Journal of Energy and Power Engineering 10 (2016) 191-198
doi: 10.17265/1934-8975/2016.03.007

Energy Efficiency of Reactive Dynamic Compensators

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Received: January 19, 2016 / Accepted: February 02, 2016 / Published: March 31, 2016.

Abstract: A parameter that allows an evaluation of power quality transmitted, or distributed, between energy source and the final user is electric system power factor. Among other aspects, a bigger power factor, close to unit value, relieves operational conditions of lines and cables, besides, it improves feeder's voltage behavior. Due to load variation along the day, the dynamic compensation of power factor allows maintaining this parameter close to the ideal. This paper brings a study about a reactive dynamic compensator based on the voltage control in a capacitive element, varying the reactive energy in accordance with the system demand, everything from the energy efficiency point of view. In distribution systems, the losses due to this variable compensation can be lower than in other compensation methods and also the voltage presents a better behavior, justifying its application.

Key words: Reactive dynamic compensator, power factor correction, losses, energy efficiency, tap changing.

1. Introduction

The electrical energy demand is growing, just as its cost. This situation supports and favors the energy efficiency surveys applied to the electrical system. According to the Brazilian National Energy Balance of 2014, hydraulic plants provided 70.6% of the electrical energy generated in Brazil [1]. Even though the advance of the other energy sources, mainly wind power, the predominance and consequently, the dependence of hydraulic sources is quite big. This kind of generation is strongly weather dependent and, when there is a lack of rain, the energy rationing issue shows up, contributing to the rise of the energy cost.

In order to illustrate this risk, Fig. 1 [2] compares the reservoirs levels of the Brazilian southeast and center west regions in the 2014 and 2015 years to the 2001 levels, year of the greatest energy crisis in Brazil.

As it can be seen, the registered values in the beginning of this year were lower than the ones registered in 2001. The only reason Brazil is not facing an energy rationing like in the beginning of the century is because a great part of the energy consumed in the country is being provided by thermoelectric plants. In this scenario, any measure taken to improve energy efficiency is greatly welcomed, since it relieves the network and allows better use of generation resources.

In the energy transmission between the load and the source, active power must be bigger than the reactive power. Reactive power demanded by the loads must be produced near the load preferably. This condition reduces feeders' line current and, as consequence, reactive power set up an important role in voltage regulation and system reliability [3]. The parameter that quantifies the rate between power and total (apparent) power is called power factor.

The basic idea of power factor correction is producing some of the reactive power demanded by the load near itself. The most common, and probably the oldest manner of supplying this reactive power is by capacitor banks.

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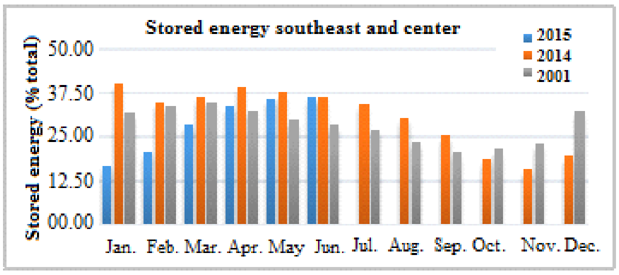

Fig. 1 **Reservoirs levels of the Brazilian southeast and center west regions.**

Considering that a power system's load along a day varies [4, 5], the demand for reactive power is also variable. This load variation can be noticed by the load curves for different consuming classes (commercial, residential or industrial) [6].

Urban and country distribution feeders have load curves with big difference between the power demanded in peak hours and in the remaining. The use of fixed capacitor banks in these cases can lead to an undesired increase in voltage and even in losses at some periods of the day. A solution could be using switched banks, however, the switching devices cost and the transient caused by the switching itself may complicate the utilization of these equipment.

An alternative solution is the variation of the voltage applied to the capacitor bank. Whereas the reactive power generated by a capacitor varies directly with the square of the voltage on it, the amount of energy can be controlled by the voltage variation. An on load tap changing device [7] is able to perform this voltage control.

The DRC (dynamic reactive compensator) is nothing but a transformer with the secondary winding divided into taps feeding a capacitor bank. The purpose of this paper is to analyze the impact the installation of the DRC will cause in a distribution feeder. This equipment was developed and patented by a brazilian company called ITB (Indústria de Transformadores Birigui) equipamentos elétricos [8].

A real network is compensated by DRCs in Ref. [9]. This paper focuses on monitoring the power factor behavior of the network for 11 months and the power factor improvement is quite satisfactory.

2. Working Principle of the DRC

As said before, the power demanded by a distribution system, both reactive and active, varies along the day. Thus, the ideal situation would be if the reactive power compensation followed this variation. Instead of what is obtained with the installation of fixed capacitor banks, the DRC provides reactive power according to the network requirement. The change in the reactive injected in the system is made varying the voltage applied on the capacitor bank.

The secondary side winding of the equipment is divided into taps, allowing a voltage variation since a minimum value until the reactive element's rated voltage. As the capacitor is not disconnected and the voltage taps are changed gradually, the switching transients are highly reduced when compared to the insertion banks made by breakers or mechanic switches. This sentence is based on the utilization of a significant amount of taps, higher than 10, resulting in voltage steps lower than 10%. Fig. 2 shows the equipment's simplified architecture.

It is important to notice that, the reactive compensation does not need to be made by capacitors, if the system presents an excess of reactive power, the capacitor bank can be replaced by a reactor. In this paper, the compensation will be made only by capacitor banks.

Along this paper, the three one-phase reactive compensators are going to have the following parameters:

- transformer rated power: 200 kVA;
- capacitor bank rated power: 200 kVAr;
- transformer percentual impedance (tap + 16): 11.26%;
- no load losses: 513 W;
- short circuit losses: 2,532 W;
- magnetizing current: 0.53 A.

For this setup, the reactive power injected on the network for each tap, assuming rated voltage applied on the equipment, is shown in Fig. 3.

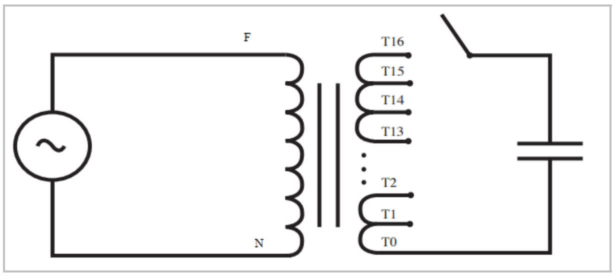

Fig. 2 Simplified DRC's squeme.

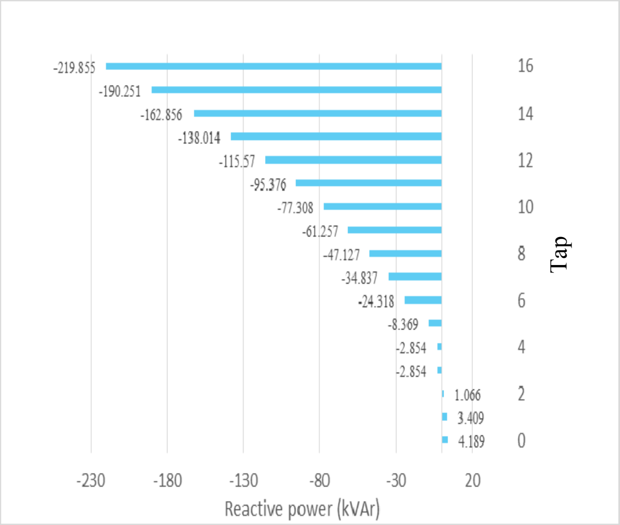

Fig. 3 Reactive power supplied by DRC in different taps, when submitted to rated voltage.

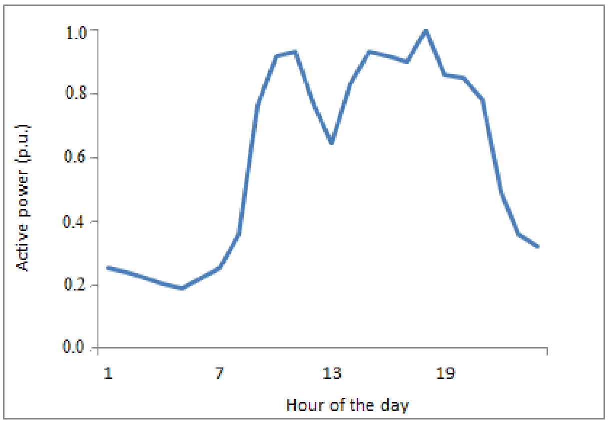

Fig. 4 Commercial load curve.

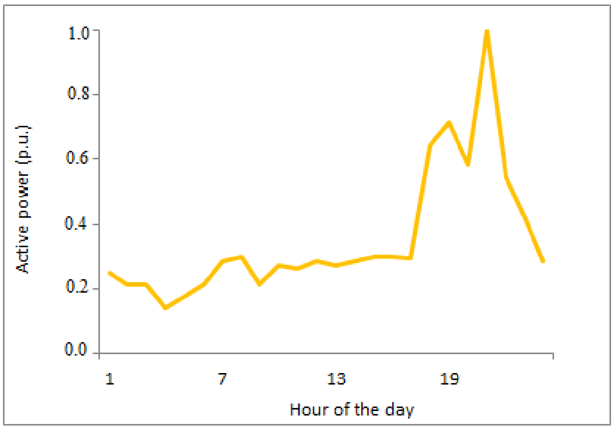

Fig. 5 Residential load curve.

3. Study Case

In order to better comprehend the DRC's functionalities, some computational simulations [10] were performed in a hypothetical distribution feeder. The loads were divided into two types: commercial and residential. The load curves were made using Refs. [6, 11] as references. These curves are shown in Figs. 4 and 5.

The simulated feeder's rated voltage is 13.8 kV and it feeds 44 transformers connected in Δ/*Y* grounded (D_{yt}), which attend 44 constant current type loads. Fig. 6 shows the unifilar diagram of the simulated circuit.

The loads were specified by phase and their power values were randomly chosen between 90% and 110% of the three-phase power. The one-phase power factor were also chosen randomly, the possible values are between 0.80 and 0.90. The purpose of this process is to obtain an unbalanced system, since the values in the load curves are for three-phase power. Thereby, apart from reactive compensation, as the DRC controls the power factor in each phase independently, it is possible to analyze the current and voltage unbalance.

Three distincts operational situations were simulated: system without reactive compensation, compensation done by fixed capacitors and compensation done by the DRCs devices.

In all the above situations, 24 cases, representing the 24 h of the implemented load curves were simulated.

3.1 No Compensation

The first of the three simulated cases was the system without compensation, i.e., only the conductors, the loads and their respective transformers were implemented. In this case, the source supplied about 5.6 MVA (*pf* = 0.841) and 0.9 MVA (*pf* = 0.852)

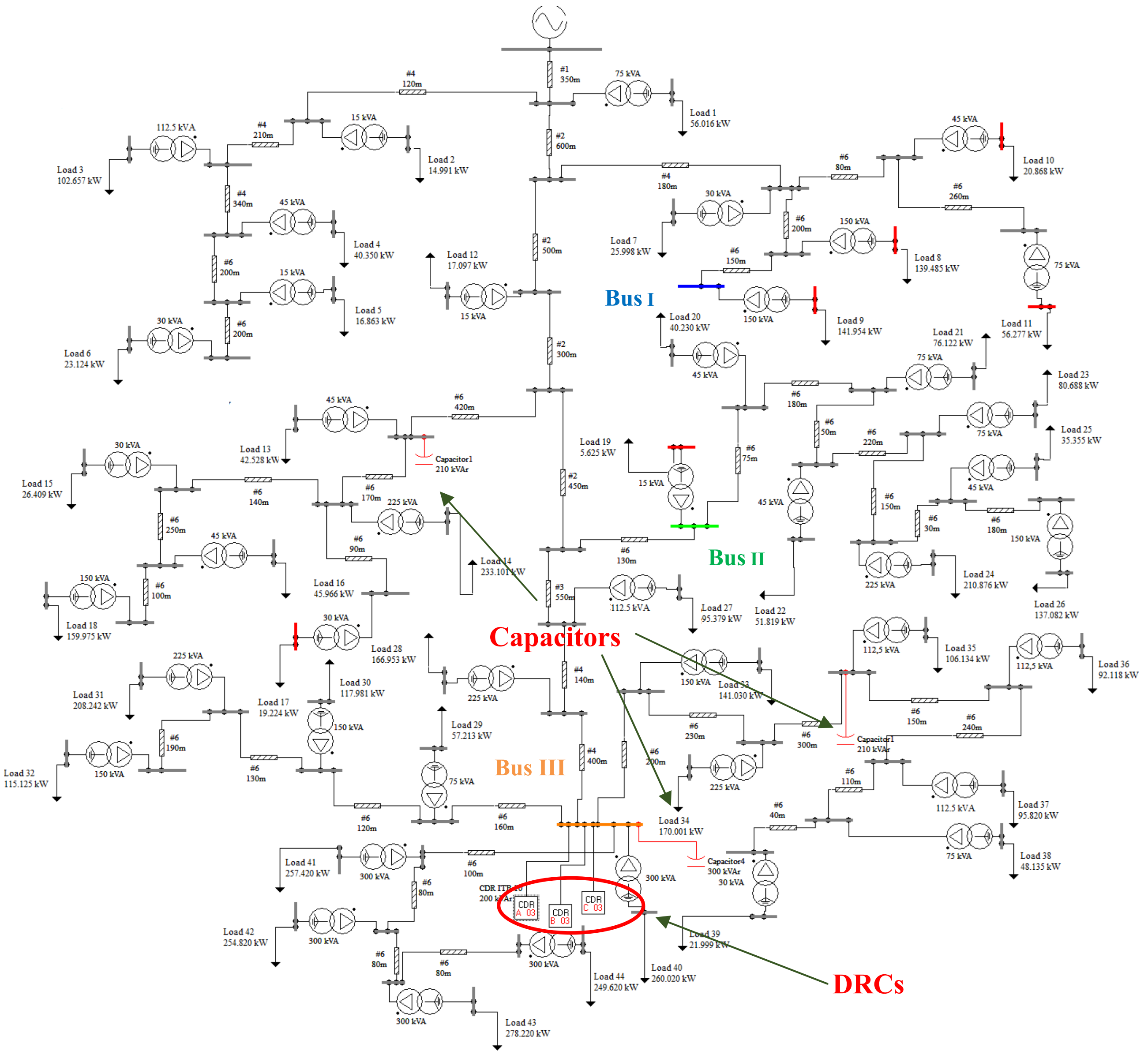

Fig. 6 Studied feeder unifilar diagram.

in the highest and in the lowest demand situation, respectively.

3.2 Compensation by Fixed Capacitors

In the second simulation, three fixed capacitor banks had been installed (two banks of 210 kVAr and one bank of 900 kVAr of rated three-phase power). To elucidate, the three banks have been installed in three different buses and the biggest bank has been installed close to the load center. The position of these three capacitor banks can be seen in Fig. 6. In this operational condition, the maximum and minimum demands were 5 MVA (*pf* = 0.929) and 1.2 MVA (*pf* = -0.691), respectively. A reduction of 600 KVAr and a power factor improvement on the highest loading period can be seen due to the compensation done by the capacitors. On the other hand, on the low loading period, the reactive power excess caused an increase in the value of the demand and a decrease in the power factor, becoming capacitive in part of the time. The DRC's purpose is to actuate on the low loading period in order to reduce the excessive reactive flowing on the network and improve the power factor.

3.3 Compensation by DRC

In the third simulation, three fixed capacitor banks were operating as well (two banks of 210 kVAr and one bank of 300 kVAr of rated three-phase power), besides three one-phase DRCs of 200 kVAr feeding 200 kVAr of capacitor banks (with identical parameters described in Section 2). Important reminder: The DRCs were installed on the same bus that the 300 kVAr bank was, which was also the bus where the 900 kVAr bank was installed in the second case (fixed capacitors only). The other two smaller banks' location and rated power are the same in both situations. In this case, the maximum and minimum demands were approximately 5 MVA (*pf* = 0.93) and 0.8 MVA (*pf* = -0.96). In the highest demand case, the control of the DRC performed the higher possible compensation, according to its rated power (operating as a fixed bank), in the low loading situation, the control set the voltage applied on the bank to zero, not allowing the equipment to inject excessive reactive power.

4. Results

Following, there are going to be presented the obtained results for the three considered operational conditions described above. The analyses were focused on three parameters: power factor, electric losses and voltage behavior.

4.1 Power Factor

Fig. 7 presents the power factor variation for each of the three cases on the bus that the DRC was installed. It is worth to remember that, the equipment was configured so that it would keep the power factor on its respective bus between -0.98 and 0.98.

As expected, the power factor values for the compensated systems were higher than the non-compensated systems. However, the utilization of fixed capacitors led the power factor to values lower than -0.5 at the low loading moments. This condition is favorable to voltage and losses enhance. Fig. 8 shows the power factor behavior in the three situations, seen by the source.

Also from the source's point of view, the power factor variation was much smaller when the time that the system was compensated by the DRC.

As it has been mentioned before, at the low loading periods, there was an excess of reactive power flowing on the system when it was compensated only by fixed capacitors, leading the power factor smaller values. As the demanded reactive power varied along the day, the DRC changed its secondary winding tap in order to change the amount of reactive injected on the network. Fig. 9 shows the tap switch's position of the three equipments (three-phase bank made by one-phase equipment) during the simulated 24 h, it can be observed that, the diagram's outline is similar to the

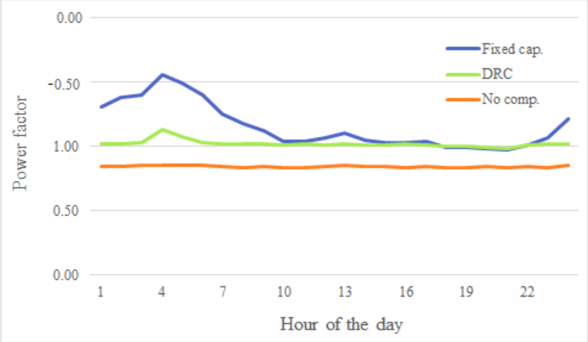

Fig. 7 DRC's bus power factor for each case.

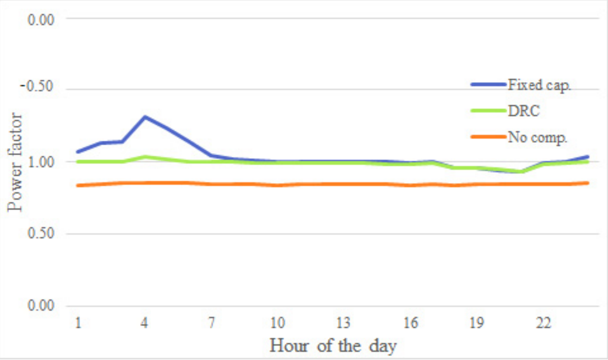

Fig. 8 Feeder's power factor, seen by the source.

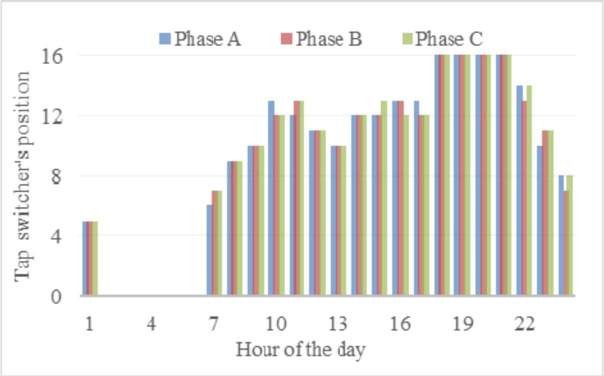

Fig. 9 DRC's tap switcher position.

load curves, once the reactive power demand has a behavior similar to the active power demand.

Once the system loads are unbalanced, each phase DRC is going to act in order to keep the one-phase power factor within the stipulated limits. As a consequence of this independence, the tap position of each equipment can be different for the same situation, as can be seen in Fig. 9. This way, the DRC installation can decrease the unbalance rate.

4.2 Technical Losses

The losses caused by the current flow through the feeder conductors are called technical losses. Figs. 10-12 show the losses in the compensation devices (capacitors and DRCs), in transformers and conductors, and the total losses of the feeder, considering the 24 h simulated.

By varying the amount of reactive injected on the system, the DRC limits the excessive reactive in the low loading periods, what is confirmed by the results shown in the charts above.

An important information obtained by the diagrams above is the difference between the conductor losses observed for the DRC and fixed capacitors situations. In the first one, the cable losses were 97 kWh lower.

The DRC disadvantage is its inner transformer, more specifically the losses caused by this element. This can be clearly noticed in Fig. 11, where the DRCs consumed more than 100 kWh during the simulation period. However, even with these high losses, the system as a whole was more efficient, been more advantageous at the low demand periods.

Fig. 13 shows the difference between the losses obtained in situation 2 (fixed capacitors only) and 3 (DRC), for each simulated hour.

It can be observed that, the system with the DRC is more efficient until hour 10 (positive inclination), after the rise of the demand, the curve changes its inclination, meaning that, the system with fixed capacitors starts to show better results from the losses' point of view. The positive inclination happens

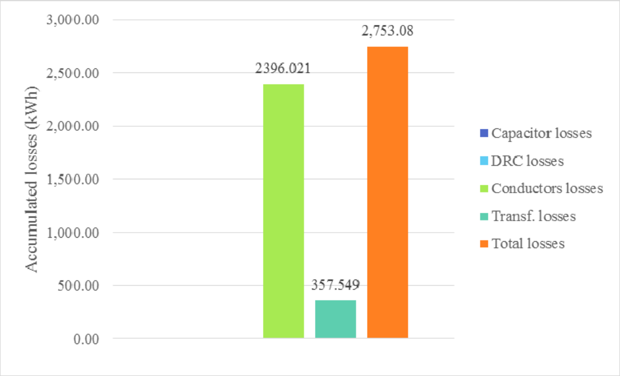

Fig. 10 Losses in the case without reactive compensation.

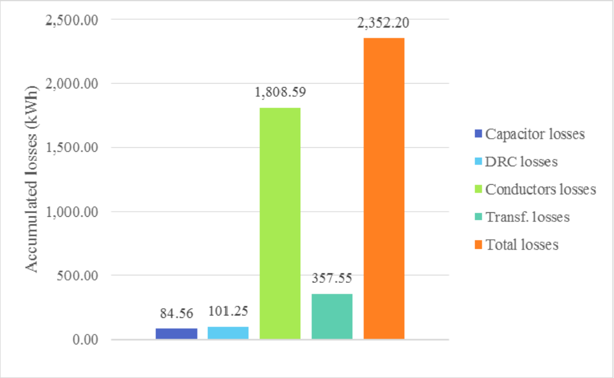

Fig. 11 Losses in the DRCs' case.

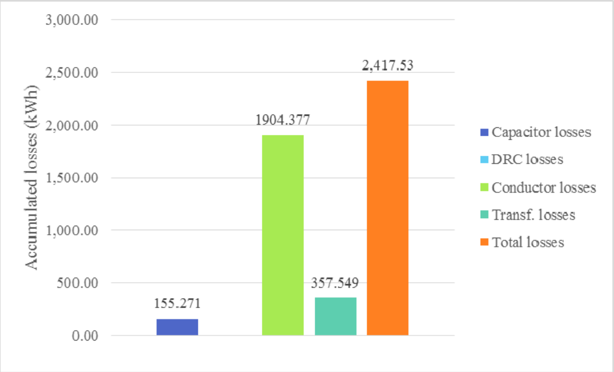

Fig. 12 Losses in the fixed capacitors' case.

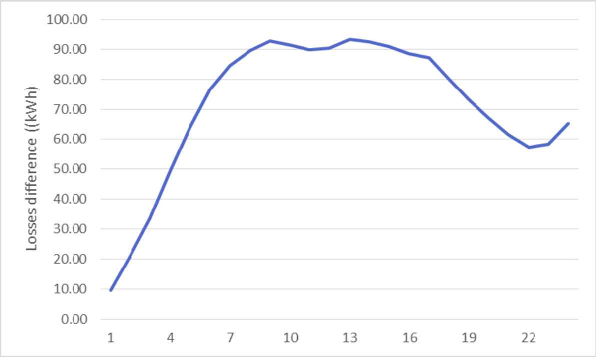

Fig. 13 Accumulated losses difference between the DRC and the fixed capacitors cases.

because there is an excessive reactive power in the low loading period when the system is compensated only with fixed capacitors, leading to higher Joule losses in the cables, different from what happens in the DRCs case, once their tap switches are in low positions (Fig. 9) and there is not excessive production of reactive power. Meanwhile, the negative inclination happens because the system demands a larger amount of reactive power and that makes the injection of reactive in both systems very close, however, the DRCs' system causes higher losses due to their inner transformers.

Nevertheless, at the end of a day, the DRC system resulted in a reduction of 61.66 kWh on the losses when compared to the fixed capacitors system.

4.3 Voltage Regulation

The amount of reactive power flowing through an electric system is deeply linked to the voltage levels along the circuit. This way, in situations with an excess of reactive power, sometimes high voltage levels are observed.

The diagrams of Figs. 14-16 show the voltage variation in three medium voltage buses. The bus number I is the closest to the source and the bus number III is the further, which is also the one where the 900 kVAr bank or the DRCs and the 300 kVAr bank are installed, depending on the simulated situation. The upper and lower limits demarcated in the diagrams are the ones described in the Brazilian standard [12]. The names and locations of the buses are shown in Fig. 5, by the colors.

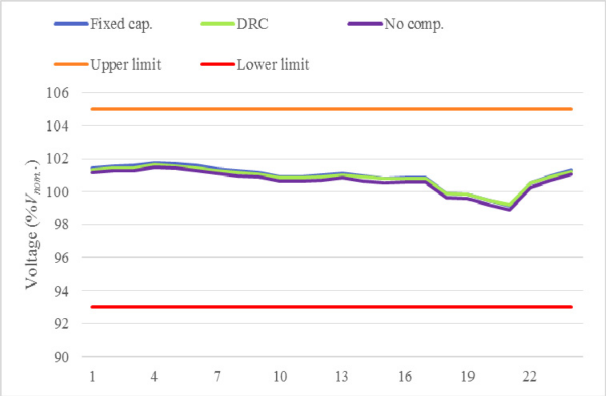

Fig. 14 Voltage at bus I.

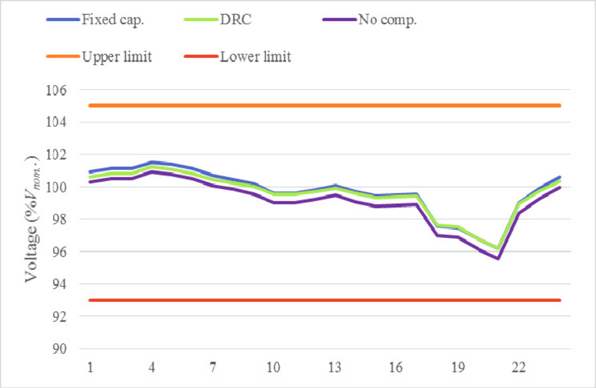

Fig. 15 Voltage at bus II.

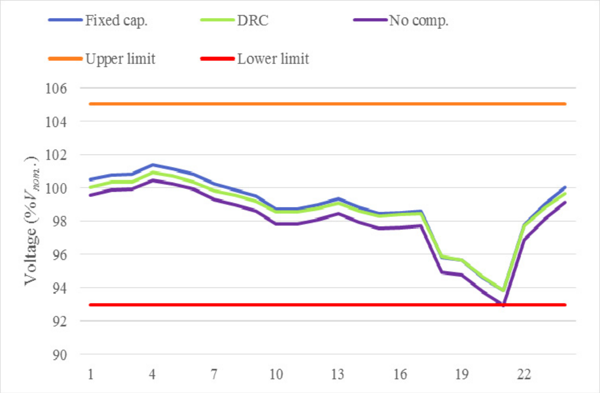

Fig. 16 Voltage at bus III.

When the amount of reactive power injected in the system is varied, the DRC does the secondary control of voltage, since its control parameter is the power factor.

In the DRC case, as a result of the control of the reactive power produced, the voltage also presented the best behavior, mainly on the low loading period (0-8 h). The voltage difference between the two cases was small due to the compensator size.

5. Conclusions

Due to the load variation along the day, a variable reactive compensation may be necessary.

The compensator presented in this paper adjusts the amount of reactive power injected on the system according to its bus power factor.

The computational simulation of the equipment was highly satisfactory. For the simulated systems, the dynamic compensator had a better performance in all the analyzed parameters when compared to the fixed capacitor banks (power factor, losses and voltage regulation in steady state). However, each system must be studied in detail before the installation of the equipment.

It can be easily seen that, the DRC presents more advantages over the fixed capacitor banks in systems with a variable demand of reactive power. This way, in systems where the demand remains steady, the trade of fixed capacitors to the dynamic compensator may not be so advantageous due to the latter inner losses.

It is worth noticing that, the compensator power is going to be another determinant factor in the obtained results with its installation. In this paper, it was installed a small bank of capacitors along with the DRC, assigning to the compensator only the fine tuning of the reactive power injected. However, if the power of each equipment was 300 kVAr instead of 200 kVAr, the voltage regulation, mainly in the moments of lower reactive demand, would be more satisfying, but the losses in the DRC transformer would be larger. In view of this situation, before the installation of the equipment, a study should be made taking in account the system to be compensated as much as the desired results.

For future works, the transient analysis of the tap switching and the actuation of the DRC as a harmonic passive filter are listed.

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