OPTIMIZATION OF MAINTENANCE ACTIONS IN DISTRIBUTION NETWORKS

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INTRODUCTION
The paper presents a methodology to determine budget resources to predictive and preventive maintenance actions. The methodology includes an optimization model to locate the resources that consider ranking indexes to network inspections and corrective actions, taking into account budget constraints.

The overall methodology envisages reducing failure rates and therefore reliability indexes such as SAIDI and SAIFI, which have been regulated through specific resolutions in Brazil.

For this work, the predictive actions were considered as the inspections in feeders and equipment located at the distribution network like reclosers, switched capacitor banks, transformers, voltage regulators and load switches. The inspections considered were tree trimming, detailed general and instrumental, for feeders, and periodical, for the equipments. The preventive actions include corrective actions (repairs) in the components of the distribution network where were detected defects by the inspections.

A mathematical programming formulation alongside a rule based system allow ranking the main actions to be executed so that the best overall index is achieved subject to the given technical and financial constraints. Regarding predictive maintenance the index takes into account attributes such as the risk of failure development, the strategic importance of the area, and the density of customers. As preventive maintenance regards, the index takes into account failure risks, accident risks and indexes related to the deterioration of SAIDI and SAIFI.

The methodology was developed through a computational program named PGMD. In order to illustrate the proposed method an example applied to the AMPLA distribution system is presented. The AMPLA is an utility company whose working area is the inner of state of Rio de Janeiro, Brazil.

METHODOLOGY
In general, power utilities in Brazil have an annual budget [1,2] to the maintenance actions rather limited, oriented to emergency situations, with low budget to preventive actions.

The developed methodology aimed at planning and optimizing the available resources to predictive (inspections) and preventive (repairs) maintenance, based in decision criteria defined by the company. The purpose is to prioritize the inspections and preventive actions to allow for an ordered maintenance plan. Such a plan should be able to decrease failure rates, and consequently, improve quality of service measured by indexes such as SAIDI and SAIFI.

The first stage of the work considered the maintenance process and strategy used in the utility [3]. Also, the inspection criteria were defined and which pieces of equipment should be managed by the maintenance procedure.

In the second stage, a survey in database and existing managerial systems in the utility [4] was accomplished. This survey facilitated data acquisition to be used in the ranking of maintenance actions and to propose changes in the process to adjust them to the new system.

Soon after, some new indexes to characterize the primary distribution network state were defined [5]. This work established parameters to reveal the risk of the system developing defects, failures and personal accidents.

In the forth stage, it was conceived the model for the optimization of maintenance actions. This model was developed through a software named PGMD – Distribution Maintenance Management Program, and applied to the feeders and equipment in the Marica substation at AMPLA.

Two main modules compose this software: Predictive Maintenance and Preventive Maintenance.

Based on circuits and equipment information (descriptive attributes) and on the available budget, the Predictive Maintenance Planning Module aims “to plan” the inspections, that is, to define a ranking of inspections according to rules, such as risk of failure development, the strategic importance of the area, and the customer density. Therefore, the rules are firstly applied to define the need of inspections. After that, the inspections candidates are prioritized through the use of integer programming techniques, by defining an objective function that maximizes the global merit index subject to a budget constraint.

The Preventive Maintenance Planning Module produces, from the defects identified in the inspections prioritized for the previous module, a plan of repairs for correction of defects, prioritized according to a model similar to the one used in the predictive module. The merit index for each repair is determined through the evaluation of the risk of defects turning into failures, the influence in SAIDI and SAIFI...
indexes, the risk of the customer claims due to damages in electric appliances and the personal accident risks.

**PREDICTIVE MAINTENANCE PLANNING MODULE**

Based on the network data and on the interruptions historical data, the Predictive Maintenance Planning Module determines an inspection plan (which, where, how many times and when). Such a plan aims at reducing failures rates in the distribution system. Each inspection can be associated with an OSI (administrative inspection order), that details the inspection procedures.

The inspections can be carried out in distribution feeders or in network equipment. There are 3 types of feeder inspections: detailed inspection, instrumental inspection and tree trimming. Equipment inspections comprise periodical ones defined by operational exhausting or manufacturer recommendation, in accordance with their own characteristics.

The decision for inspections is based on inspections rules, e.g.: **If the feeder has many long duration interruptions and important customers, then the inspection must be carried out.**

The existence of such rules suggests using an expert system, whose function is to decide on making or not each inspection. Figure 1 shows an example of a decision scheme applied to tree trimming in feeders.

The Predictive Maintenance Planning Module operates according to Figure 2. After the rules are applied, the inspections become candidate ones, associated to a merit index. As equipment inspections regard, it was stipulated that the merit index would be equal to 1. Regarding feeder inspections, the merit index is calculated based on three parameters:

- Risk of Failure Development (RDD): this index is defined as the length of the feeder subject to failures caused by natural agents (like trees, wind, animals, salinity, human causes), given by the percentage of the total feeder length.
- Strategic Importance of Area (IEA): this index is defined as the number of customers in the feeder bearing energy consumption greater than a reference value, as a percentage of the total numbers of customers in the feeder.
- Index of Customer Density (IDC): provides the relation between the number of clients and feeder supply area.

These parameters provide a ranking system to be used in the optimization model.

Once all candidate inspections have a merit index assigned, they are the prioritized based on the optimization model. This model seeks to maximize the global merit index subject to the budget constraint. The prioritization is determined by a mathematical programming method (integer programming) in which the objective function and constraints are given as follows:

\[
\text{Max} \sum_{i=1}^{3} \sum_{j=1}^{5} D_{i,j} \cdot I_{i,j} \cdot (p_1 \cdot \text{RDD}_{j} + p_2 \cdot \text{IEA}_{j} + p_3 \cdot \text{IDC}_{j})
\]

\[
s.t. \sum_{i=1}^{3} \sum_{j=1}^{5} D_{i,j} \cdot C_{i,j} \leq R
\]

where:
- \(i\): Inspection type
- \(j\): Feeder
- \(D_{i,j}\): Binary decision variable: when it is equal to one, inspection type \(i\) is carried out, otherwise it is not.
- \(I_{i,j}\): Binary decision variable, that is a result from the expert system based on the decision rules, that are applied to a given inspection \(i\) in feeder \(j\). If it is equal to one, inspection is a candidate one.
- \(C_{i,j}\): Inspection cost for type \(i\) in feeder \(j\).
- \(R\): Budget constraint.
- \(p_1, p_2, p_3\): Weights assigned to the RDD, IEA and IDC indexes.
The inspections, prioritized according to the optimization model, are then ordered according to the merit index and cost. The OSI report can then be applied according to the availability of utility inspection crews. Such procedure is repeated every month since budget changes occur frequently due to emergency maintenance actions.

**PREVENTIVE MAINTENANCE PLANNING MODULE**

After inspections are carried out, a list of network defects is available for further actions. Preventive maintenance should eliminate such defects, though there is a limited budget for it. Therefore, a specific module was developed to prioritize preventive maintenance actions, that takes this list as input and prioritize actions according to the budget and merit indexes.

The adopted model is very similar to the inspection optimization module. The main difference relies upon the fact that all defects are candidates to be eliminated; therefore there is no need for preliminary decision rules. The preventive maintenance module operates according to figure 3.

The merit index for each maintenance action is determined through the evaluation of the risk of defects turning into failures, the influence in SAIDI and SAIFI indexes, the risk of the customer claims due to damages in electric appliances and the personal accident risks.

After merit indexes are defined for each maintenance action, such actions are ranked and prioritized according to an optimization model that maximizes the global merit index subject to the budget constraint. Also, an integer programming method is used, such that the following objective function and constraints are stated:

\[
Max \sum_{i=1}^{N} D_i \cdot I_i \\
\text{s.t.} \sum_{i=1}^{N} D_i \cdot C_i \leq R
\]

where:
- \(D_i\): binary decision variable: when it is equal to one, defect i is to be repaired, otherwise it is not.
- \(I_i\): merit index for defect i.
- \(C_i\): defect i repair cost.
- \(R\): Budget constraint.

The defect repair actions, selected according to the optimization model, are then ordered according to the merit index and cost, and will generate the OSM (Maintenance Service Order), which are scheduled based on the availability of preventive maintenance crews in the company. Prioritization of such repair actions is carried out every month since budget constraints frequently vary according to emergency situations.

**COMPUTATIONAL TOOL**

The described methodology was implemented into a computational tool named PGMD – Distribution Maintenance Management Program. Figure 4 shows some windows in the PGMD.

**APPLYING PGMD TO MARICA SUBSTATION**

**Predictive Maintenance**

The proposed methodology was tested in 5 feeders of the Marica Substation. Risks of failure development in lines and equipment were estimated considering the following natural agents: trees, animals, kites, salinity and wind.

The strategic importance of area index was estimated based on data from all feeders supplied by the substation. Based on the information regarding the medium and low voltage customers the 400 kWh energy consumption was set to define the important clients.

The index of customer density in areas supplied by the Marica substation was computed based on data supplied by the company, regarding the number of clients and area per feeder, to compose the relation clients/km².
Weights $p_1$, $p_2$ e $p_3$ were considered equal to 1. The calculation resulted in the feeder ranking for predictive maintenance actions, as shown in table 1.

Table 1 - Merit Index for Feeders

<table>
<thead>
<tr>
<th>Feeder</th>
<th>RDD</th>
<th>IEA</th>
<th>IDC</th>
<th>Global Merit Index</th>
<th>Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAR01</td>
<td>0.6445</td>
<td>0.5374</td>
<td>0.9871</td>
<td>0.670</td>
<td>76.32</td>
</tr>
<tr>
<td>MAR02</td>
<td>0.5488</td>
<td>0.2477</td>
<td>0.2774</td>
<td>0.374</td>
<td>51.59</td>
</tr>
<tr>
<td>MAR03</td>
<td>0.5711</td>
<td>1.0000</td>
<td>0.0000</td>
<td>0.828</td>
<td>40.08</td>
</tr>
<tr>
<td>MAR04</td>
<td>1.0000</td>
<td>0.5685</td>
<td>0.1544</td>
<td>0.658</td>
<td>120.61</td>
</tr>
<tr>
<td>MAR05</td>
<td>0.6272</td>
<td>0.7305</td>
<td>0.5539</td>
<td>0.654</td>
<td>55.52</td>
</tr>
</tbody>
</table>

When the monthly budget constraint equals to R$ 10,000.00, which are available for inspection actions, the PGMD indicated the types and feeders were inspections should be carried out, as shown in table 2.

Table 2 - Optimization Result

<table>
<thead>
<tr>
<th>Feeder</th>
<th>Inspection Type</th>
<th>Merit Index</th>
<th>Cost [R$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAR03</td>
<td>Tree Trimming</td>
<td>0.828</td>
<td>1,202.40</td>
</tr>
<tr>
<td>MAR03</td>
<td>Instrumental</td>
<td>0.828</td>
<td>1,603.20</td>
</tr>
<tr>
<td>MAR03</td>
<td>General</td>
<td>0.828</td>
<td>1,843.68</td>
</tr>
<tr>
<td>MAR01</td>
<td>Instrumental</td>
<td>0.670</td>
<td>3,076.00</td>
</tr>
<tr>
<td>MAR05</td>
<td>Instrumental</td>
<td>0.654</td>
<td>2,220.80</td>
</tr>
<tr>
<td></td>
<td>Total Cost</td>
<td></td>
<td>9,946.08</td>
</tr>
</tbody>
</table>

Preventive Maintenance

In order to test the preventive maintenance module, the inspections in 5 feeders of Marica substation were carried out. Afterwards, the 2 major defects in each feeder, detected by such inspections, were selected to compose a list as shown in table 3.

Each defect has a specific repair cost and an associated merit index.

As for the budget available for preventive maintenance a total of R$ 2,100.00 was stipulated. The repair actions prioritized to meet this budget are shown in table 4.

CONCLUSIONS

The implementation of PGMD in the pilot area has proven that the methodology is a valuable and powerful tool to manage maintenance actions in distribution networks.

REFERENCES


