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Automatic Balancing System of Connected Single Phase Units in the Low Voltage Distribution Network

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ABSTRACT
The electricity distribution system tends to be unbalanced due to the presence of single-phase electrical charges and also due to the dynamic behavior of the radial circuits. Such serious imbalances, in addition to compromising the distribution of energy, can also interfere in the normal mode of operation of the active components in the network (electrical transformers, etc.) and shorten the useful life of the cables that make up the network. The objective of this work is to demonstrate by simulation the benefits brought by the adoption of automation in the execution of the load balancing task, however for greater efficiency of the assets and improvement of the supply quality, the present work defends the logical use for the search of the best redistribution of single-phase loads connected to the distribution network, including the fuzzy logic to support decision making and interpretation of dynamic load behavior, as well as the search optimization method for the best allocation of single-phase loads (consumer units) advocates the adoption of an algorithm based on the simplex model. The results found through the techniques employed, allow a better distribution of loads through the distribution network, reducing the risks for the people involved in the execution of the task in the field and obtaining improvements in the tension profile due to the load imbalance.
Keywords - Computational Intelligence, Fuzzy Logic, Load Balancing, Secondary Distribution Network, Simplex.

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I. INTRODUCTION

The assistance of electric energy brings with it an increase in the quality of life of the mankind, so much that the consumption of energy can be used like parameter of growth and development of a nation. In Brazil, the growth of electric energy consumption has always been speculated, so much so that in Brazil in 2008 with an accelerated economy there was some concern about the capacity to absorb energy demand by the industrial and commercial sector [1].

The power system - SEP in Brazil can be subdivided into three subsystems, namely: Generation, Transmission and Distribution. From the point of view of the complexity of operation and maintenance, the distribution subsystem is the most complex of the three, because it is in this part that the interface between the distributors (private, mixed or state-owned concessionaires) with the consumer units occurs [2]. The distribution can still be subdivided into primary and secondary distribution and this was largely impacted by the edition of RN 223 by ANEEL, which, according to its writing, obliges the concessionaires to attend to requests for new calls free of charge provided that the installed load of the applicant does not exceed 50 kW [3].

The repercussion of this normative resolution in the local concessionaire, is translated by the difficulty in the treatment of new connections, that is, by an overload in the service sector against a significant growth of charges in both regular and irregular system (clandestine connections). All these factors negatively affect the distribution of energy in the distribution subsystem of this concessionaire, generating complaints and fines for violations of collective quality of both product (DRP and DRC) and service quality (DEC, FEC and TMA). However, of all the problems and uncountable natures of its causes the main consequence for both the concessionaire and the consumers served by it is the burning of the transforming asset by overload or by severe imbalance in its secondary, which is closely linked to losses high technical and non-technical skills and poor customer service.

In dealing with the problem of clandestine connections, particularly connected with the unplanned expansion of the city of Manaus, it occurs that such connections generate harmful impacts to distributed energy, since most of them are carried out in a criminal manner, without the use of suitable connections, without measurements approved by the concessionaire nor does it observe the technical criteria described on NDEE-02, all these factors together and added to old networks, besides the contingency faced in the electric system as a whole, it is clear the need for robust optimizations of the assets, aiming at the preservation and continuity of supply, as well as improving operational quality and performance indicators. Still on the irregular connections, Figure 1 presents a scenario where the greatest non-technical losses are recorded, which coincide with areas of high concentration of irregular occupation (invasions) existing in Manaus, being a notorious point for the north zone of the city, which has experienced significant growth in this decade.

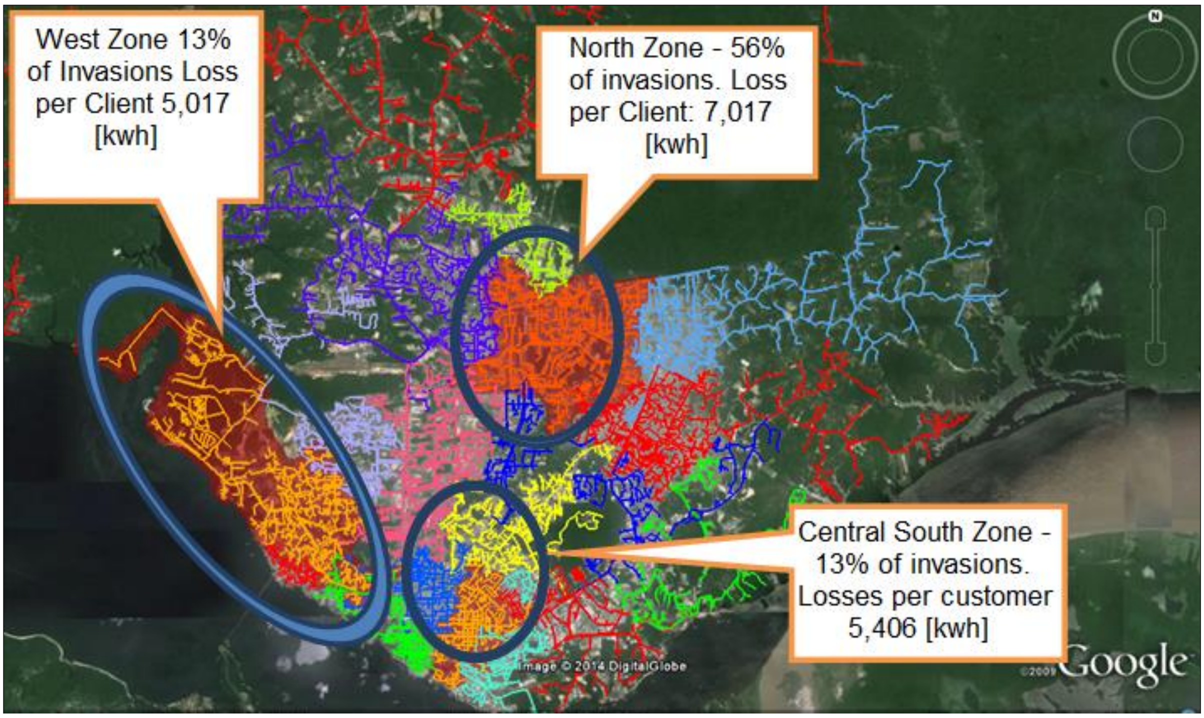

Figure 1: Location of Losses per Customer in Manaus

In the view of the optimization of the physical resources in the face of the sudden demand for the loads (consumer units) connected in the secondary distribution network, the present work discusses a low cost option, but with the use of artificial intelligence resources and the use of power electronics in order to seek the improvement of the distribution of the loads connected along the distribution network of the concessionaire, aiming at reducing the breaches of quality indicators from a product point of view (adequate levels of supply voltage), in addition to improving the technical loss, prolonging the life of active components of the network (transformers and cables) and delay in network reinforcement procedures, which almost always require the investment of resources (costs).

Load balancing (consumer units) is one of the first procedures to be adopted as a prophylactic measure in problems of violation of energy quality indicators from the product point of view (precarious or critical voltage), but its need is not so evident until there are complaints from UCs or are evidenced in the sample assemblies of PRODIST-ANEEL, however, the method applied in the concession area of the company under study is still rudimentary, without the aid of constant measurements, without the support of automation and also without a history of demand for loads, sometimes the process is carried out based on the knowledge acquired by the executing teams, and its result is not very accurate and passive to questioning, in addition to the need to expose people to electrical risk during interventions in the system, carry out stoppages in the transformation units, something that affects the collective continuity indicators (DEC and FE Ç).

The whole scenario described highlights the lack of a more effective measure, intelligent action that optimizes the available resources, in this sense proposes the adoption of a device capable of balancing loads (Consumer Units) connected in the distribution network automatically (guided by an algorithm based on the simplex model), adoption of artificial intelligence (decision-making stage using Fuzzy logic) and without the presence of human intervention in the computing process, which is performed by means of switching circuits that employ the power electronics.

II. LITERATURE REVIEW

2.1 Balancement of Consumer Units - CUs

The optimization of electric power distribution networks is the subject of many works, almost all of them concentrated in medium voltage networks, with few works being done with the low voltage network. However, [4] presented a combined whole programming model, which addressed the improvement of the losses with redistribution of the loads in the distribution circuits.

The allocation of loads in a more equitable way throughout the three phases of the distribution system is a combinational problem, in this sense the work of [5] present an entire and linear programming model with the use of open solver, giving support in the design of distribution network projects. In the work of [5], [6] presents a computational system in which it is possible to simulate the distribution of loads, resulting in the reduction of neutral current (present in severe imbalances) and preservation of the integrity of conductors and transformers in networks distribution.

But it was in the work of [7] that mathematical modeling was presented for several actions of maintenance and optimization in distribution networks, being given a load balancing approach in this work, since it served as a foundation for the development of this work.

Figure 2 shows the graphical representation of the load balancing, being the polygon formed by six edges the representation of the approximations of the balancing, that is, the bigger the number of edges, closer to the ideal would be the balancing, increasing the number of edges calls for greater mathematical effort and when implemented in algorithm it also requires greater computational effort.

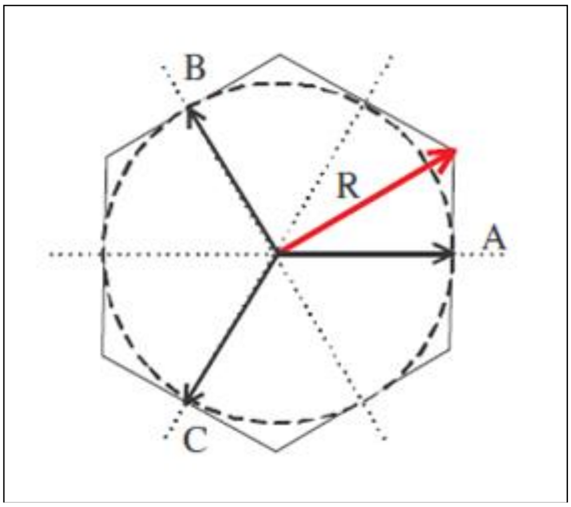

Figure 2: Graphical representation of the load balancing approach constraints
Source: [8].

Eq. (1) presents in a synthetic way the determination of the balance of the circuit.

$$\text{bal} = \left(1 - \frac{R}{A+B+C}\right) \tag{1}$$

At where:
Bal = Load balancing in the circuit;
A, B and C = Total loads in each phase;
R = Total circuit unbalance.

2.2 Nebulous Logic (Fuzzy)

The Fuzzy Logic proposed by [9] is a promising branch of artificial intelligence that is based on the question of degree of pertinence, allowing to work with information that is vague or difficult to interpret. The differential compared to Boolean logic (true and false) is that in nebulous logic the propositions can have degrees between the two extremes. The nebulous logic is applied in systems of control, system modeling, economical engineering and in this work in the decision making stage in the sense of the search of the optimization of the distribution of the monophasic CUs, therefore, translating and seeking the minimization of inherent uncertainties to the dynamic behavior of connected loads in the distribution subsystem.

2.3 Mamdani Model

The main idea of Mamdani's method is to describe process states by means of linguistic variables and to use these variables as inputs to control rules; the rules connect the input variables with the output variables and are based on the description of the diffuse state that is obtained by the definition of the linguistic variables. It is expected that each crisp input (a real number or n-up line of real numbers) will match a crisp output and in general, a fuzzy system will match each input and output. In this case, a Fuzzy system is a function of Rn in R, constructed by a specific methodology according to three modules shown in Figure 3 [10].

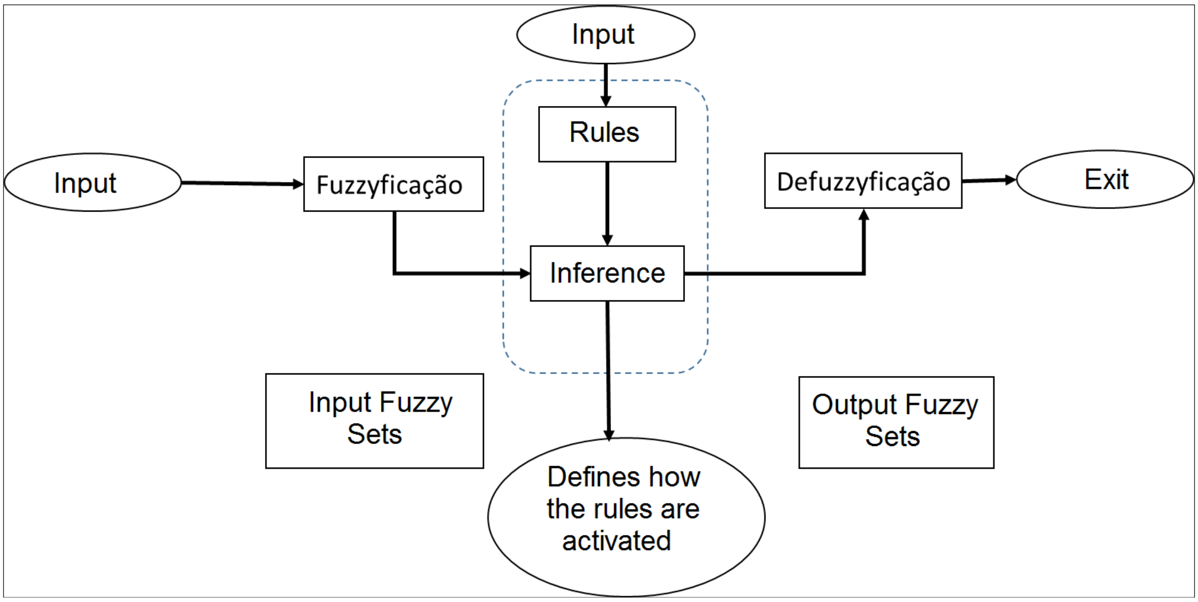

Figure 3: Structure of the fuzzy logic controller
Source: Adapted from [11].

2.4 Mathematical Optimization

In general concepts an optimization problem seeks to maximize or minimize a real function, choosing input values of a specific set and evaluating the value assumed for a said function, that is, finding the best results for an objective function in a given domain. For [12], mathematical programming studies problems, properties, solution algorithm creation and its applications in the real world.

According to [12], an optimization is composed of variables, objective function and constraints, and the objective function is the mathematical expression to be optimized, since the constraints are the limits for the variables such that the solution is feasible and the variables are the values for theobjective function. Eq. (2) presents the generic form of problems associated with optimization.

$$\begin{aligned} &\min f_o(x) \\ &sujeito_{f_i}(x) \le b_i; i = 1,\ldots,n \end{aligned} \tag{2}$$

At where:
Min f0 (x) = objective function;
Bi = Restrictions

2.5 Simplex Method

Still according to [12] the simplex method walks in the vertex region until it obtains a solution that does not have better than it in the neighborhood, therefore, this solution is the optimal one. However, there are scenarios in which it is not possible to reach the optimal solution, in which case there is no viable optimal solution to the problem, either by incompatible constraints or because the variables tend to infinity, causing the objective function to find no limits. Simplex is commonly used in optimal linear programming solutions (PL), when following the following criteria:

a) All variables are non-negatives;
b) All bi are non-negatives;
c) All the initial equations of the system are of the smaller or equal type (≤), such that only gap variable is found.

It happens that sometimes some of the criteria cannot be observed, for that, the simplex technique of two phases is used.

2.6 Usual Allocation of CUs in Distribution Circuits

Low voltage consumer units, when connected to nano sized cable distribution networks, are usually anchored close to the support structures of the nets near the poles and due to the incompatibility of the metal alloys that make up the networks (usually aluminum) and the service branches (usually insulated copper cables), it is used wedge-type or parallel-type connectors compatible with the gages in the circuit sections, thus avoiding oxidation at the connection points [13]. Figure 4 shows in a generic way the allocation of consumer units along the nodes that make up the low voltage distribution network.

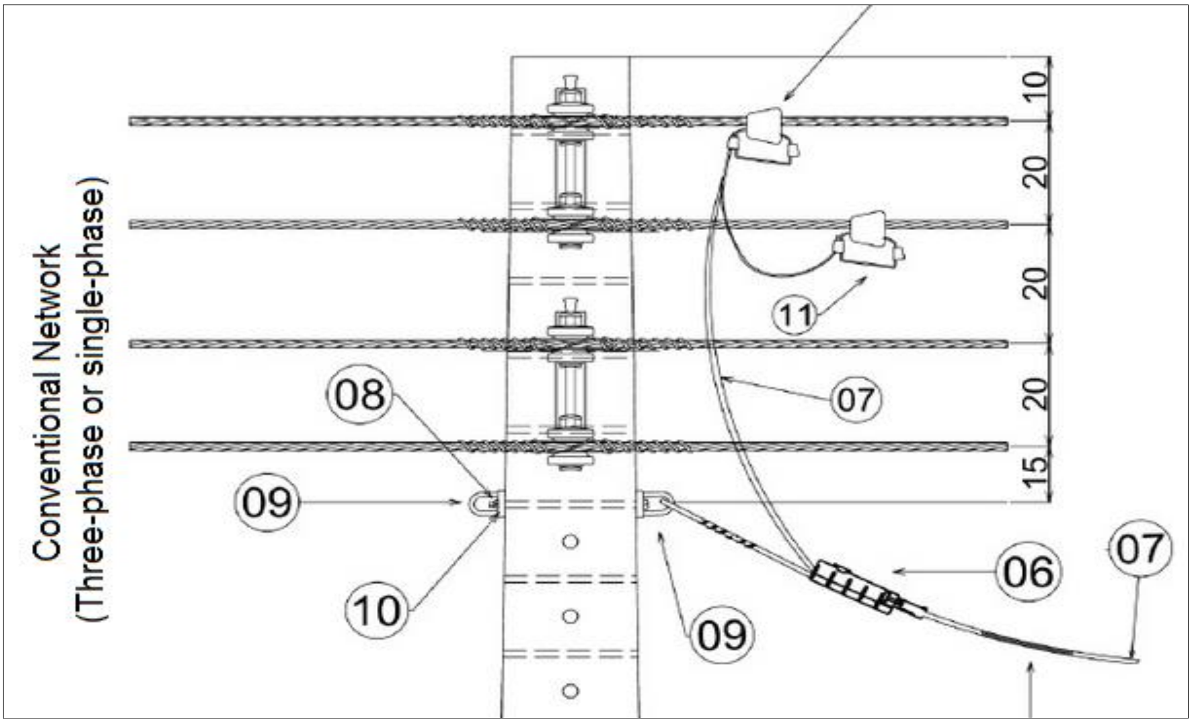

Figure 4: Connection of the branch of the distribution network
Source: [14].

III. MATERIALS AND METHODS

3.1 Data Collection and Job Design

The fomentation of the data applied in this work were collected from the local concessionaire, directly from its database of SGDREDE, whose purpose is the remote monitoring of processing units spread across several districts of the city of Manaus.

The adoption of the limits for the linguistic variables of the fuzzy sets used in the decision-making of the balancing system proposed in this work, obeyed the knowledge and experience of a specialist in the concessionaire's project body, but it was also based on two-year histograms, aiming at this a better approximation of the objective of this theme.

In order to conceptualize the proposal of the system of automatic balancing of consumer units, searches were made at first of collections of similar themes, works published in magazines and periodicals, with the purpose of better supporting the foundation of the theme, in the second stage of the development of the designer of the hardware was used the tool of CAD PROTEUS 8. The development of the control system, that is to say the third stage of the work, was carried out a computer simulation of the software MATLAB® R2014a, which the fuzzy Logic toolbox allows the creation of Mamdani models, in addition to an open solver available in Excel 2010 tool for validation of the algorithm model based on the simplex method.

3.2 Determination of the Fuzzy Block for Decision Making

The Mamdani model proposed in this work and presented in figure 5 demonstrates the strategy of daily control to be performed by the proposed system, which depending on the interpretation of the inputs, which are represented by the demand requests of the three phases of the system and the time of day, enables the CUs balancer block in the search for the best load distribution.

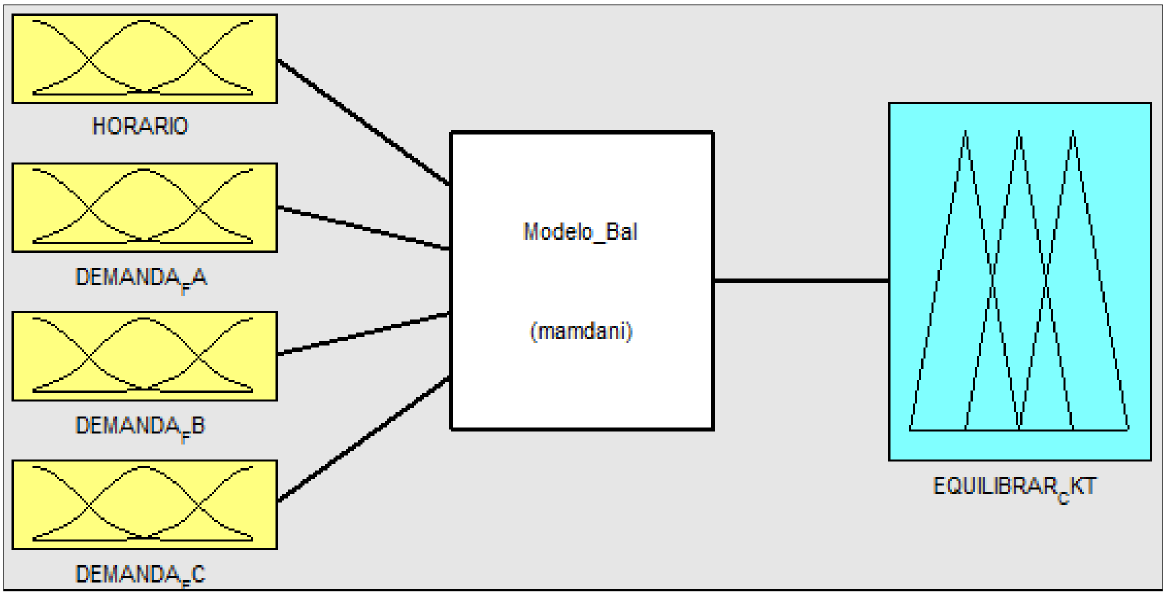

Figure 5: Mamdani model proposed

3.2.1 Mamdani Model Variables

The construction of the Mamdani method proposed in the work uses four input impacts: Demand Phase A, Demand Phase B, Demand Phase C and Schedules; and only one output: Balance Ckt. The division of impacts into linguistic levels was defined according to Table 1.

Table 1: Description of the linguistic variables and result

Language Variables		Cloudy Set
Type	Description	
Input	Schedule	Light (SL)
		Moderate (SM)
		Critic (SC)
	Demand Phase A	Light (DPLA)
		Moderate (DPMA)
		Critic (DPCA)
	Demand Phase B	Light (DPLB)
		Moderate (DPMB)
		Critic (DPCB)
	Demand Phase C	Light (DPLC)
		Moderate (DPMC)
		Critic (DPCC)
Output	Balance CKT	ON (BCL)
		OFF (BCD)

3.2.2 Input Variables

Demand Phase A, B and C - the demand of the connected consumer units in the phases of the processing unit is variable throughout the day, however each winding of the transformation unit can only provide a power compatible with its transformation capacity and when over request occurs the whole system is put at risk of shutdown due to overload. Figure 6 demonstrates the parameterization in the Fuzzy Logic Toolbox for the Phase a Demand input variable, the same is valid for the other phases that make up the system.

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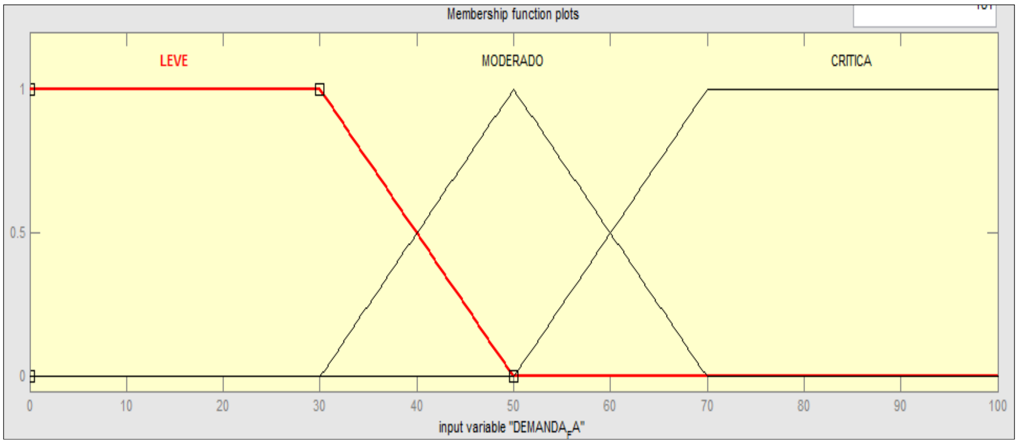

Figure 6: Variable Demand for Phase A

Daily Schedules - The sooner the likelihood of many loads being connected requesting large power blocks, but at the rush hour of the system, there is a severe risk of customer service. The parameterization of the variable is shown in Figure 7.

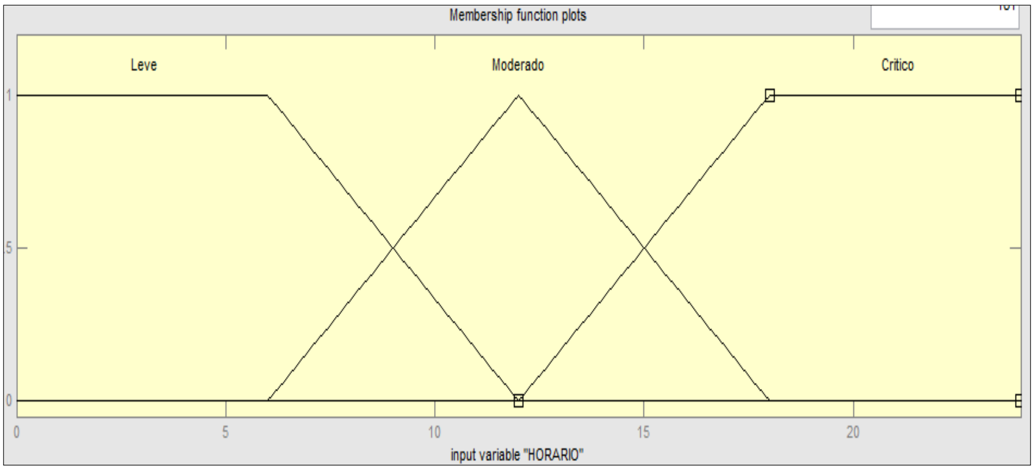

Figure 7: Time Variable

3.2.3 Rule Base

The determination of the linguistic rules, which totaled 81, followed the guidelines of specialists of the concessionaire target of this work, based on the occurrences registered in the SIAGE and SGDREDE systems, in addition to observing the unit cost of operation and quality of supply. Figure 8 shows a part of the 81 rules that make up the model.

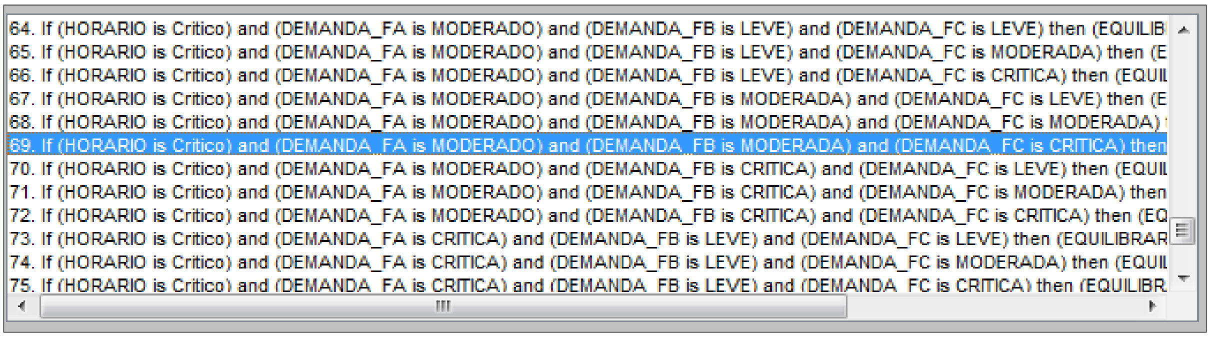

Figure 8: Inference rules of linguistic variables

3.3 Reconfiguration of CUs with Simplex Based on Solver Assistance

In order to achieve the distribution of the CUs through the three phases of the secondary of the SDBT in order to obtain the equilibrium in the allocation of load (better distribution), the present work adopts the method of distribution based on simplex, which briefly is based on bidders and applicants, being subject to restrictions inherent to the process.

Eq. (3) and (4) present the constraints imposed on the algorithm in the search for the best load balancing.

$$A + \frac{2\times \text{Dem total}\times \text{Bal}}{3} \leq \text{DemTota} \tag{3}$$

$$\frac{2\times \text{Dem total}\times \text{Bal}}{3} - A \leq \frac{\text{Dem Total}}{3} \tag{4}$$

At where:
Bal = balancing of the circuit;
Dem Total = total circuit demand;
A = phase demand any phase.

The bidders would be the three phases of the processing unit with their maximum and finite capacities to provide power and the demanders would be all the loads attached to the secondary of the processing unit.

3.4 CU Switching Interface

To perform the commutations of the consumer units the present work is based on the electronic keys, being in this case the SCR thyristors, in the antiparallel configuration, as shown in the schematic of Figure 9. To avoid switching by electrical noise and outside the time determined by the block of control of the main thyristors, that is, those that control the power supply to the CUs connected to the distribution subsystem are protected by a circuit filter of relief type RC (snubber circuit).

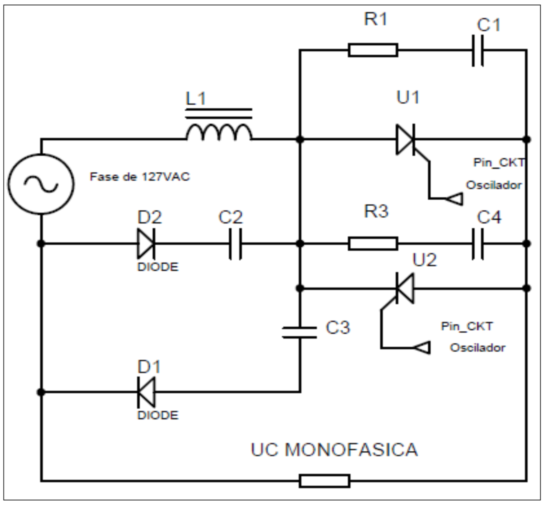

Figure 9: Simplified Schematic of the Consumer Unit Switching Circuit

IV. RESULTS AND DISCUSSIONS

For the simulation of the system proposed in this work, a circuit selection was made based on the measurements pointed out by the SGDREDE, the target circuit of this study being highly unbalanced and attending an area with a high technical and non-technical loss rate. Figure 10 shows the sketch of the circuit, whose data were simulated in this work.

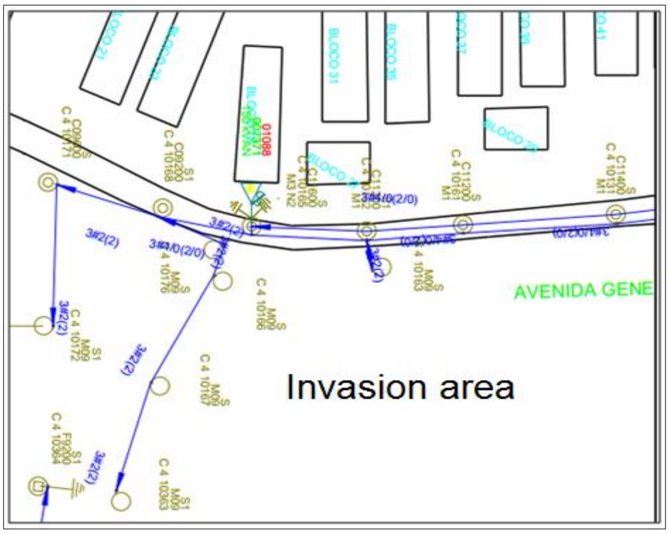

Figure 10: Sketch of the Circuit CC-03-0188
Source: [14].

Table 2 presents the characteristics of the circuit in the elaboration stage of this work.

Table 2: Technical data of the distribution circuit CC030188

Code	Nº Alm	Pot. of trafc	SE	Nº of CUs	1ϕ	2ϕ	3ϕ
0188	3	150	CC	71	34	23	14
Phase	Current (A)	Tension F-N	Tension F-F	Qtt CU 1ϕ	Qtt of CU p/ Power kVA		
					0,5	1,5	3,0
A	409,4	140	230	16	14	12	8
B	472	139,8	228	10			
C	557,8	139,5	227	8			

Source: Adapted from [14].

Once the circuit selection stage is over and based on the flow diagram of the internal operations of the proposal system, which is presented in a simplified way in figure 11, where all the sub-blocks that make up the system as a whole are arranged.

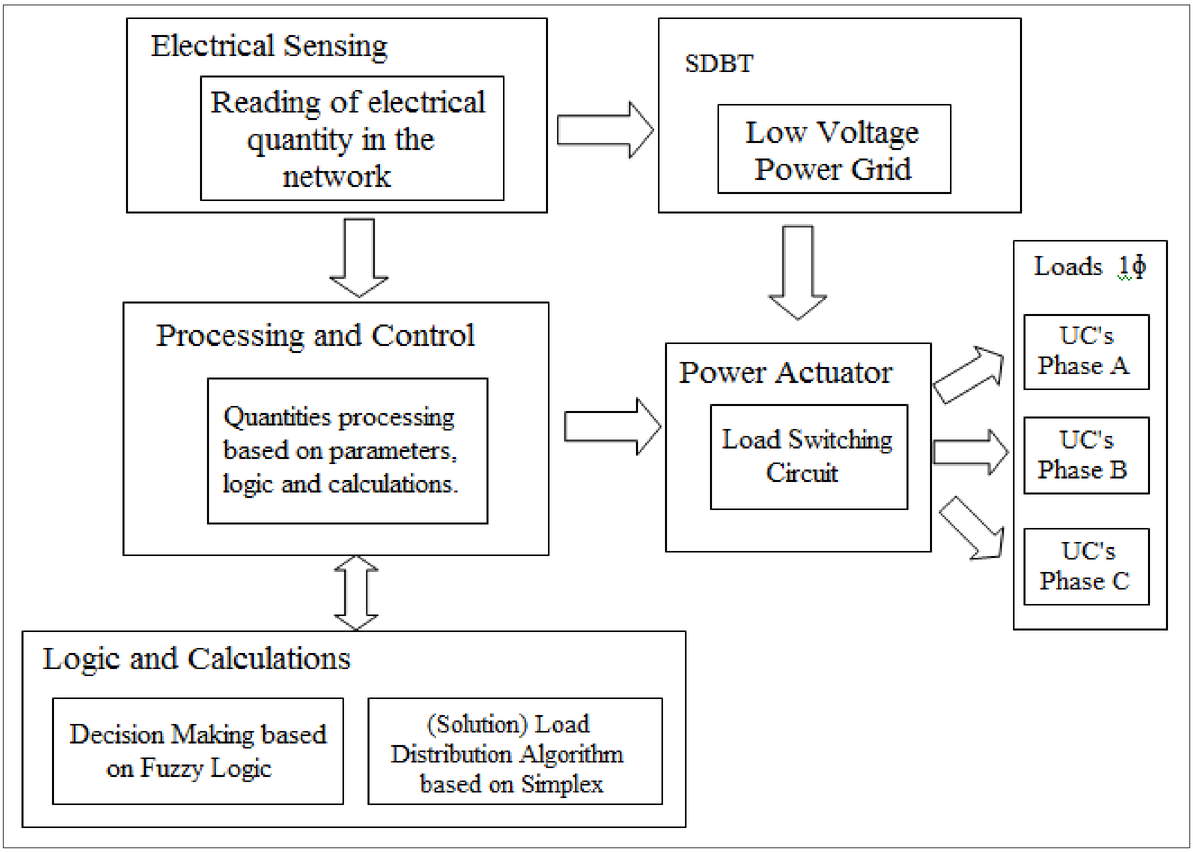

Figure 11: Simplified Flow Diagram of the Balancing System

Based on the information in Table 2, the input electronic sensing circuits of the balancer system of Figure 11 sends data to the input of the microcontroller, sensitizing it to initialize a demand-by-phase request analysis and the number of CUs per phase of the circuit, based on the Fuzzy Block decision making, obeying the nebulous logic and parameterization of Table 1 of the Fuzzy sets, occurs the fuzzification of the inputs, since observed the set of rules that best expresses the interaction. The output of the Fuzzy Block enables the optimization block, which with simplex based algorithm searches the redistribution of loads and the microcontroller enables the switching block of connected consumer units in the network.

Table 3 shows the simulation of the redistribution of the monophasic CUs through the three phases of the distribution circuit, that is, the distribution performed by the solver (block of optimization) of the system proposed in this work, being observed that it aims to meet the capacity constraints of the phases and maximize the load balancing.

Table 3: Distribution of the CUs to the circuit CC030188

Load Distribution			
CU	System Phases		
	A	B	C
TYPE 1	6	4	4
TYPE 2	4	4	4
TYPE 3	2	3	3

In Figure 12, we notice the behavior of the Fuzzy decision block, which responds by enabling the optimization block against a demand greater than 80% in phase A and a time greater than 18 hours, thus at the end.

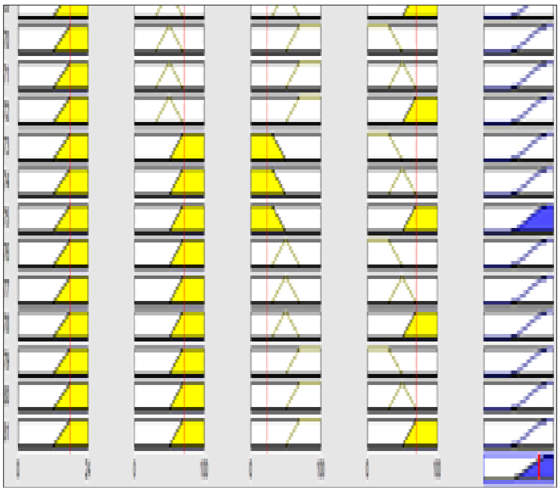

Figure 12: Response graph of the Fuzzy block

V. CONCLUSION

In the work it was proposed the implementation of an automatic system capable of searching for the balancing of connected consumer units in the low voltage distribution network. For this purpose, the artificial intelligence method of Fuzzy sets was implemented to control the task of enabling or not the system of actuation and switching of consumer units, according to this task, an optimization block based on the simplex method was elaborated, which guides and determines the quantity of consumer units to be connected in each phase of the transformation unit, respecting the power capacities to be dispatched. As a final element of performance, the system proposed here uses power switches (SCR) in the antiparallel configuration, that is, static keys to perform the manipulation of the consumer units.

The simulated results showed that, in general, the balancing model proposed here allowed, from the information collected from the network, to determine the redistribution necessary to balance the loads and at the same time reduce the need for interventions in order to improve the distribution of loads , that is, the reduction of the cost of team displacement, in addition to optimizing available resources, improving the performance of losses linked to imbalance and stress levels associated with severe imbalances.

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