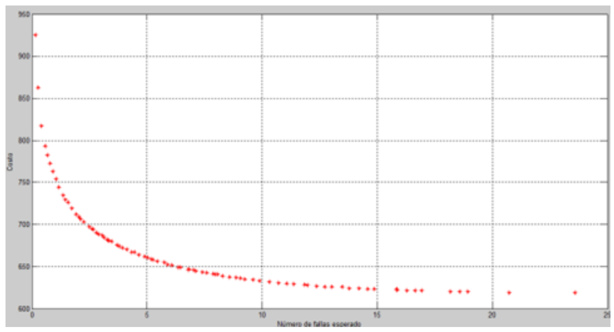

Figure 7 Pareto front with the parameters of case 5 and Table 5

Table 6 shows the end-of-life failure times for a group of generators. Out of 36 generators, the end-of-life failures of 16 pieces of equipment are used, let us assume that the generators are under the same operating conditions and maintenance policies. For this study, only the failure data of the 16 sets will be taken (L Seung-Hyuk, 2009).

Failure number	Time of failure (year)	Failure number	Time of failure (year)
1	6	9	18
2	7	10	18
3	12	11	20
4	12	12	20
5	13	13	25
6	16	14	25
7	16	15	27
8	18	16	31

Table 6 Failure time of a group of generators

Table 7 shows the parameters obtained in L Seung-Hyuk (2009) and the results obtained with the model proposed in César L. Melchor-Hernández (2015).

	Hybrid method	Maximum likelihood estimation method	Analytical method	Proposed method
Beta	2.593	2.897	2.680	2.897
Alpha	19.541	19.931	20.070	20.005
Half-life	17.341	17.757	17.875	17.856
Standard deviation	7.206	7.195	7.193	6.544

Table 7 Parameters: beta, alpha, half-life and standard deviation

The cost data used for this new case are: C1 = 1000; C2/ C1 = 3; C3/ C1 = 100 and an annual maintenance policy. Table 8 shows the most important results obtained with NSGA-II. For the first result, the logical result can be observed with NSGA-II, since, if annual maintenance is given, the equipment will not have any failure; however, the costs are equal to the cost of equipment replacement. So, in order to have no failures, the model suggests replacing the equipment every year. Since the number of failures is less than one, constraint (6) is not met. If one wants to opt for the lowest cost used in the maintenance of the equipment, it is suggested to have maintenance every seven years, with the consequence of expecting a large number of failures, forty. On the contrary, if we have biannual or minor maintenance, the failures can be reduced between sixteen and one, with a cost of 1609.20 and 2248.99, respectively.

N	T (years)	Cost	Number of failures
1	1	100000	8.43e-8
12	5	2248.99	1.93
16	5	1869.50	4.56
14	6	1762.65	9.06
17	6	1609.20	16.13
16	7	1595.48	33.69
17	7	1582.73	40.34

Table 8 Results obtained with NSGA-II, for the failure data of the group of generators

Figure 8 shows the Pareto front of Table 8. It can be seen that the options have a good spread of results. Because sixteen equipment failure data are used, the maintenance options are few.

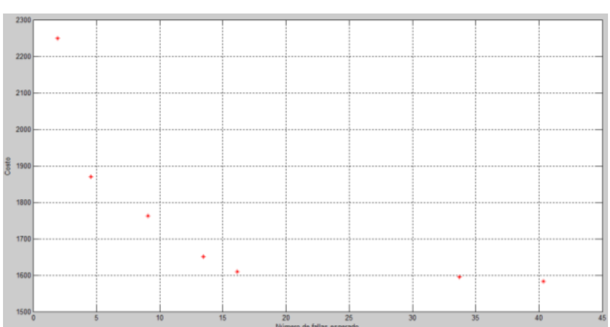

Figure 8 Options for determining maintenance on transformers

Conclusions

The main objective of this research work is to use the NSGA-II with the work developed in (César L. Melchor-Hernández., 2015). In (César L. Melchor-Hernández., 2015) only the optimal maintenance of the equipment was determined; however, with the help of the NSGA-II, the failures that the equipment will have with the maintenance obtained can be determined. In addition, with the Pareto front, different maintenance periods and the failures that the equipment under study will have are obtained. With these options, the decision making for the maintenance of the equipment will be based on: total costs, maintenance periods and expected failures. With this information, the department in charge of maintenance can make the corresponding decisions based on the reliability needed for the equipment under study. For the case of the 33kV insulator, twenty-eight equipment failure data and annual base maintenance are used. In case 1, no maintenance is required, as the cost of replacement is equal to the cost of scheduled maintenance, therefore, the Pareto front is null, as the best option is to replace the equipment when it fails. However, when equipment replacement costs tend to be higher (cases 2, 3, 4 and 5), the Pareto front works very well in giving different options of periods and, the failures that will occur in the equipment with different maintenance periods. Table 7 shows the comparison of the different statistical parameters, in a group of generators. In which we can observe that the proposed model has a lower standard deviation. The Pareto front in Figure 8 shows 7 maintenance options, this is due to the few failures used for this case, sixteen; however, the model fits well with the results obtained in previous research.

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