Fuzzy Control for Shunt Capacitors Applied in Distribution Feeders

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Abstract: - The lack of reactive energy flow control in distribution networks causes an increase of electrical losses and problems with the voltage profile. The main objective of this work is to develop a fuzzy control system for automatic capacitor banks applied to distribution feeders, which was focused on the improvement of the equipment performance allowing a better correction of the system reactive and minimizing the switching number of the capacitor banks and not causing the floating of voltage levels at the feeders. It was analyzed the controller´s performance on a 70 buses system. The main results shown that the fuzzy controller is not affected neither by the capacitor bank installation position at the distribution feeder nor by the bank capacity in kvar. Another aspect is that the fuzzy controller does not need to be tuned in the case of changes at the system's load profiles, always operating with good results for several different load profiles.

Key-Words: - Fuzzy control, distribution feeders, shunt capacitors.

1 Introduction

The Brazilian electric distribution companies are subjected to the regulation by performance comparing to stimulate the service quality improvement for the customers and the cost reduction with the objective of increase the competitivity. [1].

So, the lack of a reactive energy flow control that circulates at the distribution networks causes an increasing of the electrical losses and damages for the voltage profile. Considering the arguments mentioned before, it is desirable to compensate the reactive by optimizing the operational costs through some investments on the capacitor banks installation at the electric energy distribution feeders. The optimized application of the capacitor banks imply in a first moment on the best installation position of the equipment. Basically the capacitor banks allocation problem is to define the kind of capacitor bank (fixed or automatic), the capacity of the bank (in kvar) and the bank localization. This is a problem that is not easy to be solved because the quantity of minimum local points and the option numbers to be analyzed grow when the quantity of buses increase. [2].

However, the complete solution for the capacitor banks problem involves not only the bank allocation but also to define the kind of the bank control and its control tuning. This work is focused on the development of a fuzzy control system considering that the automatic bank localization and its capacity is already known.

The loads on real distribution systems are subjected to non-simultaneous variations on the distribution feeder buses. So, the equipment operation with the fixed tuning of the control device during a certain time horizon can not to be enough to supply the necessary reactive compensation.

Another important point is the improvement of the voltage profile that comes from the losses reduction of the system and can be gotten through the application of the capacitor bank and its control equipment.

In fact, beyond the reactive compensation, the improvement on the voltage profile becomes one of the advantages for the implementation of this device at the distribution feeders specially considering that there is a specific legislation in Brazil about the allowed voltage levels and the penalties for the limit breaking.

2 Problem Formulation

The capacitor banks are used on distribution systems to compensate the reactive, contributing for the energy and power losses minimization and to improve the voltage profile within the acceptable limits. The compensation quantity is strongly related to the capacitor banks placement at the distribution system, capacity, quantity and kind of capacitors to be installed at the system [4].

The capacitors applied on distribution systems are frequently placed at the distribution feeders or at the electrical substations. Its utilization is focused on the local power factor correction, considering that the banks may be fixed or automatics depending on the load conditions. Basically, the fixed banks are applied for light load conditions and the automatic banks for medium and heavy load of the system [5].

The Brazilian concessionaires use most of time the time-voltage control system, adjusting the voltage that turns on the bank (Von) through the voltage measured at the installation point at 8 o'clock on working days. The time adjust is fixed for the operations from 08:00am to 9:00pm.

2.1 Brazilian Regulations

The regulation ANEEL Nº 456 [6], established on 0,92 the minimum value for reference power factor inductive or capacitive at the facilities of the Brazilian electrical consumers.

The voltage values for permanent regimen have to attend the requirements of the regulation ANEEL Nº 505 [3]. The allowed values at the feeders for the voltage variation in permanent regiment are shown at the Table 1

Table 1 – Standardized nominal voltage for voltages higher than 1kV and lower than 69kV

Classification of the Voltage Attendance (TA)	Reading voltage range variation (TL) in relation to the contracted voltage (TC)
Adequate	0,93xTC ≤ TL ≤ 1,05xTC
Precarious	0,90xTC ≤ TL < 0,93xTC
Critical	TL < 0,90xTC or TL > 1,05xTC

The concessionaire must monitor when there is a customer complaining or when making a routining sampling measurement the following individual indicators:

- Precarious Relative Duration of Transgression (DRP), using the following equation:

$$DRP = \frac{nlp}{1008} \times 100[\%]$$

- Critical Relative Duration of Transgression (DRC), using the following equation:

$$DRC = \frac{nlc}{1008} \times 100[\%]$$

where: nlp = number of readings with measurements with the values placed at the precarious range;

nlc = number of readings with measurements with the values placed at the critical range; and

1.008 = number of valid readings every 10 minutes at the observation period.

2.2 Analyzed System

The distribution system that was used on this work is shown at the Figure 1, where it is possible to verify the 69 load buses [7], and also the substation (SE) bus. It was performed studies about the system's behavior under nominal condition and without the capacitor banks.

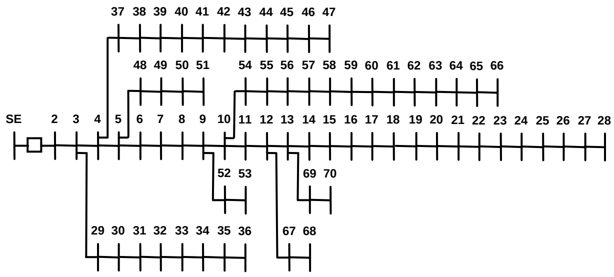

Figure 1 – 70 buses distribution system diagram.

For the power flow calculations it was considered the voltage base of 12.66 [kV] and the power of 10 [kVA].

The studied system's voltage profile where no capacitor banks were used can be visualized at the Figure 2.

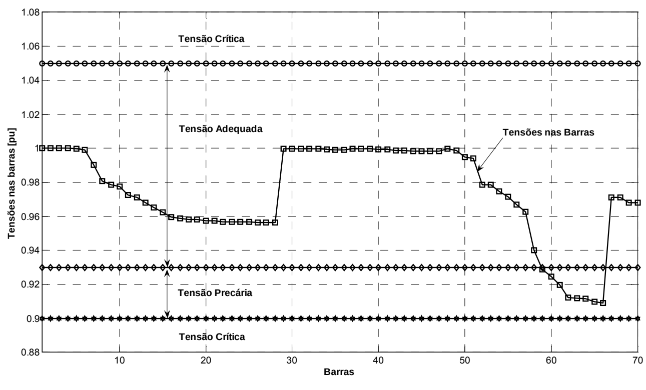

Figure 2 – System's voltage profile with no capacitor banks used.

Under nominal conditions, the active losses are 225,1 kW and the power factor of the feeder is 0,821 inductive. It is possible to verify that under nominal conditions the buses from 59 to 66 show precarious voltage levels according to the regulation ANEEL Nº 505/2001 [3] and the feeder has a global power factor (from the substation bus) worse than the limit specified at ANEEL Nº 456/2000 [6].

2.3 Fuzzy Control

The basic structure of a fuzzy controller [8] regards four main components presented at the Figure 3, considering that:

- The fuzzification interface receives the input variables values and develop a conversion to a linguistic variable in set with a membership function;
- The knowledge base regards the control rules in terms of linguistic variables.
- The decision take logic is able to emulate the human decision take process and infer fuzzy control actions;
- The defuzzification interface receives the fuzzy control actions in terms of a linguistic variable in set with a membership function and converts for values of the output variable.

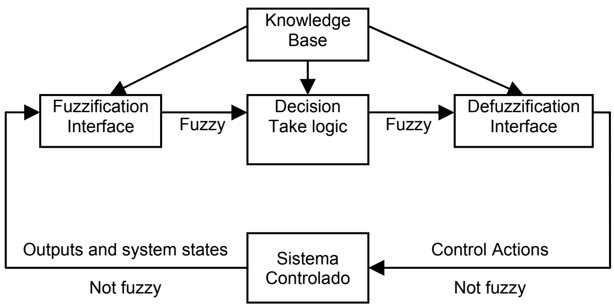

Figure 3 – Basic configuration of a fuzzy controller.

The fuzzy technology is adequate to be implemented on complex systems or not well defined, which do not admit the usage of traditional methodologies of quantitative analysis [8].

Another important aspect is the use of linguistic variables involved on the control process, which makes the controller more independent of the context (specific characteristics) of the controller application.

The controller 1 was developed with the following parameters:

- Input variables chosen: V (voltage) e ΔV (voltage variation);
- Output variable chosen: BC (represents the capacitor bank on or off).

The variable ΔV represents the voltage variation at the installation point of the capacitor banks and can be calculated by:

$$\Delta V = (V^{(k)} - V^{(k-1)}) / V^{(k-1)}$$

where: $V^{(k)}$ is the voltage at the iteration k; and
$V^{(k-1)}$ is the voltage at the iteration k-1.

The voltage V was splitted in four fuzzy subsets considering a range of [0.8,1.2] in pu. Those subsets were defined according to the regulation ANEEL Nº 505 [3], described as the following:

- Critical Low - CB: it was chosen a trapezoidal function with the parameterization [0.8 0.8 0.92 0.98];
- Precarious - P: it was chosen a trapezoidal function with the parameterization [0.9 0.94 0.96 1.00];
- Adequate – A: it was chosen a triangle function with the parameterization [0.98 1.00 1.05];
- Critical High - CA: it was chosen a trapezoidal function with the parameterization [1.05 1.07 1.2 1.2].

The variable ΔV (voltage variation) was splitted in five fuzzy subsets considering a range or possible values of [-0.5,0.05]. Those subsets were defined as described below:

- Negative Medium – MN: it was chosen a trapezoidal function with the parameterization [-0.5 -0.5 -0.28 -0.24];
- Small Negative – PN: it was chosen a triangle function with the parameterization [-0.28 -0.25 -0.225];
- Zero – ZE: it was chosen a triangle function with the parameterization [-0.24 -0.225 -0.2];
- Small Positive – PP: it was chosen a triangle function with the parameterization [-0.2 -0.19 -0.17];
- Medium Positive – MP: it was chosen a trapezoidal function with the parameterization [-0.2 -0.17 0.05 0.05].

The output variable BC was splitted in four fuzzy subsets considering a range or possible values of [0,1] in pu, considering 0 the bank turned off and 1 the bank turned on. Those subsets were defined as the following descriptions:

- Zero – ZE: it was chosen a trapezoidal function with the parameterization [0 0 0.05 0.08];
- Small Positive – PP: it was chosen a trapezoidal function with the parameterizations [0.03 0.12 0.16 0.20];
- Medium Positive – MP: it was chosen a trapezoidal function with the parameterizations [0.17 0.23 0.7 0.8];
- Big Positive – GP: it was chosen a trapezoidal function with the parameterization [0.7 0.8 1 1].

The developed rules for the knowledge base for the controller 1 are shown at the Table 2.

Table 2: Developed rules for the controller 1

Output BC		ΔV				
		MN	PN	ZE	PP	MP
V	CB	GP	GP	GP	GP	GP
	P	GP	GP	GP	GP	GP
	A	GP	MP	ZE	PN	MN
	CA	ZE	ZE	ZE	ZE	ZE

The second developed controller uses the output variable BC splitted in four fuzzy subsets considering a range or possible values of [-1,1] in pu, considering 1 the additioning of the total reactive power to the system and -1 o total decreasing of the reactive power of the system. Those subsets were defined according to the described below:

- Big Negative - GN: it was chosen a trapezoidal function with the parameterization [-1 -1 -0.8 -0.65];
- Medium Negative – MN: it was chosen a trapezoidal function with the parameterization [-0.75 -0.7 -0.5 -0.4];
- Small Negative – PN: it was chosen a trapezoidal function with the parameterization [-0.5 -0.35 -0.25 -0.1];
- Zero – ZE: it was chosen a triangle function with the parameterization [-0.2 0 0.2];
- Small Positive – PP: it was chosen a trapezoidal function with the parameterization [0.1 0.25 0.35 0.5];
- Medium Positive – MP: it was chosen a trapezoidal function with the parameterization [0.4 0.5 0.7 0.75];
- Big Positive – GP: it was chosen a trapezoidal function with the parameterization [0.65 0.8 1 1].

The developed rules for the knowledge base for the controller 2 are shown at the Table 3.

Table3 - Regras desenvolvidas para o controlador 2

Output BC		ΔV				
		MN	PN	ZE	PP	MP
V	CB	GP	GP	GP	GP	GP
	P	GP	GP	GP	GP	GP
	A	GP	GP	ZE	ZE	ZE
	CA	ZE	ZE	ZE	ZE	ZE

The first control strategy uses the controller 1 and uses a saturation block, according to the Figure 4. The function of the saturation block is to implement the system output for {0,1} turning off or turning on the capacitor banks.

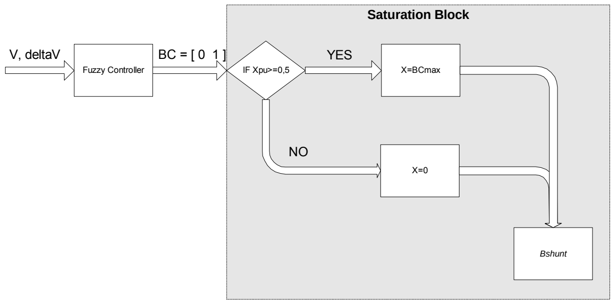

Figure 4 – Block diagram of the control system with a saturation block.

According to the Figure 4, every time the output variable gets bigger than 0.5, the capacitor banks are turned on. For output variables smaller than 0.5 the capacitor banks are turned off. The output of the saturation block is loaded at the Bshunt vector (system's shunt capacitor banks vector) for the power flow.

The second control strategy uses the controller 2 and uses an accumulation block and a saturation block, according to the Figure 5. As the controller 2 was developed based on the philosophy of increase and decrease reactive power from the capacitor bank, the accumulation block has the objective of anticipate the turn on and delay the turn off of the capacitor banks.

To avoid negative values for capacitive reactive power, the output variable was limited to [0,1], so values smaller than zero were limited to zero and values bigger than one were limited to one. And also, the saturation block is responsible to implement the output of the control system to {0,1} turning off of turning on the capacitor banks. In the same way, the saturation block output is loaded at the Bshunt vector.

The third control strategy implemented is similar to the second one, except the saturation block, so the output variable can assume values of [0,1]. This control strategy was implemented to verify the efficiency of this kind of methodology, even knowing that currently it is not feasible to implement this strategy yet.

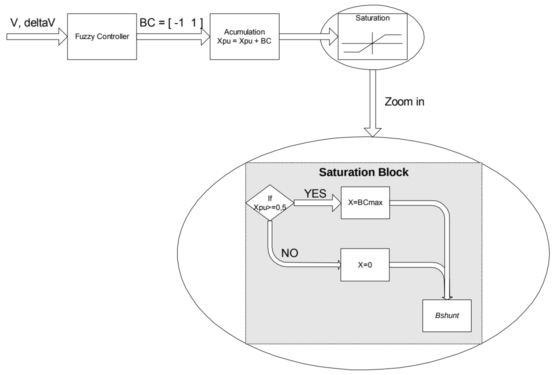

Figure 5 – Block diagram for the control system with acumulation and saturation.

The three control strategies developed shown behaviors that are adequated to the real problem behavior and were tested at the analyzed system to prove the best controller and control strategy.

3 Problem Solution

The tests were defined in two categories as the following:

- Sensibility analysis to the capacitor banks allocation, where the study was focused on check the performance if the performance of the fuzzy controllers were affected by the connection point of the capacitor banks;
- Sensibility analysis to the load profiles, where the study was focused on check if the controllers have different performance for different load profiles for the analyzed system.

3.1 Sensibility analysis to the Capacitor Banks allocation

The load profile used at the simulations of the feeder regarded a rate of 15% of low incomes houses, 55% of medium incomes houses, 10% of high incomes houses and 20% of commercial facilities at the feeder for working days, Saturdays and Sundays/holidays (Figure 6).

It was simulated two cases with the load profile from the Figure 6, according to the described below:

- Case 1: capacitor banks of 300 kvar allocated at the buses 13, 48 and 58 of the system;
- Case 2: capacitor banks of 300 kvar allocated at the buses 13 and 48 and capacitor banks of 600 kvar allocated at the bus 58 of the system

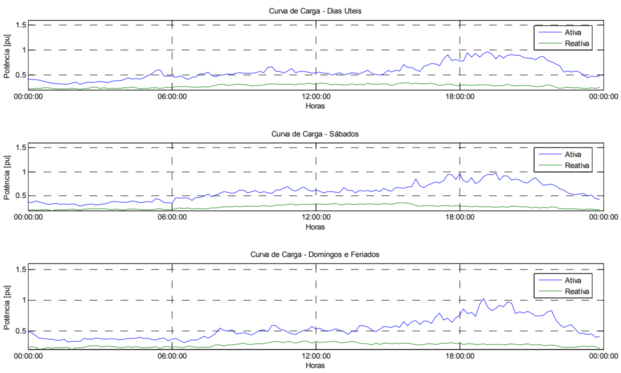

Figure 6 – Load profiles.

At the Table 4 are shown the results of the energy losses for one year at the system for the five configurations simulated at the three cases.

Table 4 – Energy losses for several capacitor banks configurations – 70 buses system

	Case 1	Case 2
Energy Losses [MWh] - No Capacitor Banks	473,5618	473,5618
Energy Losses [MWh] - With Capacitor Banks - Time-Voltage	450,9869	454,2389
Energy Losses [MWh] - With Capacitor Banks - Fuzzy 0 ~ 1 Saturation	441,0059	452,6448
Energy Losses [MWh] - With Capacitor Banks - Fuzzy -1 ~ 1 Saturation	446,4907	453,4541
Energy Losses [MWh] - With Capacitor Banks - Fuzzy -1 ~ 1	444,9483	445,8952

It is possible to check that the system with the best performance in terms of losses is the fuzzy controller 0 ~1 with saturation block, according to the Table 4. The fuzzy control strategy -1 ~ 1 with saturation block had more switching of the capacitor banks, that can be noticed every time that the losses at the simulation get equal to the losses of the simulation with no capacitor banks.

It was observed that excepting the fuzzy controller 0 ~1 with saturation block, there were problems with the power factor below 0,92 inductive.

The fuzzy controller -1 ~ 1 with saturation block causes more switching at the earliness times and after the peak rate time on Saturdays and Sundays, what reduces the lifetime of the oil switches.

The fuzzy controller -1 ~ 1 with no saturation shows a good performance with reduced losses because there is no excessive capacitive power reactive insertion. But, in some moments at the earliness time, when there are no problems about voltage, the inserted values of reactive capacitive power can not be enough to improve the global power factor.

The DRP (Relative Duration of the Precarious Voltage Transgression) is shown at the Tables 5 and 6, showing only the buses that shown problems with the voltage level. The DRC (Relative Duration of the Critical Voltage Transgression) is zero for all the system's buses.

Table 5 – Relative Duration for the Precarious Voltage Transgression - Case 1

Controls for Capacitor Banks	DRP [%]				
	Buses				
	62	63	64	65	66
No Capacitor Banks	0,10	0,20	1,39	1,69	2,68
Time-Voltage	0,10	0,10	0,10	0,10	0,10
Fuzzy 0 ~ 1 saturation with acumulation	0,10	0,10	0,10	0,10	0,10
Fuzzy -1 ~ 1 saturation with acumulation	0,10	0,10	0,10	0,30	0,30
Fuzzy -1 ~ 1 with acumulation	0,10	0,10	0,10	0,20	0,30

Analyzing the results from Tables 5 and 6 it is possible to conclude that the fuzzy control strategy 0 ~1 with saturation block had a similar good performance of the time-voltage controller at the voltage levels problems mitigation. It is understandable because the severe problems with voltage levels will occur on the conditions of medium and heavy loads of the system, which will appear at the time frame from 08:00am to 9:00pm, when the time-voltage controller is supposed to keep the capacitor banks turned on too.

Table 6 – Relative Duration for the Precarious Voltage Transgression - Case 2

Controls for Capacitor Banks	DRP [%]				
	Buses				
	62	63	64	65	66
No Capacitor Banks	0,10	0,20	1,39	1,69	2,68
Time-Voltage	0	0	0	0	0,10
Fuzzy 0 ~ 1 saturation with acumulation	0	0	0	0	0,10
Fuzzy -1 ~ 1 saturation with acumulation	0	0	0	0,20	0,30
Fuzzy -1 ~ 1 with acumulation	0	0	0	0	0,10

3.2 Sensibility analysis to different load profiles

On this study it was used three different load profiles shown below:

- Load profile 1:
  - 25% of low incomes houses;
  - 40% of medium incomes houses;
  - 5% of high incomes houses; and
  - 30% of commercial and service facilities.
- Load profile 2:
  - 5% of low incomes houses;
  - 35% of medium incomes houses;
  - 5% of high incomes houses; and
  - 55% of commercial and service facilities.

The configuration used for the simulation of the 70 buses system regards capacitor banks of 300 kvar at the buses 13, 48 and 58 with the 3 load profiles.

At the Table 7 it is shown the results of the energy losses for a year at the system for the five simulated configurations for the three load profiles with capacitor banks of 300 kvar at the buses 13, 48 and 58.

Table 7 – Energy losses for 2 load profiles – 70 buses system

	Load Profile 1	Load Profile 2
Energy Losses [MWh] - No Capacitor Banks	522,236	692,6106
Energy Losses [MWh] - With Capacitor Banks - Time-Voltage	498,0302	660,9863
Energy Losses [MWh] - With Capacitor Banks - Fuzzy 0 ~ 1 Saturation	487,3213	643,1459
Energy Losses [MWh] - With Capacitor Banks - Fuzzy -1 ~ 1 Saturation	491,2828	648,2855
Energy Losses [MWh] - With Capacitor Banks - Fuzzy -1 ~ 1	491,3056	648,9824

Checking the behavior of the global power factor for the five simulations, it is possible to observe again that the fuzzy controller -1 ~ 1 with saturation block causes more switching at the capacitor banks, what will reduce the lifetime of the oil switches. Also it is possible to notice that sometimes the switching turning off the capacitor banks of the system makes the global power factor for levels lower than 0,92 inductive for light load times.

The DRP (Relative Duration of the Precarious Voltage Transgression) is shown at the Tables 8 and 9, showing only the buses that shown problems with the voltage level. The DRC (Relative Duration of the Critical Voltage Transgression) is zero for all the system's buses.

Table 8 – Relative Duration for the Precarious Voltage Transgression – Load profile 1

Controls for Capacitor Banks	DRP [%]					
	Buses					
	61	62	63	64	65	66
No Capacitor Banks	0,10	3,17	3,37	3,47	5,65	6,75
Time-Voltage	0,00	0,10	0,10	0,10	2,18	2,18
Fuzzy 0 ~ 1 saturation with acumulation	0,00	0,10	0,10	0,10	2,18	2,18
Fuzzy -1 ~ 1 saturation with acumulation	0,00	0,10	0,10	0,10	2,18	2,18
Fuzzy -1 ~ 1 with acumulation	0,00	0,10	0,10	0,10	2,18	2,18

Table 9 – Relative Duration for the Precarious Voltage Transgression – Load profile 2

Controls for Capacitor Banks	DRP [%]					
	Buses					
	61	62	63	64	65	66
No Capacitor Banks	0,10	5,65	7,84	9,03	16,37	17,76
Time-Voltage	0,00	0,10	0,10	0,10	2,38	2,48
Fuzzy 0 ~ 1 saturation with acumulation	0,00	0,10	0,10	0,10	2,38	2,48
Fuzzy -1 ~ 1 saturation with acumulation	0,00	0,10	0,10	0,10	2,48	2,68
Fuzzy -1 ~ 1 with acumulation	0,00	0,20	0,20	0,20	2,38	2,48

Analyzing the results from Tables 8 and 9 it is possible to conclude again that the fuzzy control strategy 0 ~1 with saturation block had a similar good performance of the time-voltage controller at the voltage levels problems mitigation. It is understandable because the severe problems with voltage levels will occur on the conditions of medium and heavy loads of the system, which will appear at the time frame from 08:00am to 9:00pm, when the time-voltage controller is supposed to keep the capacitor banks turned on too

4 Conclusion

Currently, the Brazilian distribution concessionaires that use automatic capacitor banks generally adopt the time-voltage control.

The fuzzy logic control technology was chosen to be implemented because it is proper for implementation on complex systems or not well defined, and is not solved by traditional quantitative analysis methodology.

Analyzing the results of the two fuzzy controllers implemented and the control strategies used to adequate the controllers for the reactive optimization problem on distribution systems, where it is possible to highlight:

- The fuzzy controller is not affected neither by the installation position of the capacitor bank at the distribution feeder nor by the performance difference caused by the bank capacity in kvar.
- The fuzzy controller doesn't need new adjusts in the case of changes with the system's load profiles, operating with good results for the different load profiles.
- The developed system showed a superior performance compared to the time-voltage control system for the different load profiles at the simulated systems.
- The fuzzy controller doesn't need different tunings for working days, Saturdays, Sundays and holidays; and
- Allowed improvements for the voltage profile at the feeders, contributing for the problem mitigations related to the regulation ANEEL No. 505 [3].

For future developments the suggestion is to implement the fuzzy controller on a real system, as there is the necessity of improve the performance of the automatic capacitor banks applied to the distribution feeders and the implementation cost of this controller on a hardware platform micro processed is not so high.
For this implementation there is the possibility to use not only the 3 voltage signals but also the 3 current signals, what could allow the development of a control strategy more complex and powerful, in terms of optimization of reactive at the distribution systems.

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