A GENETIC ALGORITHM BASED METHODOLOGY FOR PRIORITIZING MAINTENANCE ACTIONS OF POWER DISTRIBUTION UTILITIES

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ABSTRACT

Yearly, power distribution utilities plan preventive maintenance actions, aiming at reducing durations and frequencies of power outages. Currently, utilities planning engineers prioritize maintenance actions based on multiple spreadsheets, personal experience and cumbersome procedures. Typically, they simply rank the actions according to their expected benefits. Then a set of actions is selected depending on their costs and on the budgets available. This paper proposes a Genetic Algorithm (GA)-based methodology which provides an optimal plan of maintenance actions considering the financial restrictions. Four major types of actions are addressed, regarding the targeted assets: general Medium Voltage (MV) equipment, general Low Voltage (LV) equipment, MV/LV transformers and poles. To apply the proposed methodology, a case study was set up considering a Brazilian power distribution area. By executing the methodology for each of the four major types of actions, a plan of optimal maintenance actions was produced, considering the corresponding budget restrictions. The methodology succeeded in providing an optimal plan of suitable actions for a real power distribution substation.

INTRODUCTION

Yearly, power utility engineers plan preventive maintenance actions involving the whole concession area. With such actions, they intend to replace stressed equipment, make trees pruning, prevent malfunctioning from shutting down the entire power feeder and improve the power network overall operability. Conducting the referred maintenance actions is crucial to decrease failure rates, reduce the utility service time and lessen the number of customers that undergo power outages. Consequently, continuity indexes SAIDI and SAIFI (represented by the Brazilian continuity indexes DEC and FEC [1]), portrays improvements in the power network reliability. Furthermore, customers complaints are reduced, and many regulatory penalties are avoided. Ideally, conducting all necessary maintenance actions would bring the highest benefits. However, such actions are restricted by CAPEX and OPEX budgets limitations. Then, planning engineers attempt to determine the most efficient set of maintenance action orders which fits the budgets restrictions.

This paper mainly focuses on maintenance action orders regarding the distribution networks of EDP, a Brazilian power utility which supports this work. Currently at EDP, the optimal set of action orders is determined based on multiple spreadsheets, concerning power outages records, field equipment measurements and action orders proposed by the field inspectors, according to the utility standard [2]. This may be considered a cumbersome process, because it relies on personal experience, is time consuming and is not assisted by any automation scheme. Besides, typically, actions are simply ranked in terms of their expected benefits and selected according to their costs and budgets available. As no optimization is carried out, the selection made does not assure that an optimal planning is executed.

This work proposes a Genetic Algorithm (GA)-based methodology as an attempt to improve the overall process of prioritizing maintenance action orders. Four major types of actions are addressed: general MV equipment, general LV equipment, MV/LV transformers and poles. Due to the information available towards them, specific formulations are required for each of the action types.

The methodology was implemented as a software module inside the power utility planning environment, where topological data, power outage records and field equipment measures are available. Though most of data and specific procedures were design to meet typical power distribution requirements. With such methodology,

planning engineers' work is streamlined. They are only required to ensure the input data are available, start the prioritization process and, ultimately, consolidate the set of action orders that are supposed to be effectively carried out.
In a case study, the methodology was applied to some power distribution networks belonging to EDP/SP, which is a Brazilian utility that attends approximately 1,800,000 customers. Then, a feasible set of maintenance action orders fitting the financial restrictions was provided, and the methodology was considered successful.

METHODOLOGY

The proposed methodology comprises three main steps: input data reception, evaluation of all necessary maintenance action orders and prioritization process for determining the optimal set of orders.

Input data

Topology

The conducted power network simulations are supported by a Geographic Information System (GIS) which contains line sections lengths, customers' demands, lines connectivity, etc.

Power outages records

Power outages affecting the monitored power networks are recorded in the Outage Management System (OMS). Such records support the assessment of the equipment failure rates and the utility's service times, providing statistical data to simulations concerning continuity indexes.

Field equipment records

Based on records of automated devices through the utility's Supervisory Control and Data Acquisition (SCADA), overloaded equipment is detected.

Automatic action orders producer

Given that maintenance action orders are produced only through field visual inspections, a complementary software-based module is demanded in order to produce. Then, the Automatic Action Orders Producer (AAOP) is devised to enable the production of MV/LV transformers and general LV equipment action orders.

Maintenance action orders

Annually, the power utility assets are inspected by maintenance crews, when they notice ongoing problems and predict future hurdles. Then, they produce Maintenance Action Orders and record them in the utility Enterprise Resource Planning (ERP) system. These orders represent the needs for intervention. Due to the high amount of orders and limited budgets, they need to be prioritized.

Evaluating maintenance action orders

The maintenance action orders are evaluated in terms of a Merit Index (MI), which numerically relates the benefits provided with their associated cost. The following subsections present further details concerning the MI assessment for each of the four types of action orders.

General MV equipment

For actions in general MV equipment, the benefits are represented by reductions in the continuity indexes – SAIDI (System Average Interruption Duration Index), SAIFI (System Average Interruption Frequency Index), and ENS (Energy Not Supplied). To compute such reductions, a Continuity Indexes Calculation Module (CICM) is devised. Based on the power outages recorded in the utility's OMS, the CICM estimates the statistical parameters: failure rates (FR) and service times (ST). Each action in general MV equipment provides reductions in FR and ST.
To assess the benefits of a particular maintenance action, the continuity indexes are recomputed by the CICM, as illustrated by Figure 1, where SAIDI, SAIFI and ENS are the initial indexes and SAIDI', SAIFI' and ENS' are the computed ones after the maintenance action is conducted.
The Merit Index is computed through Equation (1) where $\Delta SAIDI$, $\Delta SAIFI$ and ΔENS are the reductions in SAIDI, SAIFI and ENS, respectively, representing the benefits. $Cost_{gen.\ MV}$ means the financial value of the assessed action order.

$$MI_{gen.\ MV} = \frac{\Delta SAIDI + \Delta SAIFI + \Delta ENS}{Cost_{gen.\ MV}} \quad (1)$$

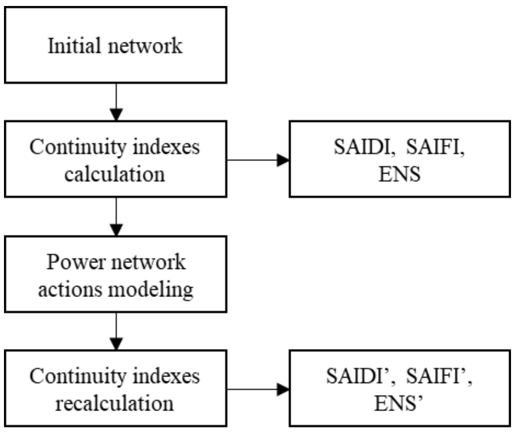

Figure 1 – Continuity indexes recomputing

General LV equipment

Posed that field inspections do not generate maintenance action orders in general LV equipment, they are produced by the AAOP. Such module selects deficient LV networks matching the following conditions:

- Cable arrangements are not fully compact;
- The LV network has at least one power outage record belonging to the group of associated causes:

- winds, corrosion, vegetation, downed trees, tree twigs, kites and objects on the network;

For a selected LV network, three possible maintenance action orders are produced: compact cable installation, spacer installation and tree pruning. During the prioritization step, one of these three orders will be optimally chosen.

All three maintenance action orders benefits are indirectly quantified as the numbers of registered power outages that could be mitigated. A list of avoided power outage causes is presented by Table 1.

Table 1 – Maintenance actions and avoided power outage causes

Maintenance action	Avoided power outage causes
Compact cable	Vegetation, tree twig, winds, kite, corrosion, object on the network
Spacer	Vegetation, tree twig, winds
Tree pruning	Vegetation, downed tree, tree twig

The MI for each of the three maintenance action orders is computed according to Equations (2), (3) and (4). In these equations, NO_{mult}, NO_{spacer}, and NO_{prun} are the numbers of registered power outages that could be tackled by multiplex, spacer and pruning trees, respectively. $Cost_{mult}$, $Cost_{spacer}$ and $Cost_{prun}$ are the corresponding costs.

$$MI_{gen.\ LV}^{mult} = \frac{NO_{mult}}{Cost_{mult}} \quad (2)$$

$$MI_{gen.\ LV}^{spacer} = \frac{NO_{spacer}}{Cost_{spacer}} \quad (3)$$

$$MI_{gen.\ LV}^{prun} = \frac{NO_{prun}}{Cost_{prun}} \quad (4)$$

MV/LV transformer

For maintenance actions in MV/LV transformers, the MI is computed according to Equation (5), where EO is the transformer equivalent overload, NC is the number of customers and NO is the number of power outages. The corresponding multiplying coefficients - k_{EO}, k_{NC} and k_{NO}, respectively – are initially unitary, but may be calibrated based on usage. $Cost_{transf.}$ means the financial value of the transformer action order.

$$MI_{transf.} = \frac{k_{EO}EO + k_{NC}NC + k_{NO}NO}{Cost_{transf.}} \quad (5)$$

Poles

By replacing old poles, the utility's goal is to prevent the network continuity indexes from worsening. To assess maintenance action orders involving poles, some steps are taken.

First, maintenance action orders in adjacent poles are gathered, producing the *Grouped Maintenance Action Orders*. All subsequent procedures consider the compound orders concept. Second, each of these grouped orders are evaluated, considering the following quantities as the benefits quantification:

- Number of customers downstream the related poles;
- Number of registered power outages concerning customers downstream the related poles;

At last, the MIs for grouped maintenance action orders are computed, based on the benefits quantification and the corresponding cost, according to Equation (6). In this equation, NC is the number of customers downstream the related poles and NO is the number of registered power outages concerning the customers downstream the related poles, with k_{NC} and k_{NO} the respective coefficients. These are initially unitary but may be calibrated based on usage. $Cost_{poles}$ means the financial value of the poles action order.

$$MI_{poles} = \frac{k_{NC}NC + k_{NO}NO}{Cost_{poles}} \quad (6)$$

Prioritizing maintenance action orders

This work proposes a methodology to determine the optimal set of maintenance action orders, which brings the highest benefits while considering the budgets restrictions.

Problem codification

Considering a GA approach, an individual – regarded as a particular solution - consists of a chromosome, in which each gene means an action order that may be conducted. Integer 0 represents no action order. In the following example, an individual's chromosome (*Indiv*) indicates that the orders 5, 10, 12, 21, 23 and 30 are selected from all N necessary action orders.

$$All\ orders = \{1, 2, 3, \dots N\}$$
$$Indiv = (5, 10, 12, 21, 23, 30)$$

The chromosome length is estimated as the number of possible maintenance action orders that could be carried out, according to Equation (7).

$$Chrom. length = \left\lceil \frac{Total\ budget}{Avg\ cost} \right\rceil \quad (7)$$

In this equation, $Total\ budget$ is the sum of CAPEX and OPEX portions destined to the referred type of maintenance action orders. The term $Avg\ cost$ is the average cost of the evaluated action orders.

Objective function and restrictions

An individual's grade, which equals the objective function f_{Obj}, is computed according to Equation (8).

$$f_{Obj} = k_{pen} \cdot (MI_1 + \cdots MI_i + \cdots + MI_m) \qquad (8)$$

In this equation, m is the number of non-zero action orders in the individual's chromosome and MI_i is the MI of the action order represented by the i-th position in that string.

Concerning the restrictions, the weighting coefficient k_{pen} accounts for the restrictions mismatching. As synthesized by Equation (9), the assessed individual is slightly penalized if the action orders total cost is inferior to the available budget. Yet, it is severely penalized if the orders total cost surpasses the available budget.

$$k_{pen} = \begin{cases} \sim 0, & Tot.Cost > Budget \\ \dfrac{Tot.Cost}{Budget}, & Tot.Cost < Budget \end{cases} \qquad (9)$$

Problem solution

From the last GA generation, the best evaluated individual is considered the problem solution. Its genes correspond, one by one, to the maintenance action orders that should effectively be carried out.

RESULTS

The proposed methodology was applied to a real Brazilian power distribution system belonging to an EDP concession area, depicted by **Erro! Fonte de referência não encontrada.**. It comprises seven power feeders and the related area contains around 33,404 customers. The power utility OMS system indicates 16,564 power outages concerning the investigated area, registered from January 2015 to December 2018. The referred area was visually analyzed by the utility's field inspectors. They then produced several maintenance action orders, due to ongoing and likely problems affecting the power utility network.

Through real inspections in the pilot area, the utility's maintenance crews produced maintenance action orders concerning poles (Table 2), transformers (

Table 3) and MV general equipment (Table 4). In order to optimally produce the sets of maintenance action orders, the devised methodology is executed.

All costs were provided in Brazilian currency (R$), as all actions and budgets were obtained in R$. Nevertheless, the methodology may be applied to any other currency.

In the tables, the orders are sorted in descending order in terms of their MI. Moreover, the action orders highlighted in blue are the prioritized ones. The corresponding portions of the CAPEX and OPEX budgets are the following: R$ 100,000.00 for actions at poles, R$ 700,000.00 for actions at MV/LV transformers and R$ 425,000.00 for actions at general MV equipment.

Based on the results obtained, some comments may be stated. First, one may notice that the highest ranked action orders, in terms of MI, are all picked. In fact, they provide greatest benefits with the least costs.

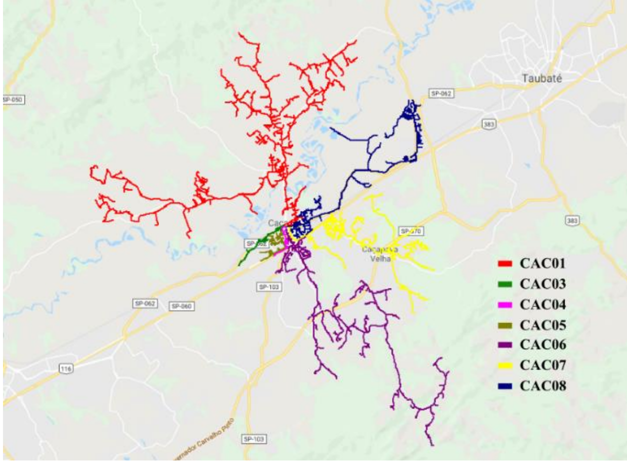

Figure 2 – Area where tests were conducted

Table 2 – Maintenance action orders at poles

No.	Circ.	Location Reference	MI	Cost (R$)	Prioritized order(R$)
1	CAC01	FF015235	5968.82	3,560	3,560
2	CAC01	BF015287	2108.35	3,560	3,560
...					
22	CAC01	BF015237	23.83	3,560	3,560
23	CAC06	BF510399	14.52	3,560	
24	CAC06	BF510399	14.52	3,560	
25	CAC06	BF015259	13.74	3,560	3,560
...					
35	CAC01	BF015058	0	3,560	
Total cost (R$)				**132,300**	**98,720**
Total budget (R$)				**100,000**	

Table 3 – Maintenance action orders at MV/LV transformers

No.	Circ.	Location reference	MI	Cost (R$)	Prioritized order (R$)
1	CAC06	ET30469	64.98	18,000	18,000
2	CAC02	ET505243	57.79	18,000	18,000
...					
37	CAC02	ET30141	24.87	18,000	18,000
38	CAC06	ET31667	24.43	18,000	18,000
39	CAC06	ET30458	23.61	18,000	
...					
78	CAC02	ET502572	3.84	18,000	
79	CAC02	ET4768	3.51	18,000	
Total cost (R$)				**1,422,000**	**684,000**
Total budget (R$)				**700,000**	

Second, by selecting intermediate-graded action orders, the methodology succeeds in an efficient utilization of the total budget. During poles actions prioritization, it allocates R$ 98,720.00 out of R$ 100,000.00 (98.72%).

For MV/LV transformers, R$ 684,000.00 out of R$ 700,000.00 (97,71%) is consumed. By prioritizing actions in general MV equipment, R$ 424,844.00 is allocated out of R$ 425,000.00 (99,96%).

Table 4 – Maintenance action orders at general MV equipment

No.	Circ.	Maintenance action	Location reference	Ext. (km)	MI	Cost (R$)	Prioritized order (R$)
1	CAC06	Compact cable	BF15138	0.09	1601.42	10,512	10,512
2	CAC07	Compact cable	BF15160	0.105	596.58	12,264	12,264
...							
8	CAC07	Compact cable	BF519802	0.055	194.48	6,424	6,424
9	CAC06	Compact cable	RL509625	0.14	157.29	16,352	16,352
10	CAC07	Compact cable	BF519803	0.165	83.09	19,272	
...							
14	CAC07	Compact cable	BF15266	0.93	38.35	108,624	108,624
15	CAC06	Compact cable	BF15298	0.685	35.18	80,008	80,008
16	CAC02	Recloser	BF1471	1	16.29	50,500	50,500
17	CAC02	Tree pruning	RL7038	1	9.41	30,954	
...							
25	CAC02	Recloser	BF3719	1	3.07	50,500	
26	CAC06	Compact cable	BF15253	0.275	2.44	32,120	32,120
...							
33	CAC02	Tree pruning	BF512536	1	0.02	4,397	
					Total cost (R$)	**763,059**	**424,844**
					Total budget (R$)	**425,000**	

Third, the devised methodology represents a great breakthrough as it allows the comparison among action orders of multiple types, concerning general MV equipment. This is accomplished by computing the Merit Indexes based on the continuity indexes SAIDI, SAIFI and ENS reductions.

CONCLUSIONS

This paper deals with the problem of producing an efficient set of maintenance action orders with limited CAPEX and OPEX budgets. To address such challenge, a GA-based methodology is proposed.

A first outstanding point is the utilization of multi-sourced data in order to assess the maintenance action benefits. This assessment is conducted based on information such as topological data, field devices readouts and power outage records. Then, the proposed methodology is even more beneficial if the utility's corporate systems are fully available and integrated.

The development of the Continuity Indexes Calculation Module was paramount for evaluating maintenance action orders towards general MV equipment. By calculating actions benefits based on the continuity indexes reductions they provide, the module establishes a common basis to evaluate distinct maintenance actions.

By adopting a Genetic Algorithm approach, the methodology proved to succeed in selecting an efficient set of maintenance action orders, considering budgets restrictions. Based on the results, it was possible to allocate budget efficiently, with more than 97% of utilization.

Further investigating the results, some intermediate-graded action orders are selected to gather the set of prioritized orders, proving that the prioritized orders are not simply those with the highest grades.

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