RISK ASSESSMENT AND MINIMIZATION OF VOLTAGE LEVEL VIOLATIONS IN DISTRIBUTION SYSTEMS

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INTRODUCTION

In the last few years the Brazilian Electrical Energy Regulation Entity – ANEEL – has passed new resolutions regarding the quality of the electrical energy supply.

ANEEL's Resolution 505/2001 specifies long-term voltage variation indicators, with the following items to be measured: individual and collective indicators, the limits for such indicators, the methods for data collection (measuring the voltage at selected customers or in response to customer claims regarding voltage level) and the penalties for not complying with the established limits.

Three voltage supply levels were set for the customer units: adequate, inadequate and critical, as well as two violation indicators: Relative Duration of Inadequate Voltage Violation - RDI and Relative Duration of Critical Voltage Violation – RDC. These indicators refer to the relative duration of voltage readings, in the inadequate and critical levels respectively, and they should not surpass the maximum time percentage of the voltage readings for the set period.

ENERSUL – the distribution company of the EDP Group (Eletricidade de Portugal), with over 600,000 customers in the Brazilian state of Mato Grosso do Sul, and ENERQ – Center for Regulation and Power Quality Studies – are carrying out an R&D project for the development of a methodology and simulation software that will enable the company to evaluate circuits or map areas in terms of those quality indicators.

A computational module has been specified and developed to calculate the load flow with a probabilistic approach. Based on typical daily load curves (average and standard deviation curves), representing the time variation (10-minute intervals) of the demand (active and reactive) and the electrical network model, distribution curves are obtained for voltage probability, so that the risk of violating the RDI and RDC indicators can be calculated, for each point in the network.

For the second stage of the project, presently ongoing, a mathematical model is being developed for the technical and economic assessment of corrective and preventive actions, for low and medium voltage circuits, so as to minimize the risk of violating the previously mentioned voltage compliance indicators.

NETWORK BUILDING STANDARDS

The electrical distribution networks in Brazil present some specific features that need to be mentioned, so as to facilitate the readers' comprehension of this article.

Most medium voltage distribution networks are radial and carry loads between 13.8 kV and 34.5 kV. They have three-phase circuits at the main feeder and may present two phase or single phase branch circuits, the latter especially in rural areas. The length of these circuits varies from a few to hundreds of kilometers.

These networks feed distribution transformers, whose function is to lower the load to, normally, 220 V between phases, and 127 V between phase and neutral. Each distribution transformer feeds a low voltage circuit which includes a neutral cable and one or more phase cables (up to three phases), varying in length from a few to several hundred meters. In the case of ENERSUL most of these networks are aerial, with structures mounted on concrete posts, and with the cable closest to the ground at a height of 6.3 meters.

The low voltage circuits branch out into service circuits reaching the supply points of the low voltage consumers. These are the supply points that need to be measured, at each consumer, in the case of consumer claims regarding the quality of the supply. It is also part of the program of regular measurements carried out by the electrical distribution utilities, in accordance with the directives issued by the regulatory agency, in order to set the voltage limits required to guarantee the quality of supply regarding voltage levels.

LEGISLATION

As per ANEEL's Resolution Number 505/2001 (ANEEL is Brazil's Regulatory Agency), the customer may request the utility to measure the voltage level of the supply , should the consumer believe that such level is not in compliance with the legally set levels. The utility shall inform the customer, within 48 hours of such request, the value of the service for which the customer will be billed, should the claim not be valid, as well as the date and time in which the reading equipment will be installed to proceed with the customer's request.

The final report of the reading shall be presented to the customer who originated the claim, in writing, within 30 days of receipt of the formal request.

ANEEL has also determined a regular program of measurements, by which a sample is set to verify the voltage compliance indicators.

These measurements shall last 168 hours, with ten-minute integration intervals, starting with readings of 12 to 15-cycle fixed and consecutive windows, totaling 1008 readings. Measurements should be taken between phases and between phases and neutral.

The measured indicators are: *RDI - Relative Duration of Inadequate Voltage Violation* and *RDC - Relative Duration of Critical Voltage Violation*.

RDI represents the number or readings taken at the inadequate voltage levels, as a percentage of the total valid readings taken during the measurement period (1008 readings).

In the same way, *RDC* represents the number of readings taken at the critical voltage levels, as a percentage of the total valid readings taken during the measurement period (1008 readings).

The top limit for *RDI* was set at 6% for 2004 and will be reduced by 1% each year, for the period 2005 – 2007, at which time it will stand at a fixed value of 3%.

Similarly, the maximum limit for *RDC* was set at 1.1% for the year of 2004, decreasing by an absolute value of 0.2% per year from 2005 to 2007, when it will remain at the fixed value of 0.5%.

The voltage limits representing the inadequate and critical ranges are shown in Table 1.

TABLE 1 – Voltage Limits for Inadequate and Critical Ranges

Low Voltage Networks		**Voltage Ranges [V]**		
Type	**Nominal Voltage [V]**	**Adequate**	**Inadequate**	**Critical**
3-phase	220 / 127	$201 \le V_A \le 231$ / $116 \le V_A \le 133$	$189 \le V_I < 201$ or $231 < V_I \le 233$ / $109 \le V_I < 116$ or $133 < V_I \le 140$	$V_C < 189$ or $V_C > 233$ / $V_C < 109$ or $V_C > 140$
	380 / 220	$348 \le V_A \le 396$ / $201 \le V_A \le 231$	$327 \le V_I < 348$ or $396 < V_I \le 403$ / $189 \le V_I < 201$ or $231 < V_I \le 233$	$V_C < 327$ or $V_C > 403$ / $V_C < 189$ or $V_C > 233$
1-phase	254 / 127	$232 \le V_A \le 264$ / $116 \le V_A \le 132$	$220 \le V_I < 232$ or $264 < V_I \le 269$ / $109 \le V_I < 116$ or $132 < V_I \le 140$	$V_C < 220$ or $V_C > 269$ / $V_C < 109$ or $V_C > 140$
	440 / 220	$402 \le V_A \le 458$ / $201 \le V_A \le 229$	$380 \le V_I < 402$ or $458 < V_I \le 466$ / $189 \le V_I < 201$ or $229 < V_I \le 233$	$V_C < 380$ or $V_C > 466$ / $V_C < 189$ or $V_C > 233$

LOAD REPRESENTATION

In this work, the load of every consumer is represented by a daily load curve that shows the actual demand (active and reactive) at 10-minute intervals. The starting point was the computation of typical daily load curves, which were established from a comprehensive set of field measurements. A typical curve consists of an average curve and a standard deviation curve, and it was established for each type of consumer (residential, commercial, industrial, street lighting and rural) as well as for different monthly energy consumption ranges, for each type of consumer (e.g. 0-100 kWh per month, 101-300 kWh per month, etc.). These curves are given in pu of the monthly average active demand, so that, once a particular consumer's monthly energy is known, together with its typical load curve, the computation of its daily load curve is straightforward. Figure 1 shows the typical active curve for residential consumers with monthly energy above 500 kWh.

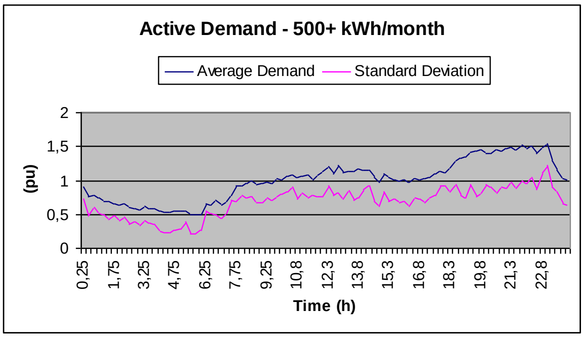

Figure 1 – Typical load curve - active demand

METHODOLOGY

The following section describes the methodology used for this work, and it encompasses two different approaches for the calculation of load flow.

Deterministic Load flow

The deterministic load flow is the basis for the probabilistic load flow, the methodology of which will be presented further ahead in this article. The deterministic load flow is calculated for three different load levels, representing the load conditions during the morning, afternoon, evening and early morning periods. The result of this load flow will, at the user's discretion, either trigger or not the probabilistic load flow, which requires a longer processing time.

Based on the customers' monthly consumption and their respective typical load curves (the average curves), the demand can be calculated at each point of the circuit. Subsequently, the load current is calculated for all the portions of the circuit as well as the voltage for all the nodes. This is possible because ENERSUL holds a detailed database, with all the topological information regarding its circuits as well as their billing data.

As a result, figures can be obtained for all the load and voltage levels along the network, disregarding the uncertainties in load representation (standard deviation curve). This procedure is normally used for the setting and assessment of technical criteria such as load and voltage drops.

Probabilistic Load flow

The probabilistic load flow is based on the processing of the deterministic load flow described above, using simulations based on the Monte Carlo Method. This method is adopted to deal with loads in different scenarios, taken from the probability curve of demand.

The figures obtained as a result of this model are more realistic as regards the random behavior of the loads, present in distribution networks.

The deterministic calculations simply display the results of a load distribution scenario along the network, whereas the probabilistic ones are more realistic, in as much as they show results associated with a distribution of probabilities, which represent the load in several scenarios, called samples.

The probabilistic method requires large computational resources because it simulates the system several times until it reaches the convergence of the process.

Deterministic approach for load randomness. One way to lower the risks connected with the use of fixed demand values, to represent the load, is to determine a value for which there is a low probability of the demand being exceeded.

Considering a normal distribution of probability and setting the demand equal to the average μ, adding a standard deviation σ, the probability is of approximately 16% that demand be exceeded. For $\mu + 2\sigma$, the probability stands at 2.3%, and for $\mu + 3\sigma$, it is 0.03%.

Thus, it appears that for high standard deviations, the simple use of the average demand μ may represent high levels of risk in breaking the technical parameters of the circuit that is being analyzed, as for example, voltage and load.

This leads to the use of a demand value that includes a $k\sigma$ factor. The higher the value of k, the lower the risk of breaking the technical parameters; yet, the equipment used for the electrical system would need to have larger capacity.

The main difficulty in the use of this method is that, for each portion of the electrical network there is a different σ standard deviation. Due to the load aggregation, the further from the consumers and the closer to the supply source, the lower will be the figures for standard deviation.

The proportionality coefficient k must be chosen so as to minimize the risks resulting from violating the technical criteria regarding voltage.

Thus, the aim is to set a value for the demand, which is above the average demand and is proportional to the standard deviation of each load and also to the total deviation of the low voltage network. Such value should also allow the most accurate calculation, without the risk of large errors in estimating the values for voltage drops.

This model is then called the deterministic approach for the representation of load randomness, which precedes the probabilistic model.

In the case of a secondary network, fed by a distribution transformer (DT), the following formula may be used to measure the demand at each consumer i at time t:

$$D_{i,t} = D_{med,i,t} \cdot \left(1 + \frac{k \cdot \sigma_{DT,t}}{D_{med,DT,t}}\right) \tag{1}$$

where:

$D_{i,t}$: demand of consumer i at time t [kW];

$D_{med,i,t}$: average demand of consumer i at time t [kW];

$D_{med,DT,t}$: average aggregate demand at the distribution transformer at time t [kW];

$\sigma_{DT,t}$: standard deviation of aggregate demand at the distribution transformer at time t [kW];

k : proportionality factor.

Opting for the method presented above, in order to calculate consumer demand, guarantees that the load in the circuit will be $k\sigma_{DT,t}$ above the average value, which means the risk (which depends on parameter k) of having the demand exceed this value can be previously estimated.

As a rule, the standard deviation in the initial portion of the circuit is quite small, due to the aggregation of a large number of consumers. This would entail using the average demand for all loads.

Yet, in the portions closest to the loads, where the figures for the standard deviation curves are higher, the risk of using the average demand is also greater.

Thus, the load randomness should be shown from the point of view of the probabilistic approach, as presented in the following section.

Probabilistic approach for load randomness.

In this model, applying the probabilistic load flow requires that the demands be random variables, as they have an associated probability distribution.

The dependable variables, as for example the voltage at each circuit node, are also random. Therefore, they have a distribution curve of associated probabilities, with values for each average and standard deviation.

Based on this approach, the voltage drop, for example, in any of the circuit nodes should be taken as a range of values with occurrence probability such that: ‘the voltage drop at node *i* varies from 3 to 6% with 90% of probability’, or ‘there is 1% of probability (or risk) of a voltage drop at this node *i* being above 7.5%’.

The method being used (Monte Carlo) requires running a sufficient number of tests, which will identify possible scenarios of diversified demands for all the customers on the network (for a given time), based on the generation of random figures with normal distribution probability.

In order to simulate the function of accumulated probability, it is necessary to generate a random figure *y*, with uniform distribution on the interval [0;1] and obtain the corresponding value for *Z’*, as shown in Figure 2. Based on the customer’s average demand in kW and on the value of *Z’*, which can be understood as the normalized demand for that particular customer, the demand ‘chosen at random’ in kW is calculated as follows:

$$D_{i,t} = D_{med,i,t} + Z' \cdot \sigma_{i,t} \qquad (2)$$

where:

$D_{i,t}$: demand of customer *i* at time *t* [kW];
$D_{med,i,t}$: average demand of customer *i* at time *t* [kW];
$\sigma_{i,t}$: standard deviation for customer *i* at time *t* [kW];
Z' : normalized demand chosen at random.

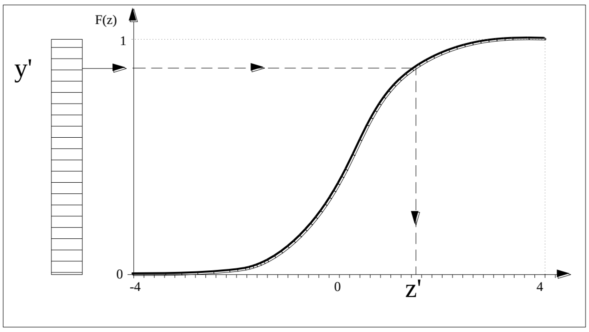

Figure 2 – Demand chosen at random for a consumer

It is worth mentioning that in the case of this probabilistic approach, the normalized demand *Z’* shown in (1) corresponds to the proportionality factor *k* in (2). The difference is that for this approach, it is not established previously but rather, chosen at random.

For a close monitoring of the Monte Carlo method, as regards process convergence, the total number of tests is normally divided into groups. As an example, 10 groups of 100 tests each are performed, and for each group, the electrical parameters in question are monitored by measuring their averages and accumulated standard deviations.

When the average values and the standard deviation values of the variables no longer show changes – or when the variation is lower than a preset tolerance figure – this indicates process convergence.

APPLICATION

This section presents the computational module, that was developed in order to apply the methodology, as well as the results that were obtained at ENERSUL.

Computational Module

The Computational Module for the Simulation of the Probabilistic Load Flow (*FlowProb*) was developed on the basis of a computational system named *Interplan*. This is a georeferenced system that supports planning analyses in distribution networks.

Both *FlowProb* and *Interplan* allow simulations to be made in low voltage circuits, and the results obtained are presented in a friendly GIS environment.

As the Monte Carlo Method, used in *FlowProb*, demands a large computational effort, the module that was developed includes a tool to analyze low voltage circuits. With this tool, a deterministic load flow is performed at four load periods. Should the voltage of any of the phases in any one of the nodes on the circuit be outside the limits set by the user, the circuit is selected for the Monte Carlo method.

The following figure (Fig. 3) illustrates one of ENERSUL’s medium voltage circuits (shown in red) with all the low voltage circuits (in blue) it supplies.

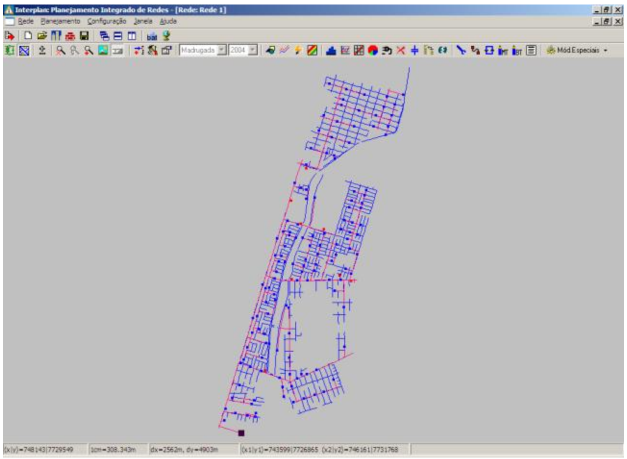

Figure 3 – *Interplan* with an ENERSUL network

Executing the *FlowProb* enables the setting of simulation parameters and the selection of the circuits to be simulated

(Fig. 4). Once the simulation has been performed, a graph is displayed with the probability distribution of the voltage at each node, for each of the simulated circuits, as shown in Figure 5. The probabilities associated with the yellow and red bars correspond to the estimated *RDI* and *RDC*. The circuit being analyzed by the *FlowProb* and its worst node as regards the estimated indicators are highlighted in the GIS environment.

Results

At the present time, the module that was developed is being implemented in a pilot area at ENERSUL. This area comprises 17 feeders (medium voltage) in an urban area.

Each one of these 17 feeders in the pilot area, together with their respective low voltage circuits, has been carefully analyzed. The *FlowProb* has identified the circuits that might present violations of voltage levels (the research step using the deterministic load flow). The Monte Carlo simulation was then applied for each one of those circuits (probabilistic load flow).

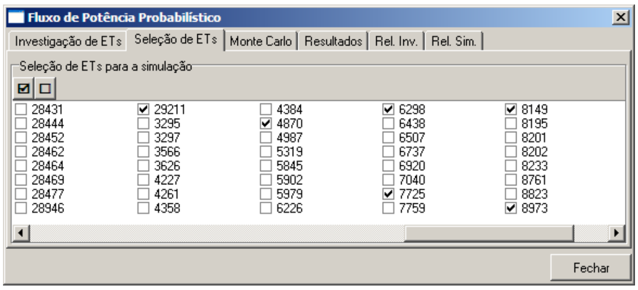

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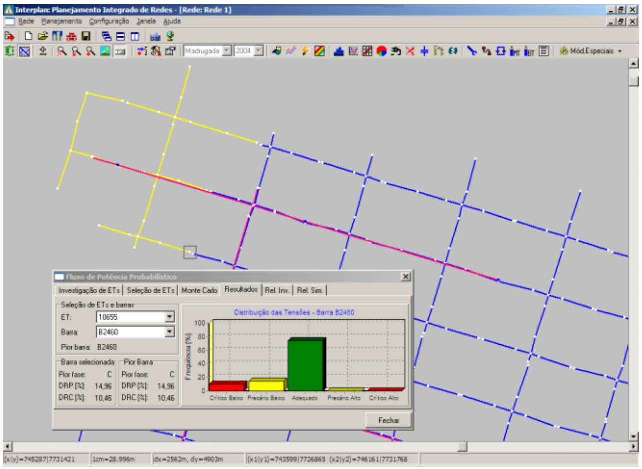
Figure 4 – The *FlowProb* and the circuits selected for simulation



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DRC [%]: 10,46

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DRC [%]: 10,46

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Figure 5 – Results of the simulation for a low voltage circuit

For each feeder, a list was made including the six worst low voltage circuits with the worst indexes of voltage compliance, calculated by the computational module. The following table (Table 2) presents the results obtained for one of the feeders, listing the low voltage circuits and their respective nodes, where the worst indexes appeared.

It is worth noting that the *software* provides the geographic location of the point in the low voltage circuit where the worst indexes were obtained. Later on, the utility may monitor the point that was identified, to check whether the estimated results are close to reality, or whether the model warrants any adjustments.

TABLE 2 – Results for feeder CGL01

Network	RDI [%]	RDC [%]	Node
14972	16.55	10.90	B1007
18151	15.17	4.58	B2254
20208	12.92	4.86	B2385
6298	13.44	6.49	B1134
8973	15.87	8.58	B1242
9583	14.58	6.69	B1841

CONCLUSIONS

The methodology and the computational module that were developed for this work are of great value for the utility, allowing it to anticipate possible voltage problems in its low voltage circuits. The randomness of the load is studied by means of several scenarios and as a result, a probability distribution curve of the voltages is set for each node. This curve offers an estimate of the voltage compliance indicators, thus allowing the utility to correct possible voltage problems that may be encountered in its networks, as a result of the measurements required by the regulatory agency. It also prevents claims on the part of the consumers.

ACKNOWLEGMENTS

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