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RESEARCH ARTICLE **OPEN ACCESS**

AUTOMATIC SYSTEM FOR CONTROL OF OVERFLOW REACTIVE IN OBSOLETE SUBSTATIONS BY COLOR PETRI NETWORK MODELING (RDP)

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ABSTRACT

This work presents a new approach for the treatment of surplus reactive energy in industrial plants that has capacitor banks in the substation in obsolescence and limited to high numbers of maneuvers. The purpose of this thesis is to perform studies for the purpose of optimizing a discrete distributed system, from data sampled in the industrial sector, which contains problems in the substation power factor control system and consequently reactive energy surplus. In order to propose solutions to these problems, the modeling of the distributed system and the analysis of its properties were carried out through computer simulations. The tool that was used for a discrete system is the Colored Petri Net in CPN TOOLS. From the RDP model we obtain an autonomous decision-making system to connect and disconnect the capacitor banks according to the current of the furnaces, voltage, time of operation of the loads, discharging time of capacitor banks and time of day defined by resolution ANEEL 505, of November 26, 2001 aiming at reaching the power factor close to 1.00 and minimized numbers of high voltage circuit breaker operations. Implementing the model eliminates over reactive, fines, extends the lifetime of circuit breakers, capacitor banks, reduces the exposure of people in circuit breaker maneuvers and does not send noise on the transmission lines of the concessionaire. Completing the development and implementation of the new logical model of the power factor automation system, it was possible to achieve a 96% reduction in excess reactive energy, equivalent to 720,423 kWh per year in energy bills sent by the utility and a reduction of 90.4% number of circuit breaker operations compared to the traditional method of capacitor bank automation. The system also enabled a better structured understanding of the automation logic and assertiveness in the implementation of the system in the industrial controller, not generating interference in the process and rework.

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INTRODUCTION

Capacitor banks are used in distribution systems for reactive compensation, helping to minimize power and energy losses and improve the voltage profile within acceptable limits. The amount of compensation provided is related to the location of capacitors in the distribution system, size, quantity, and type of capacitors to be installed in the system. Capacitors applied in distribution systems are usually located in distribution feeders or substations. Its use is focused on the correction of the local power factor, noting that the banks can be fixed or automatic depending on the load conditions. Basically, fixed benches are applied for light load conditions and automatic benches for medium and heavy loads of the system. With the increase in demand on distribution systems, the management of reactive power has become increasingly important for distribution companies that need to keep voltages within pre-established limits and minimize losses in the system, thus ensuring good levels of quality and reliability. for the consumer. Certain changes in the system can result in voltage variations in the buses, and thus compromise the quality of the electrical energy supplied. The causes of these unwanted voltage variations are:

- Increase in loads;
- Distance from generating units;
- Long transmission lines operating at light load;
- Growth of transmission and sub-transmission systems with the addition of more lines.

On the other hand, the high level of inductive reactive power demanded in distribution systems causes increased losses and voltage drops in the distribution system itself, such as problems in the transmission system, making it difficult to control voltage. The installation of Capacitor Banks aims not only to reduce losses and improve voltage profiles, but also some other advantages, such as:

- Power flow control;
- Improved system stability;
- Power factor correction;
- Compensation of reactive energy produced by inductive loads and line reactances.

To minimize the problems arising from the high level of inductive reactive power, capacitor banks are installed in the distribution system in the feeders (primary distribution voltage) and in the substations, which then supply part of the inductive reactive power requested by the loads. Normally, standardized single-phase capacitive units of 100 and 200 kvar, 7960 V are used, forming three-phase banks connected in an isolated star of 300, 600, 900 and 1200 kvar. The application of capacitor banks in distribution feeders must respect the technical standards of the concessionaires and be in accordance with the provisions of ANEEL Resolutions No. 456/2000 and 505/2001.

Objective: The objective of this article is to propose a discrete dynamic system method in obsolete capacitor banks of industrial substations with a focus on automatic control that avoids excess reactive energy in the energy bills generated by the concessionaire and is a method that provides the least possible number of maneuvers in the circuit breakers and capacitor bank due to obsolescence. The method is also concerned with the performance of the controller, optimization of the number of steps and its scan cycle, without dead lock, without loop and that in the end it is also documented. The method also seeks to perform implementations in the controller assertively at once, without rework, failure potential and unscheduled machine interruption. To achieve the objective, the method chosen to develop the model was Petri Nets. In order to be assertive in the study of the problem that affects so many industrial plants in Brazil, a steel plant founded in 1944 (the second oldest in the country) was chosen as a case study, which has a set of capacitors in the substation from 1985, with manual operation, huge numbers of financial fines due to excess reactive energy, limitation in the number of maneuvers in circuit breakers and capacitor banks as they are obsolete and limited investments due to the country's unstable moment. Proving the gains of the system, which seeks the development and implementation of a model that solves the problem and has an implementation cost close to zero, the usability and interaction of this method in other industrial equipment that present this problem is totally possible.

Excess Reactive Energy in a Steel Plant – Case Study: The research will use as a case study an industrial problem in a steel mill with electric arc furnace, in which the instability of the power factor in the main substation was seen, where it was necessary to understand the indicators of excess reactive capacitive energy and which were more impacting on the fines imposed by the concessionaire.

Fig1.Capacitor banks of the plant's substation [Author]

In this case study, the utility power supply is 138 KV and there are 2 36 MW electric arc furnaces with 23 KV transformers. In addition to electric furnaces, there are several equipment such as motors and frequency inverters in 440 V low voltage hot rolling mills that impact the power factor. In the substation of this plant, there are harmonic filters and two sets of capacitor banks of 9.6 Mvar (composed of 48 capacitors) and 16 Mvar (composed of 84 capacitors). The set of capacitors were manufactured in 1985 by the company Inducon and each capacitor has a capacity of 200 Kvar, as shown in Figure 1 above. The capacitor banks in this plant operate on a manual basis, where maintenance technicians turn the circuit breakers on and off according to the operating mode of the plant. The manual operation mode must comply with ANEEL Resolution 505, of November 26, 2001, where in a practical way, in order for the power factor to remain within the limits, it is necessary for technicians to turn on the capacitor banks during daytime when the electric arc furnace is producing, thus avoiding excess inductive reactive. At night time, it is necessary to turn off the capacitor banks, thus avoiding excess capacitive reactive. As the installed capacitor banks are not switched so that it is possible to adjust the amount of capacitors needed to meet the reactive power needs of the system according to its daily load profile, there is no option to connect only some capacitors, therefore the scenarios The existing ones are to connect only thecomplete bank of 8 Mvar or only the complete bank of 14 Mvar or to connect the 2 banks together.

Fig. 2. Capacitor plate data of banks [Author]

Historical Analysis of Excess Reactive x Penalty: Initially, sample data of the power factor were captured in the software Follow energy in order to diagnose the oscillation of the power factor and excess of reactive in the period between 2011 to 2018. It can be seen in figures 3 and 4 that demonstrate the closure of all months of the year 2012 and the month of March 2012 exploded, proving the accounting for both capacitive and inductive reactive energy. It was possible to observe that the penalties become more serious when the plant's production regime is changed to a reduced number of days or times, because in this way it would be necessary to carry out routine manual maneuvers in the substation, which often did not happen due to indiscipline of the operators. employees or lack of worker.

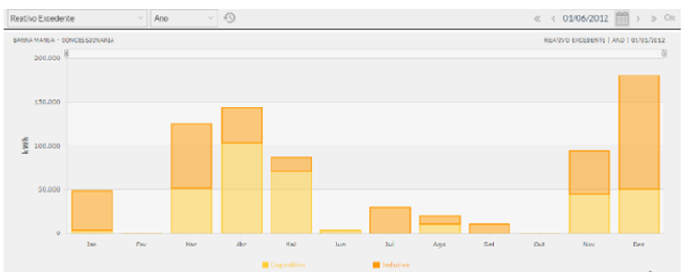

Fig. 3. Plant reactive excess in 2012(software: Follow energy) [Author]

In figure 4 electrical factors noted the behavior of the power factor 30 days, month sampling of 201 indicators of two factors that caused the "Out of capacity". Capacitors connected between 00:30 and 06:30:

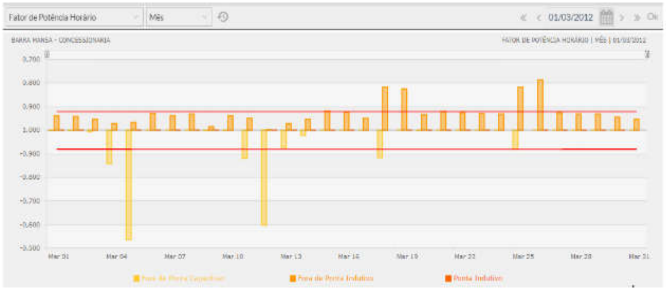

Fig. 4. Power factor behavior during 30 days (software: Follow energy) [Author]

In Figures 5 and 6, all surplus reactive from the steel plant in the period from 2011 to June 2018 was accounted for, thus totaling approximately 5.7 million kWh of surplus reactive and R$2.5 MM.

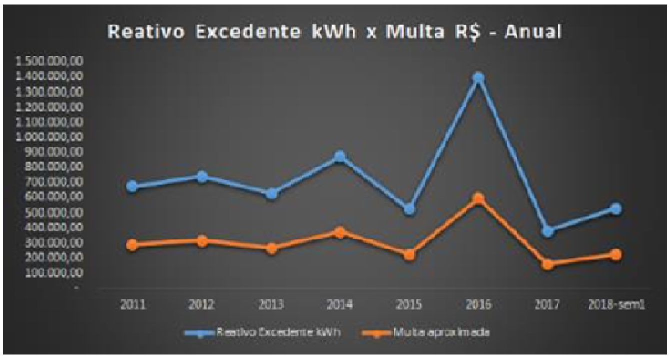

Fig. 5. Excess reactive and penalties per year at the steel plant Power [Author]

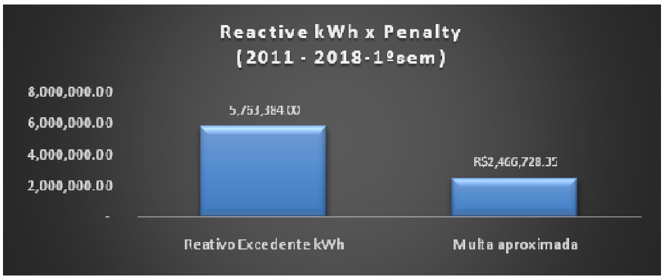

Fig. 6. Totalization of excess Reactive and fines between 2011 and 2018 at the plant (author)

In Figure 7, we show as an example the way in which energy concessionaires apply the penalties supported by the current ANEEL regulations. The penalty cost in May 2016 was R$0.40 / kWh of off-peak surplus reactive energy. The energy concessionaire charges a fine in the kWh unit: (The ratio of the converted unit between 1 kWh x 1var= 0.001).

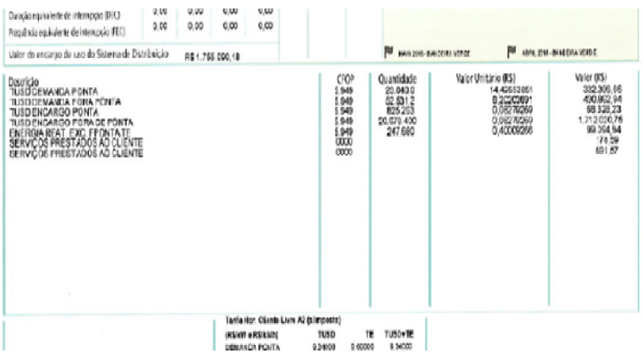

Fig. 7. Example of penalties by the concessionaire for reactive energy (Author)

Development of the model in color petri nets Analysis and Results: In order to define the type and model of automation to be adopted without compromising the useful life of the capacitor banks and circuit breakers, two types of models for power factor control will be simulated: In the first model, we will make the maneuver of the banks from the real value of the power factor, which is believed to present a high number of maneuvers. In the second model, we will carry out the maneuver based on the combination of factors related to the electric current of the electric furnaces of the steel plant, the input voltage of the plant and the time of day for the insertion of capacitive load, respecting the tolerable limits of the ANEEL 456 standard, of 29 November 2000 to maximize the number of manoeuvres. Based on regressive data collected in the IBA PDA software as shown in Figure 8 below, it was possible to analyze the behavior of the electric current of the furnaces during the production period, as well as the input voltage of the plant.

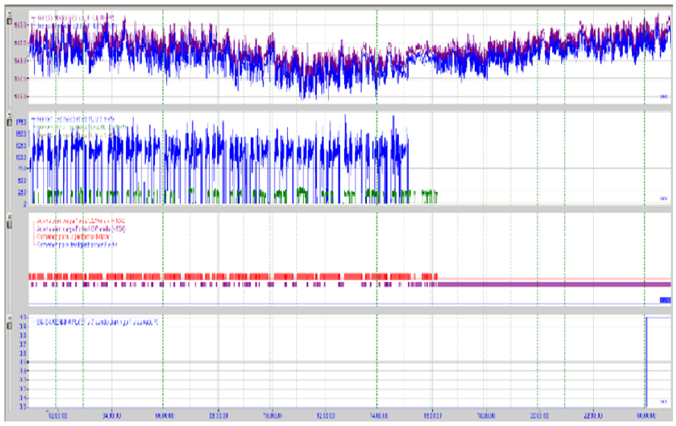

Fig. 8. Iba – Current in the furnaces [Author]

As the initial simulation parameters, the following values were used as a premise in the variables listed below:

Number of runs per day: 23
Time period: 1 Year (value 3)
Desired power factor: 0.92

The software was subdivided for simulations for both power factor maneuvers (modeling and simulation option No.)

A-RDP Manipulation model by power Factor: For the processing of the model and the analysis of its properties, a simulation of state space analysis was performed for both models. First, the power factor model (A) presented 8395 production runs in the electric oven, where it reached the number of 67,433 Steps, resulting in an average of approximately 7 maneuvers/day or 2,644 maneuvers/year, representing at least 1 bench maneuver. In 31.5% of production run.

RDP Manipulation model by Current/Time/Date: For the current, time, date and voltage model, 8395 production runs were obtained in the electric oven, reaching the number of 4,293 Steps and an average result of approximately 0.7 maneuvers/day or 252 maneuvers/year, representing at least 1 maneuver bank account at 3% of runs.

B – RDP *Manipulation model by Current/Time/Date:* For the current, time, date and voltage model, 8395 production runs were obtained in the electric oven, reaching the number of 4,293 Steps and an average result of approximately 0.7 maneuvers/day or 252 maneuvers/year, representing at least 1 maneuver bank account at 3% of runs.

C– Definition of the RdP Model: About the RdP properties of the models, both are of the "reachable" type in the reachability tree. As for the liveness and blocking analysis, the network is said to be "live and without blocking ""dead lock", because from any state reached there is a trajectory in which any transition can trigger. The systems are also L2-live, as given a positive integer K, it can be fired at least K times in some firing sequence.

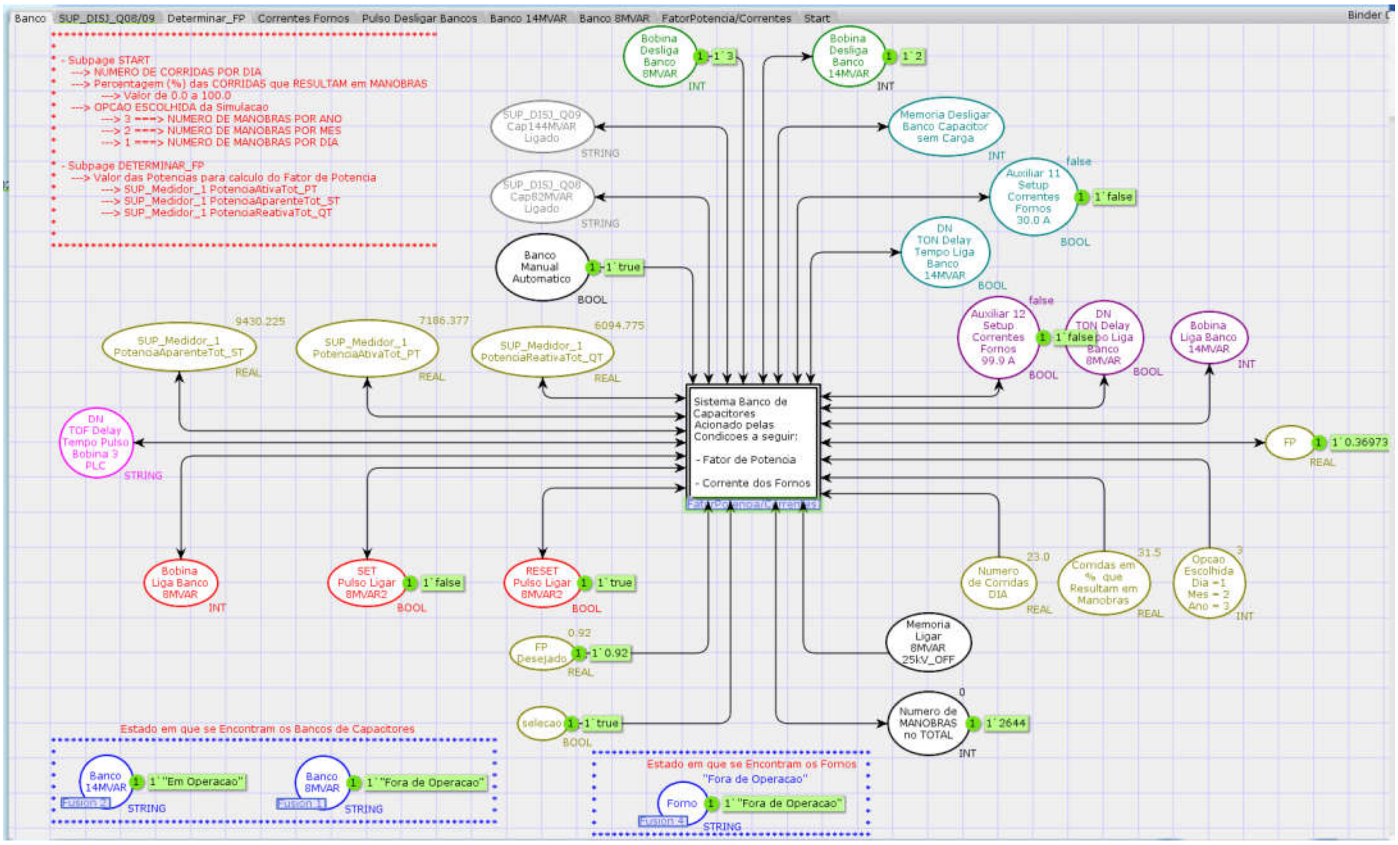

Fig. 9. Simulated result for 12 months of production with the power factor model [Author]

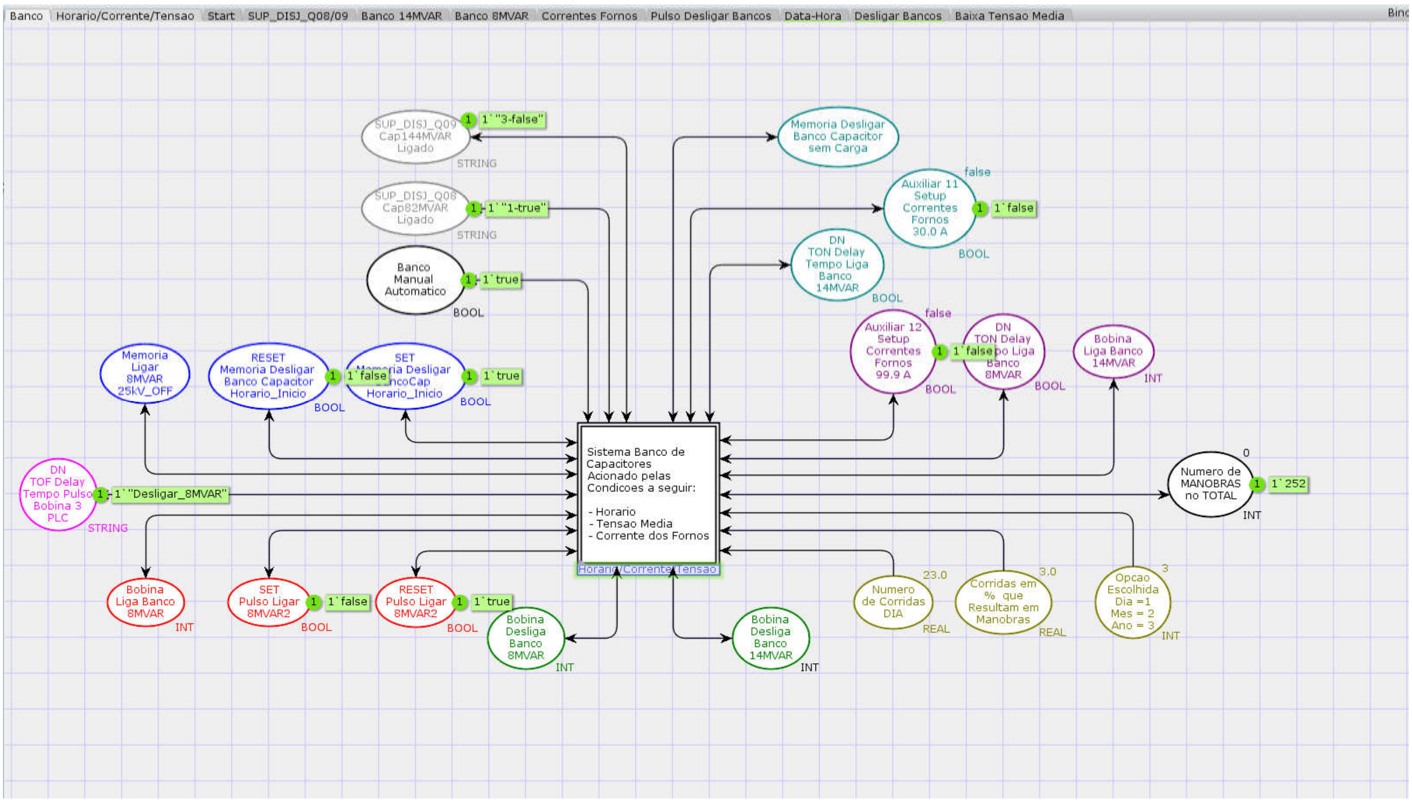

Fig. 10. Simulated result for 12 months of production with the model adjusted by current, time and data [Author]

The models are considered Finished because they have finite occurrence sequences and none of them are infinite “Fairness Properties”, this is because at some point in the model, a “low balance of races” transition is activated in a way that prevents a new trigger. The models are considered limited "boundedness" and safe because the number of marks or tokens in each place does not exceed the number of the initial K value, having their report "upper" value less than or equal to K.

The models are reversible because they are capable of returning to the original or initial state. Thus, the results demonstrate that the models satisfy the desired properties for the system. After proving that the models satisfy the desired properties for the system, it is concluded that the current, time, voltage, time model (B) is the most suitable model for an obsolete capacitor bank, as it handles 10 times less circuit breakers in relation to the power factor model (A)

Change in the Logic of the Controller (PLC) of the Controller of the Industrial Substation: From the model simulated in Petri Nets in CPN tools, the system developed in the Allen Bradley Controllogix 5555 controller of the main substation of a steel plant was implemented. There is no tool available on the market that automatically converts a program from Cpn Tools in Petri Nets to conventional controller language. To do this, theoretical knowledge of automation logic is required to perform the conversion. The software was subdivided for maneuvers by furnace current, time for activating the capacitive banks and plant input voltage, thus obtaining the following steps in the controller logic:

Note: Only a few steps will be shown by figures due to the size of the algorithm.

1) Protection timers for capacitor banks and drives;
2) Counters of the number of operations of the Circuit Breakers of the Capacitor Banks;
3) Furnace Current - Detection of loaded and unloaded system;
4) 8Mvar Capacitor Bank;
5) 14Mvar Capacitor Bank;
6) Shutdown of Capacitor Banks;
7) Date-Hour-Minutes to Turn Capacitor Banks On/Off;
8) Low Medium Voltage Shutdown;

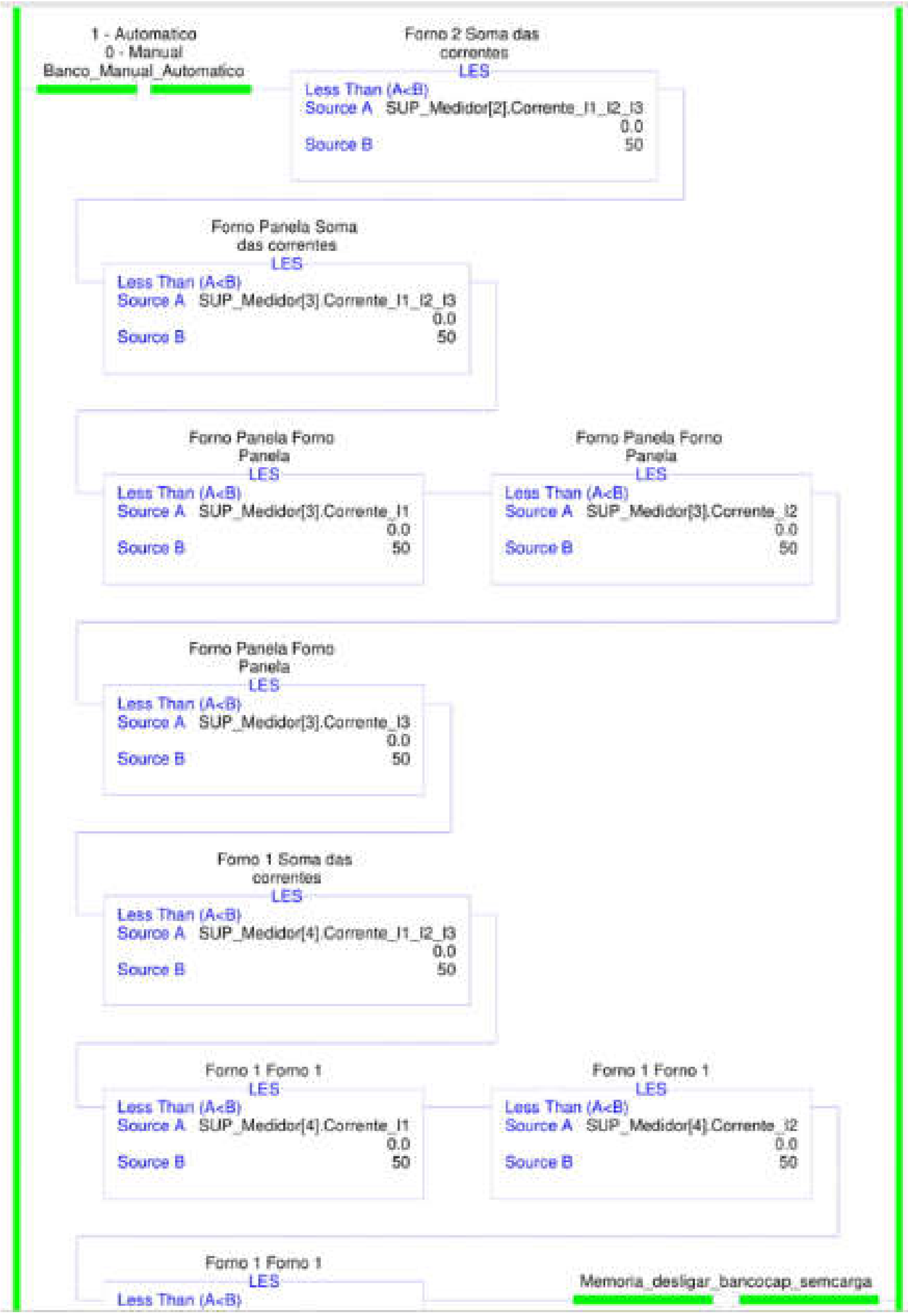

Fig. 11. Controllogix –No-Load Furnace (Eletric current < 50A) – (Author)

Fig. 12. Controllogix –Load Furnace (Eletric current >50A) – (Author)

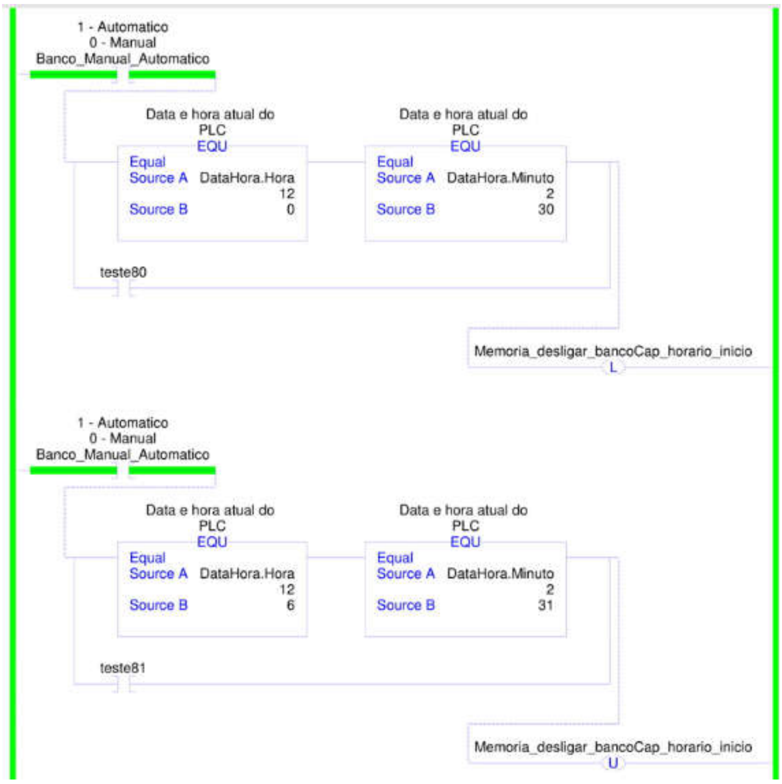

Fig. 13. Controllogix - Hour and Minute for On/Off Banks (Author)

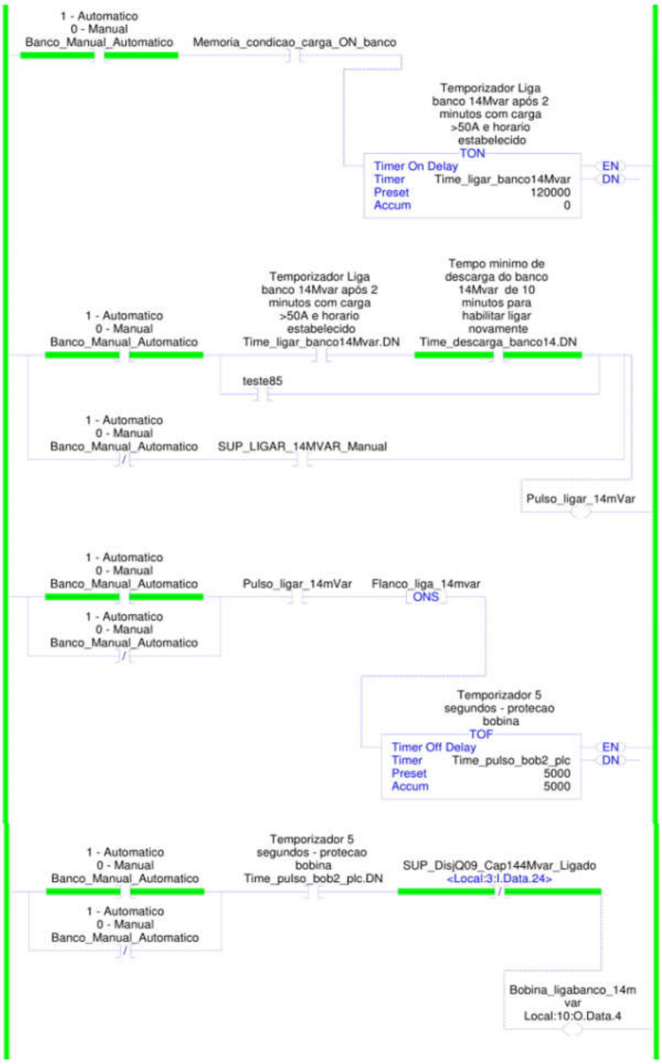

Fig. 14. Controllogix –14Mvar Bank Activation (Author)

RESULTS

After implementing the automation logic in the controller using the model for maneuvers by values of current, time, time, voltage and modifications in the field, a reduction of 96% of excess reactive in kWh was obtained. Previously, we had an annual average of 710,423 kWh between 2011 and 2018. After the implementation of automation (2nd semester of 2018) the average annual result until 2021 was reached of 28,442 kWh. Figures 15 and 16 demonstrate the results.

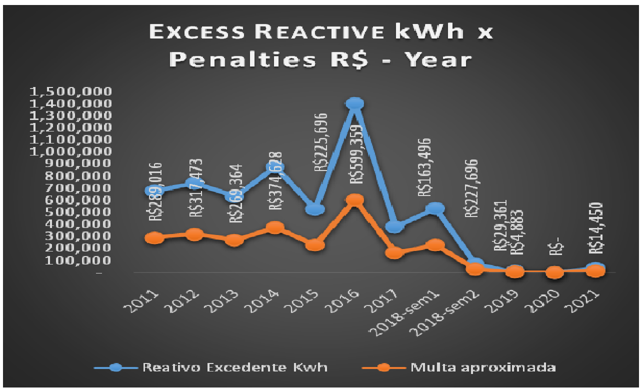

Fig. 15. History of excess reagent and fines at the plant (Author)

For the current, time, time and voltage model, 8395 runs were simulated in the electric oven in 12 months, reaching the number of 4293 Steps and an average result of approximately 0.7 maneuvers/day or 252 maneuvers/year, representing at least 1 bank maneuver in 3% of runs. Figure 17 demonstrates the behavior of the excess reactive and the power factor during 30 days of production.

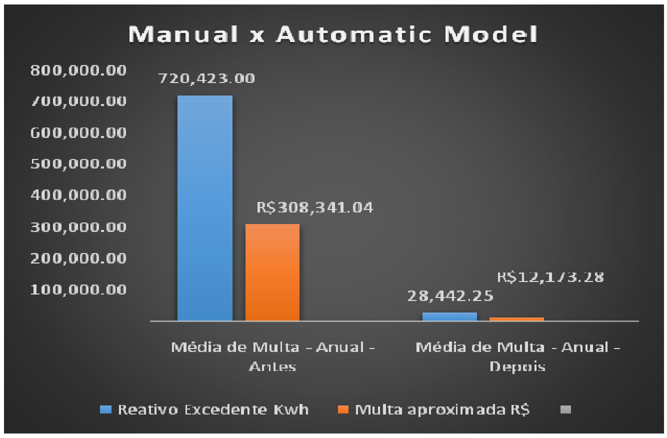

Fig. 16. Consolidated excess reactive and penalties at the plant (Author)

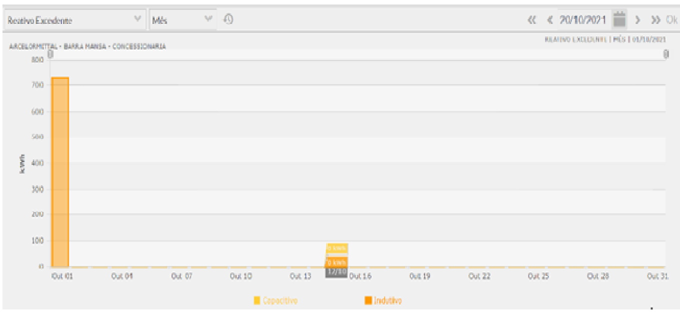

Fig. 17. Excess reactive with automation in Capacitor Banks (Author)

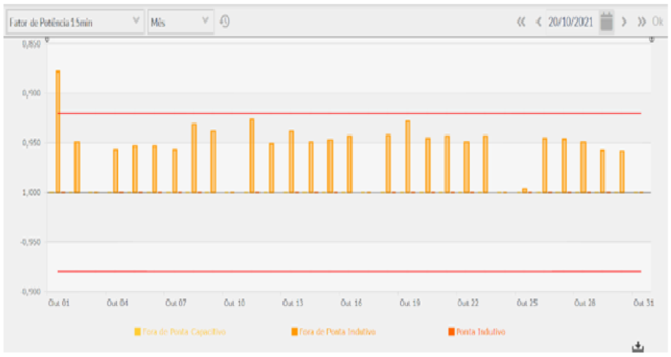

Fig. 18. Power factor with automation in Capacitor Banks (Author)

It is possible to observe the counter of the number of maneuvers carried out in practice in the 8.4 Mvar and 14.4 Mvar capacitor banks on the steel substation supervisory in Figure 19.

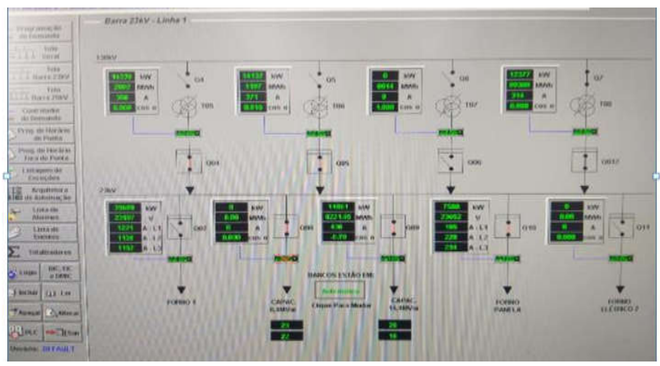

Fig. 19. Substation IHM - Counter of bank circuit breakers (Author)

The number of maneuvers in December 2021 is 20 maneuvers until December 20th, which is close to the simulated values. The reduction in this model compared to the traditional one (model A) is a 90.4% reduction in the number of circuit-breaker operations compared to the traditional method of capacitor bank automation.

CONCLUSION

From the objective of this article, the main goal was the development of a common method for dealing with the presence of excess reactive in obsolete industrial substations with the requirement of a low number of maneuvers in the capacitor banks for power factor control. To this end, we conclude that the Colored Petri Nets methodology can assertively direct the development of a correct and optimized logic model to be implemented in the programmable logic controller (PLC) of the equipment. Another product achieved was to find, through Petri Nets modeling, the best health and performance of the controller, with optimized number of steps and scan cycle, without dead lock and without loop. As a secondary and no less important objective, this theme showed how interesting the automation of critical processes for work safety is, since with this action the man does not need to expose himself in these circuit-breaker maneuvers daily. An observed and conclusive point is that the automation engineer working in the industrial area hardly has the time to carry out the modeling before applying changes to the controller, this generates negative consequences, because in this way implementations are carried out in the controller and not always it is possible to predict all the variables and influences in the system, having the same to change their modification after unsatisfactory or incomplete results occur. The modeling makes it possible to map all the possible alternatives of the system and treat an algorithm for each event. After the analyses, actions and results presented and experienced, it is conclusive that it is possible to apply an automatic control system for power factor control through obsolete capacitor banks with limitations of maneuvers in industrial substation, making the business more profitable due to minimization fines for excess reagent, extension of the useful life of circuit breakers and capacitor banks, contribution to the health of the country's electrical network due to not sending noise to the electrical network and protection of employees in terms of reducing exposure to risks. It is also worth mentioning that this action has an implementation cost close to zero, just using technology embedded in CLPS existing in the plant. The simulation of the model in colored Petri nets, before implementation in the controller, proves that in this way it is possible to fully understand the process and avoid implementing wrong logic directly to the controller. As future work, it is suggested to use this autonomous system in other industrial plants that suffer fines from the energy concessionaire due to excess reactive in the transmission line because they have obsolete capacitor banks limited to a high number of maneuvers. This scenario can occur in substations in other sectors such as food, automotive, oil, pharmaceuticals, etc. Another suggestion for future work would be the development of a platform that could allow the conversion of the model developed in CPN tools to the conventional controller language automatically. In this way, the automation engineer could model the system and implement it in the controller without having to rework the logic conversion. In this way, it would be feasible to model in the daily life of an industrial automation engineer.

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