GOAL PLANNING AND RISK ANALYSIS FOR DISTRIBUTION RELIABILITY INDICES

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SUMMARY

This paper deals with a methodology for the assessment of reliability indices in electric power distribution companies based on Monte Carlo simulation models. Risk analysis regarding frequency and duration of interruptions for individual customers can be readily applied for actual distribution systems based on some few network attributes, on the company’s general network protection practices and on current system average reliability indices. The paper also shows how existing models for investment planning can be extended to consider individual customer reliability indices, so that actions and future system reinforcements are evaluated to meet such established goals. Some applications illustrate the proposed methodology.
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ABSTRACT
This paper deals with a methodology for the assessment of reliability indices in electric power distribution companies based on Monte Carlo simulation models. Risk analysis regarding frequency and duration of interruptions for individual customers can be readily applied for actual distribution systems based on some few network attributes, on the company’s general network protection practices and on current system average reliability indices. The paper also shows how existing models for investment planning can be extended to consider individual customer reliability indices, so that actions and future system reinforcements are evaluated to meet such established goals. Some applications illustrate the proposed methodology.

1. INTRODUCTION

Following the privatisation of distribution companies in Brazil, strong changes have occurred both in the open competitive market and in the way companies are controlled by state regulators. Such control is related to many issues. This paper deals with those related to reliability standards and targets companies should follow.

Before privatisation, reliability indices were basically monitored on average figures, that is the duration and frequency of yearly interruptions for an “average customer” of the system. However, new rules are being applied and enforced for distribution companies to comply with stricter reliability standards. Reliability indices now consider each individual customer, so that actions and future system reinforcements are evaluated to meet such established goals. Some applications illustrate the proposed methodology.

On the other hand, distribution companies have to prepare their investment plans bearing in mind the compliance with such reliability targets. An investment planning computational tool is being used in many distribution companies in Brazil [5,6], which determines investments (distribution substations, primary feeders, etc.) regarding expansion reinforcements to meet the demand growth. This tool also evaluates the impact of such investments on the quality of service, related to the aforementioned “average” reliability indices.

However, it is well known that there are many measures to improve reliability performance of the system besides the installation of expansion facilities. Different operation and maintenance practices, as well as the use of new technologies can considerably affect reliability indices.

This paper also discusses how to extend such planning tool to consider such measures on the top of expansion investments so that reliability annual targets are satisfied.

2. METHODOLOGY

2.1 Overall Model

An investment planning model [2-5] aims at relating investment to quality levels, by considering a number of scenarios that take into account uncertainties due to financial, technological and social-economical aspects. In order to do so, the model must be fast enough to assess such combinations of multiple scenarios. The assessment of network performance regarding component loading, voltage drops, losses and other quality indices are evaluated in a statistical manner. They are determined based on the information of existing network characteristics as well as utility technical standards.

The method developed provides statistic equations for the rapid computation of operational and topological network parameters as functions of EDS (Elementary Distribution Systems) group descriptors.
Fictitious radial networks are randomly generated by the Monte Carlo Method, bearing technical, topological and load characteristics previously defined so that the universe of EDSs is represented. Such characteristics comprise the independent variables. The randomly generated networks have their main technical parameters (dependent variables) evaluated by conventional way, that is, a load flow computing voltage drops, component loading and losses. This procedure is very efficient for it deals with radial networks only. Quality indices (energy not supplied and other customer interruption indices) are determined based on average failure rates, restoration times as well as some general criteria that incorporate utility practices concerning protective and switching equipment allocation along the network.

The methodology can be described according to the following steps:

i. Generate a radial network feeder randomly, according to a set of attributes (demand, number of load points, feeder angle and area, lateral and main conductor types, etc.);

ii. Evaluate the parameters (network length, voltage drops, losses, energy not supplied, interruption indices) by the use of direct methods;

iii. Repeat steps i and ii for N simulations. N is fixed in such a manner that it can be assured, within a given probability, that the maximum confidence interval in relation to the mean value of each parameter is not exceeded;

iv. Repeat steps i to iii for many combinations of input attributes;

v. Based on the results obtained in the previous steps, determine statistical equations by regression analysis in a n-dimension space, i.e. dependent variables will be given as functions of the n independent variables.

2.2 Rules for network random generation

A radial network must be randomly generated according to the given system attributes. The location of load nodes is randomly distributed over a circular sector and a covering area, as shown in Fig. 1. Each new load node is connected to the existing network by a minimum length criterion. Such location considers a load density function throughout the primary feeder, which is given by:

\[ D_r = D_0 \cdot r^\alpha \]  \hspace{1cm} (1)

where:

- \( D_r \): Load density for a radius \( r \) related to a circular sector defined by the action angle and the feeder covering area;
- \( D_0 \): Load density for \( r=0 \), in kVA/km²;
- \( \alpha \): Exponent defining the variation of the load density along the radius \( r \).

By varying the values of \( \alpha \), urban and rural feeders can be fairly well represented, e.g. by assigning values around 0 (uniform distribution) and -1 (load density decreases with the distance from the substation), respectively. Long feeders, supplying load at distant locations (also called express feeders) can be represented by assigning \( \alpha \geq 2 \).

Fig. 1 – Random generation of a radial network

The system considers all load nodes having the same demand. Each individual load demand is assigned according to the maximum feeder demand and the number of load nodes.

Regarding the definition of laterals and main branches formed by the network randomly generated, the procedure starts at the substation node towards the demand nodes. For every deriving node the main branch is chosen as the one having a larger current whereas the other outcoming branches are defined as laterals. The main branches are ended to be listed when the current at a branch is less than or equal to a current at a previous listed lateral. Branch currents in Fig. 1 illustrate such procedure.

2.3 Influence of the Protection Practices

The evaluation of interruption and reliability indices for a feeder randomly generated during the Monte Carlo method is based on design practices used by the distribution company for the installation of switching and protection devices along its system.

The following rules are generally used in the procedure for the location of switches in the distribution feeder:

i. in rural feeders, the distance between switching devices in the main branches must not be greater than a given pre-defined distance. In urban feeders, a given number of switching devices is defined to be uniformly located along the main branches.

ii. every lateral having total length greater than \( L_{\text{min}} \) or a loading greater the \( I_{\text{min}} \) must have fuse switches installed;

iii. feeder interconnection switches are available to restore the power supply for those downstream customers that become isolated by the change in status of the proper switching devices, that will allow network equipment repair.
2.4 Reliability Indices

The computation of reliability indices is carried out by the simulation of failures in all network branches, by considering the corresponding failure rates and average restoring times.

A demand block is defined as the set of branches derived from switching or protection devices, as shown in fig. 2. Three parameters regarding the restoration time are defined:
- \( T_1 \): average time to restore customers located upstream to the faulty block;
- \( T_2 \): average time to restore customers located in the faulty block;
- \( T_3 \): average time to restore customers downstream the faulty block;

Regarding the restoration of power supply, two rules are applied:
- fault in a lateral protected by fuse: only customers in the lateral are affected and the power supply is restored within a \( T_2 \) time;
- fault in the main branch or in a lateral not protected by fuse: initially all customers in the feeder are interrupted by the switching of the circuit breaker installed at the substation site. Upstream customers are restored after the faulty block is isolated for repair (time \( T_1 \)). Downstream customers are restored after being transferred to another feeder by an interconnection switch (at time \( T_3 \)). Customers located at the faulty block will be restored after time \( T_2 \) (repair time).

The following parameters are defined:
- \( \lambda_i \): failure rate for branches belonging to demand block \( BL_i \) (number of failures/km/year);
- \( \ell_i \): total length (km) for the branches in demand block \( BL_i \);
- \( FIC_i \): annual individual frequency regarding interruptions for customers located in \( BL_i \);
- \( FEC_i \): average annual frequency regarding interruptions for all customers in the feeder;
- \( DIC_i \): contribution of block \( BL_i \) to the average feeder index \( FEC \);
- \( DEC_i \): contribution of block \( BL_i \) to the average feeder index \( DEC \);
- \( \Omega_p \): set of demand blocks comprising the main branches or laterals without fuse protection;
- \( T_{ij} \): restoring time for \( BL_i \) when a failure occurs in demand block \( BL_j \) (equal to \( T_1, T_2 \) or \( T_3 \), according to the position of block \( BL_i \) in relation to block \( BL_j \)).

The corresponding reliability indices are then defined as follows.

a) customers located in a lateral protected by fuse:

\[
FIC_i = \lambda_i \ell_i + \sum_{j \in \Omega_p} \lambda_j \ell_j
\]

\[
DIC_i = \lambda_i \ell_i T_2 + \sum_{j \in \Omega_p} \lambda_j \ell_j T_{ij}
\]

\[
FEC_i = \left( \lambda_i \ell_i + \sum_{j \in \Omega_p} \lambda_j \ell_j \right) \frac{NC_i}{NC} / \frac{NC_i}{NC}
\]

\[
DEC_i = \left( \lambda_i \ell_i T_2 + \sum_{j \in \Omega_p} \lambda_j \ell_j T_{ij} \right) \frac{NC_i}{NC} / \frac{NC_i}{NC}
\]

b) customers located in the main branches or in a lateral without protection:

\[
FIC_i = \sum_{j \in \Omega_p} \lambda_j \ell_j
\]

\[
DIC_i = \sum_{j \in \Omega_p} \lambda_j \ell_j T_{ij}
\]

\[
FEC_i = \sum_{j \in \Omega_p} \lambda_j \ell_j \frac{NC_i}{NC} / \frac{NC_i}{NC}
\]

\[
DEC_i = \sum_{j \in \Omega_p} \lambda_j \ell_j T_{ij} \frac{NC_i}{NC} / \frac{NC_i}{NC}
\]

The average feeder indices are then determined by:

\[
FEC = \sum_{i=1}^{nbl} FEC_i = \frac{1}{NC} \sum_{i=1}^{nbl} \left( FIC_i \cdot NC_i \right)
\]

\[
DEC = \sum_{i=1}^{nbl} DEC_i = \frac{1}{NC} \sum_{i=1}^{nbl} \left( DIC_i \cdot NC_i \right)
\]

where \( nbl \) represents the total number of demand blocks in the feeder. It is seen that the average indices \( FEC \) and \( DEC \) are exactly the same as the average values of the individual indices \( FIC \) and \( DIC \), respectively.
The computation for all demand blocks in a feeder results in a distribution curve for the individual indices, as shown in fig. 3.

2.5 Calibration of probability distribution curves for DIC and FIC to the measured DEC and FEC

As described in section 2.1, N fictitious radial networks, having the same given attributes, are randomly generated during the Monte Carlo method. For each network, the indices DIC and FIC are computed in all demand blocks. After generating the N networks, cumulative distribution curves regarding such indices are readily obtained, as illustrated in fig. 3.

Expressions (10) and (11) have proven that the average values for DIC and FIC are equal to, respectively, the DEC and FEC for the feeder. Moreover distribution companies measure such system indices by composing network occurrences and corresponding interruptions in power supply (a posteriori evaluation). Therefore, distribution curves for the individual indices DIC and FIC can be calibrated to the measured average values, by conveniently adjusting the values for failure rate and average restoring, i.e:

$$\lambda_f = \lambda_i \frac{FEC_{measured}}{FIC_{average}}$$

(12)

where:
\(\lambda_f\): adjusted failure rate;
\(\lambda_i\): initial given failure rate;
FEC_{measured}: measured FEC;
FIC_{average}: average FIC for \(\lambda_i\);

$$T_f = T_i \frac{DEC_{measured}}{DIC_{average}}$$

(13)

where:
\(T_f\): adjusted restoration times \(T_1, T_2, T_3\);
\(T_i\): initial given restoration times \(T_1, T_2, T_3\).

After the adjustment of the DIC and FIC values through equations (12) and (13), probability distribution curves given in fig. 3 can be transformed in the ones shown in fig. 4.

2.6 Goal Planning

Probability distribution curves for the indices DIC and FIC are obtained for all combinations of the attributes that describe the distribution company’s feeders. For a given set of attributes, the values of DIC_{x%} and FIC_{x%} are readily obtained from the respective distribution curves, as shown in fig. 4. The index DIC_{100%}, for instance, indicates that 100% of the customers in that specific feeder present value less than or equal this value. By using such procedures, for all combinations of system attributes, table 1 can be obtained.

**TABLE 1 – DIC as a function of feeder attributes**

<table>
<thead>
<tr>
<th>Attributes</th>
<th>DIC (hours/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>angle (\theta)</td>
<td>area (Z)</td>
</tr>
<tr>
<td>(\theta_1)</td>
<td>(Z_1)</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>(\theta_1)</td>
<td>(Z_1)</td>
</tr>
<tr>
<td>(\theta_2)</td>
<td>(Z_2)</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>(\theta_k)</td>
<td>(Z_k)</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

By using regression analysis, the results obtained in table 1, allow for statistic equations that relate the values DIC_{x%} and FIC_{x%} with the attributes that describe the primary feeder:

$$DIC_{x%} = \alpha_1 \theta^\beta N_p^\delta Z^\gamma P^\varepsilon \lambda_f$$

(14)

$$FIC_{x%} = \alpha_2 \theta^\beta N_p^\delta Z^\gamma P^\varepsilon \lambda_f$$

where:
\(\alpha, \beta, \delta, \gamma, \varepsilon\): regression analysis coefficients;
θ: action angle of the feeder;

$N_P$: number of load points along the feeder;

$Z_d$: feeder area;

$P$: feeder demand;

$\lambda_f$: feeder failure rate;

$f_c$: load factor.

The inclusion of equations (14) in the investment planning model presented in [5] allows for risk analysis concerning the individual reliability indices, when penalties for constraint violations can be easily incorporated into the model.

The planning engineer (or the decision maker) is able to check the specific scenarios that led to such risks and possibly modify annual budgets so that risks are reduced, minimized or even eliminated.

The investment planning model (named SISPAI) determines new reinforcements in the system so that technical constraints are met. However, such expansion plans can become too costly for attaining reliability indices.

Such targets can be attained by additional measures, such as efforts to reduce restoration times following contingencies in the network, tree trimming programs to reduce failure rates in overhead systems, and so forth. Such measures can be incorporated in the software by the determination of new statistical equations, as described in this section.

3. APPLICATION EXAMPLE

The proposed methodology was implemented in a software that obtains probability distribution curves regarding the indices DIC and FIC that will allow for risk analysis. Table 2 presents the basic data utilised by the model in a case study for a specific primary feeder.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Voltage</td>
<td>13.8 kV</td>
</tr>
<tr>
<td>Monte Carlo samples</td>
<td>100</td>
</tr>
<tr>
<td>Feeder area</td>
<td>400 km²</td>
</tr>
<tr>
<td>Action angle</td>
<td>60°</td>
</tr>
<tr>
<td>Main branches cable</td>
<td>336.4 MCM</td>
</tr>
<tr>
<td>Lateral branches cable</td>
<td>2 AWG</td>
</tr>
<tr>
<td>Feeder demand</td>
<td>10 MW</td>
</tr>
<tr>
<td>Power factor</td>
<td>0.92</td>
</tr>
<tr>
<td>Number of demand centres</td>
<td>200</td>
</tr>
<tr>
<td>DEC</td>
<td>55 h/yr</td>
</tr>
<tr>
<td>FEC</td>
<td>40 interruptions/yr</td>
</tr>
<tr>
<td>Maximum DIC</td>
<td>100 h/yr</td>
</tr>
<tr>
<td>Maximum FIC</td>
<td>80</td>
</tr>
<tr>
<td>Initial failure rate $\lambda_i$</td>
<td>1 failure/km/yr</td>
</tr>
<tr>
<td>Initial restoration times $(T_1, T_2, T_3)$</td>
<td>(2, 3, 3) h/failure</td>
</tr>
</tbody>
</table>

By applying the proposed methodology to the primary feeder with the basic attributes presented in table 2, the calibrated probability distributions for DIC and FIC were obtained as shown in figure 5.

Figure 5 – Example of Reliability Indices Estimation and Risk Analysis
The failure rate was adjusted to the value 0.69 failure/km/yr by applying equation (12). The restoration times \((T_1, T_2, T_3)\) were adjusted from \((2,3,3)\) h/failure to \((1.02, 1.54, 1.54)\) h/failure.

The results allows for risk analysis concerning the individual reliability indices. The risk for \(DIC\) exceeding 100 h/yr/customer is 5.3% whereas the risk for \(FIC\) exceeding 80 interruptions/yr/customer is null. The maximum values for \(DIC\) and \(FIC\) are respectively 121 h/yr and 79 interruptions/yr.

4. CONCLUSION

This paper presented a model for the evaluation of risk analysis regarding reliability indices in primary distribution feeders. The required data concerning network attributes are easily obtained from corporate data bases existing in distribution companies. Statistic equations for the evaluation of individual reliability indices can be estimated and incorporated in investment planning models.

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REFERENCES


