A Methodology for Real-time Quantification of Financial Losses in Distribution Systems Based on Automated Measurements

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***Abstract*—This paper presents a methodology to provide information for decision-making toward the real-time quantification of financial losses in distribution systems. Using multi-criteria analysis and data from an automated measurement system, the proposed method includes the evaluation of main factors that impact on power quality and reliability indexes. Additionally, aspects related to economic issues and energy efficiency are considered for different operating conditions. The decision is made taking into account the performance of the medium voltage transformers and distribution system reliability standards of Regulatory Agency requirements. Loss of life in transformers, technical losses, voltage levels, and utilization factor are evaluated together with continuity and availability of power supply in order provide efficient and reliable operation, avoid penalties for unsatisfactory performance. The methodology allows an easy way to compare financial losses from feeders, substation and geographical regions of the distribution system. To illustrate the use, the methodology is applied in a real distribution system, and the result are analyzed and discussed.**

***Index Terms*—Distribution system, expansion planning, multi-criteria decision analysis, transformer loss-of-life**

I. Introduction

The direction of investments for expansion planning in electrical systems depend on detailed studies about the real operational conditions including the use of computational resources to achieve the correct sizing of the new installations, or even making changes in the existents systems.

Over the past decades several works that employ analytical processes for obtaining optimal solutions has been developed in this field. For generation systems projects, Yang and Chen [1], formulated a methodology to make optimal choices based on multi-criteria analysis method. Through hierarchical grouping, assignment of the relative importance and weighting the criteria, is obtained the Euclidean distance to the ideal decision, that defines the best solution. Based on AHP (Analytical Hierarchy Process), Silong *et al* [2] describe an evaluation methodology resulting in relative weights of indexes covering the operating characteristics, system capacity, reliability, power quality and economy. In [3], Yang *et al* propose a methodology for evaluating the use of equipment in the system, assessing the load rate of lines and substation transformers under normal operating conditions and when maximum capacity is reached. More recently, for project prioritization in distribution systems, Mussoi and Teive [4] suggest a methodology to optimize the value of the portfolio projects as part of the expansion planning process. For such, is considered the financial impacts, number of consumers and aspects related to system reliability and power quality. By using a multiobjective genetic algorithm (NSGA-II) is obtained a set of portfolios commitments and the project restrictions, reducing the subjectivity in decisions.

The approaches cited are specific for each application and help in prioritizing investments indirectly, based on the operation, reliability, and power quality indexes. In other words, forward the decision is still required an interpretation in scale to have knowledge about the financial impact related to the indexes.

Aiming to make the decision more clear and direct, based on the greater dynamism given by the automated measurement system, this study shows the implementation of a method to aid the decision-making process, combining technical to economic criteria, being these, the analysis results. This will enable decision-makers, who works in distribution systems, to be guided quickly on equipment or line identification that require investments to increase the power quality and reliability levels.

II. Proposed Model Formulation

Based on the objectives highlighted in Section I, the method proposed must relate economic criteria to technical

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well know parameters. To achieve this goal here is proposed the use of the theory of MCDA (Multi-Criteria Decision Analysis) as a way to achieve the desired results.

Given the characteristics inherent to MCDA process, in this work was chosen some features that are part of the *AHP* method, allowing to reach a solution of a reduced set of steps. Among the characteristics used, can be highlighted the prioritization process, selection or the criteria, standardization, and finally, the results validation.

In distribution systems, the number of variables to be analyzed and controlled is somewhat worried. As a result, any analytical methods must select the right criterias as requirement.

As a first step, to assist in the prioritization process, are explored three areas that are related to economic aspects in distribution systems: operational conditions, power quality and quality of service. In addition, the criteria selection are supported by the following requirements: (*i*) the criteria are regulated by the Regulatory Agency and, therefore, subject to penalties if limits are exceeded, (*ii*) the criteria directly reflect losses and consequent energy waste, and (*iii*) the criteria represent financial losses due to improper use of the equipments. As a result, the select criterias for the proposed method are: losses in lines and transformers, reliability levels, voltage levels, loss of life in transformers and load factor.

Considering the criteria grouping by categories, according to the criteria described above, we obtain a criteria value tree representation of the decision model illustrated in Figure 1.

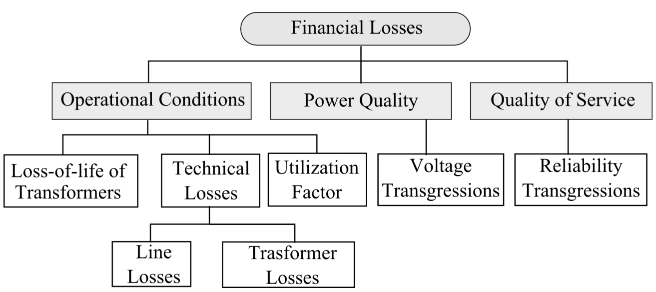

Fig. 1: Criteria values tree

In this methodology, it is assumed that all data needed to calculate the criteria, comes from a database, which has, among other information, the result of power flow solution and data reliability of the distribution system. The database is fed with the total energy measurement of each consumer. By automated measurements is obtained the active power from a limited number of consumers, selected by consumption type (residential, commercial and industrial) and its location. Joining these data with the energy measurement for each consumer, the load cycle characterization is achieved by using statistical analysis. For power flow solution is used a method for large weakly meshed network, proposed by Lue and Semlye [6]

Figure 2 illustrates the process of reading and power flow solution process based on the information stored in the database.

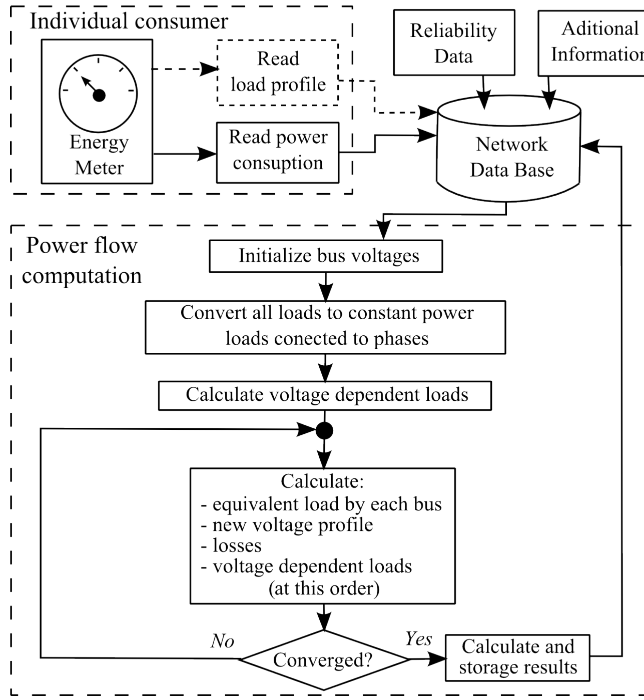

Fig. 2: Power flow computation process

Based on the result of power flow solution, and reliability data, the criteria are calculated.

The next section presents the development of each criterion. Aiming to standardize and put on the same financial base, for each criterion is given an equation that establishes the assessment method for selected criteria with the financial costs, here represented by $c(x)$, where x is the evaluated criteria.

III. Criteria Definition

For better understanding, this section provides a brief overview of the calculation methods in order to obtain the cost associated with each criterion.

A. Loss-of-Life in Transformers

The durability evaluation of a transformer, in economical and reliability studies, is related to the conditions of how the transformer is used. The relationship between insulation aging and time variation and temperature can be represented by an adaptation of the Arrhenius reaction-rate theory [7], expressed by the equation (1), where L is the insulation life, in p.u., Θ_H is the winding hottest spot temperature, in $^\circ C$.

$$L = 9,8 \times 10^{-18}.e^{\left[\frac{15.000}{\Theta_H+273}\right]} \tag{1}$$

From Equation (1) is obtained the Equation (2), which describes the Accelerated Aging Fator (F_{AA}) for a given load and temperature, or else, at a variable load and temperature profile in a 24 hour period.

$$F_{AA} = e^{\left[\frac{15.000}{383}-\frac{15.000}{\Theta_H+273}\right]} \tag{2}$$

To determine the aging over a given period and temperature cycle, Equation (2) may be modified resulting in equation (3).

$$F_{EQA} = \frac{\sum_{n=1}^{N} F_{AA,n}.\Delta t_n}{\sum_{n=1}^{N} \Delta t_n} \tag{3}$$

F_{EQA} is the equivalent aging factor for a period, n is the index of the interval Δt, N is the total number of intervals, and Δt_n is the interval itself.

Using Equation (1) we can calculate the percentage of loss of life in the transformers (4). The reference for the calculation is the transformer rated life at continuous operation and load at the nominal rate. Currently, the most used reference is 180000 hours (20.55 years) which is a requirement for transformers produced according to the standard IEEE C57.12.00 [8].

$$PV = \frac{F_{EQA} \times t \times 100}{L_N} \tag{4}$$

In Equation (4), L_N represents the transformer rated life, PV is the loss of life in percentage and t is the analysis period for F_{EQA}. As this criterion is already expressed in percentage, within the chosen time horizon, the financial value associated with the loss of life, $c(PV)$, is given by the expression (5), where $c(S_{N_i})$ is the transformer acquisition cost at the rated power.

$$c(PV) = \sum_{i=1}^{N} \frac{PV_i \times c(S_{N_i})}{100} \tag{5}$$

B. Transformer Losses

The total losses in transformers (ΔP_{TR}) are composed by losses in the windings and losses in the core ($\Delta P_{TR} = \Delta P_{Fe} + \Delta P_{Cu}$). The core losses are approximately proportional to the rated power of the transformer. On the other hand, the losses in the windings are dependent on the current flowing through the transformer, and can be expressed by equation (6).

$$\Delta P_{Cu} = \left(\frac{P_{avg}}{P_{nom}.cos\varphi}\right).P_{N_{Cu}} \tag{6}$$

In the equation $P_{N_{Cu}}$ is the windings losses in the transformer at rated load condition, in kWh, which is obtained by the difference between total losses and losses in a no-load condition in *kW*, P_{avg} is the power average, obtained by the consumed energy by consumers connected to the transformer divided by time in hours, P_{nom} is the rated power of the transformer in *kVA* and $cos\varphi$ is the power factor, set at 0.92 in this study.

To determine the financial, $c(P_{TR})$, is used the expression show in (7), where TE is the energy fare.

$$c(P_{TR}) = \sum_{i=1}^{N} \Delta P_{TR_i} \times TE \tag{7}$$

C. Line losses

For the determination of technical losses in distribution lines, the vast majority of distribution companies uses the power flow procedures, statistical processes, and geometric models for estimating losses. In this study, a Top-Down method was used, which is based on simplifying assumptions.

For financial losses, $c(P_L)$, are associated the percentage losses of each section with the energy fare (TE). The financial losses for the whole system is the summation of the financial losses of all segment section (1 to N_s), according to the expression (8).

$$c(P_L) = \sum_{i=1}^{N_s} \Delta P_{L_i} \times TE \tag{8}$$

D. Voltage Level

From the consumer's viewpoint, changes in mains voltage, different from the equipment rated voltage, can reduce the lifetime, even causing malfunction and, and in some cases, decreasing its efficiency. Similar to other criteria previously cited, the voltage levels are regulated and supervised by the regulatory authority.

In some countries, these limits are defined by indicators obtained through the voltage distribution frequency, which, by using percentiles, is obtained the quality of the voltage levels. In other countries, in a simplified form, is established limits for critical and precarious voltage levels, monitoring the time that these level remain within these limits, thus, obtaining indexes equation that represent the quality of voltage level.

Usually, utility distribution companies use expressions for financial compensation, which may vary depending on the laws of each country. In this work is used the method described by the Equation (9) which is used in Brazil, based on PRODIST standard[9]. The total cost of voltage compensation $c(\Delta V)$ is calculated by the sum of all values of violation for each consumer connected to the transformers (i to N).

$$c(\Delta V) = \sum_{i=1}^{N} \left[\left(\frac{DRP_i - DRP_M}{100} \right) \cdot k_1 + \left(\frac{DRC_i - DRC_M}{100} \right) \cdot k_2 \right] \cdot EUSD \quad (9)$$

In the equation, DRP_M and DRC_M refer to the maximum values allowed ***DRP*** and ***DRC*** are the indexes for Relative Duration of Transgression for Precarious and Critical Voltage respectively, both in percentage, k_1 and k_2 are constants that depends on the DRP and DRC values when compared with its limits. In this study, DRP_M = 3 % and DRC_M = 0,5 % was used. EUSD is the value relative to the charge of use of the distribution system, corresponding to the reference month from the last measurement, which is obtained obtained by multiplying the TUSD by the total energy consumption (EUSD = TUSD × kWh).

Knowing the DRP and DRC values, the active power consumption by transformer in the analysis period and the distribution company TUSD, is possible to get the amount paid in financial compensation for each consumer.

E. Utilization Factor

The utilization factor for a given equipment, in a given period of time *t*, is denominated K_u and represents the ratio between the maximum demand and its rated capacity ($K_u = S_{max}\ S_N$).

K_u is dimensionless and indicates how the system or a particular equipment is being used, that is, whether or not it is under-utilized or overloaded.

For distribution transformers, this is especially relevant because this index can point financial losses by sub-use, or also, indicate a possible reduction of life, in which case the machine operates in overload for long periods.

The relative cost due to the error in sizing the transformer, associated with the utilization factor, $c(K_U)$, is obtained by the expression (10) defined as follows:

$$c(K_U) = \sum_{i=1}^{N} \left[\frac{c(S_{N_i}) - c(K_U.S_{N_i})}{\Delta t \times 20} \right] \quad (10)$$

$c(S_{N_i})$ is the cost related to the acquisition of the installed transformer, $c(K_U.S_{N_i})$ is the cost transformer that best fits for that loading condition and Δt is the analysis horizon. In this way, is obtained the financial value due to the transformer incompatibility $c(K_U)$ based on their estimated life of 20 years.

F. Reliability

For reliability evaluation, is used the System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) that quantify the frequency and duration of the occurred interruptions, weighted in relation to a group of consumer. By violating the limits, established for the verification period, utility distribution companies must compensate the consumers making credit on the electricity bill. Equations (11) and (12) describe the calculation of the compensation amount based on the standard PRODIST [9].

$$c(SAIDI) = \left(\frac{SAIDI}{SAIDI_L} - 1 \right) .SAIDI_L. \left(\frac{EUSD}{730} \right) .kei \quad (11)$$

$$c(SAIFI) = \left(\frac{SAIFI}{SAIFI_L} - 1 \right) .SAIFI_L. \left(\frac{EUSD}{730} \right) .kei \quad (12)$$

$SAIDI_L$ and $SAIFI_L$ are the limits of continuity established in the period considered for the SAIDI and SAIFI indicator respectively, 730 is the average number of hours in the month and key is the scale factor which depends on the voltage level to which the consumer is supplied.

Finally, the financial cost for SAIDI and SAIFI $c(R)$ parts to be compensated for every customer, can by obtained by $c(R) = c(SAIDI) + c(SAIFI)$.

IV. Case Study

To evaluate the method, it was applied in a distribution network located in the state of Rio Grande do Sul, Brazil. The system consists of a substation comprising 8 feeders, which provides power to 46436 consumers.

The selection of this network was motivated because its presents load diversity in urban and rural regions. Moreover, in its composition there are section with old and new types of equipment which enables a better view of the sensibility of the method with respect to various parameters. Figure 3 show the real network topology.

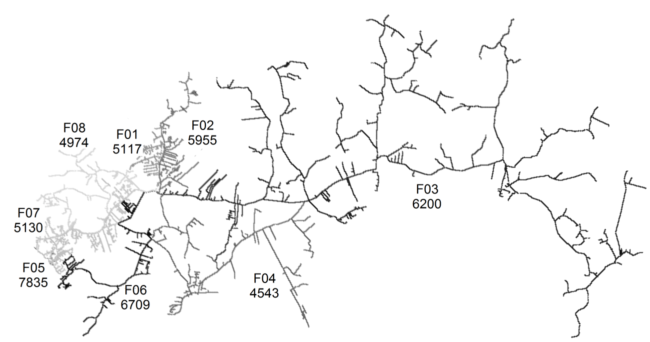

Fig. 3: Network topology of the distribution system

In this case study, we selected a time horizon of one month.

Based on power flow results, percentage losses rates for each section of the system was obtained. Technical losses in the transformers windings were obtained considering the monthly average of the active power based on the load profile for each transformer. Using the respective classes and nominal output voltage, there was obtained the core percentage loss.

To determine the transformer loss-of-life was considered transformers class 65°C and cooling type ONAN (Natural Oil Natural Air).

The values for voltage transgression were obtained through the voltage profile of the primary network for typical days of the month. As the penalties levied on the secondary network, the voltages of the primary network were converted to secondary voltages based on the *Tap* adjust for each transformer.

To determine the reliability results, were calculated the costs for each customer based on the values of SAIDI and SAIFI, recorded by the company for each consumer.

As a final result, in Figure 4, we have the composition of all economic criteria selected for evaluation of the distribution system. As can be seen, it is clear and direct, which feeder has the greater financial loss during the month selected for analysis.

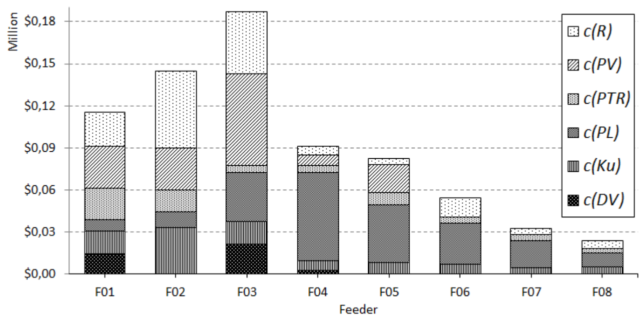

Fig. 4: System cost composition by feeder

As a method complement, the losses compound results can be confronted with the revenues according to the query criteria and the selected period. Thus, we obtain the relationship between losses and gains, enabling the decision-maker an additional element in the choice of their decisions. The Table I show the ratio between the financial losses and revenues for each feeder.

TABLE I: Profit/revenue ratio by feeder

Feeder	F01	F02	F03	F04	F05	F06	F07	F08
%Loss	1.36	1.86	10.84	4.75	2.62	2.60	1.75	1.87

The graph in Figure 5 illustrates the composition of the losses for the substation studied, being *r(SED)* the net revenue of all feeders for the substation. Losses are detailed, showing the contribution of each criterion analyzed.

V. Conclusion

In this work we seek to add to the set of existing methods, a more simplistic way to evaluate results using automated

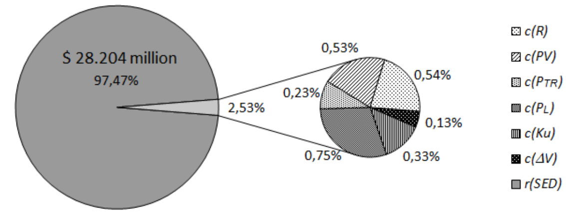

Fig. 5: Cost composition by criteria compared to total revenues

measurements process, linking technical criteria to financial marks. The method was able to meet the desires of those looking for economic evidence in a direct way, enabling simultaneous analysis of criterias in distribution systems.

By the case study, we identified the feeder F03 having the greatest financial losses, deserving action plans to mitigate the problems. It is observed that the method can easily be applied where there are already other tools for analyzing the network performance. Starting from the power flow solution, are joined the normally analyzed elements and is established a link which quantifies the losses and gains of the system.

Based on the results, can be stated that the method shows high potential to be used by decision-makers who work in utility distribution companies. This tool can support theirs strategic decisions on expansion planning, reducing financial losses and help to increase the system efficiency.

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