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Optimal Sizing of Capacitor Bank for Increasing Substation Capacity of Mamou

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Abstract

In order to increase the available power of the electrical energy distribution station and improve the voltage profile of the distribution lines, the use of shunt capacitor banks is indicated. The main results obtained during this study are: a reduction in subscribed power from 14913.978 kVA to 14010.100 kVA, a reduction in the transformer load rate from 99.4% to 93.4%, a reduction in reactive power called from 5481.729 kVAr to 481.729 kVAr, an increase in the active power transported by the substation from 8505.062 kW to 8962.323 kW, a reduction in the voltage drop from 4.8% to 3.9%, an increase in the power available at the secondary of the transformer station at full load from 13950 kW to 14700 kW and an annual electrical energy saving of 339943.48 kWh of electrical energy, therefore fuel savings and a reduction in CO_2 and SO_2 emissions due to this energy saving will be achieved. The installation of capacitor banks for optimization of reactive energy allowed a reduction in the current called therefore a reduction in the absorbed power: 14153.061 kVA, *i.e.* a reduction of 903.876 kVA. It is therefore essential that energy players are convinced of the need to install capacitors to reduce or even eliminate their reactive energy bill. This is necessarily accompanied by an investment by Electricité De Guinée by setting up active and reactive energy meters but also by implementing pricing in line with the reduction in the transfer of reactive energy in the network.

Keywords

Compensation, Power, Reactive, Optimal, Battery, Capacitors

1. Introduction

Any electrical system using alternating current involves two forms of energy: active energy and reactive energy. In processes using electrical energy, only the active energy is transformed within the production tool into mechanical, thermal, light, etc. energy. The other, reactive energy, is used in particular to supply the magnetic circuits of electrical machines (motors, autotransformers, etc.). In addition, certain components of electrical transmission and distribution networks (transformers, lines, etc.) also consume reactive energy in certain cases of operation.

The circulation of active and reactive power causes power losses in the distribution networks (approximately 13% of the total energy produced) [1] and voltage drops in the conductors [2] [3]. Active losses reduce the overall efficiency of networks and voltage drops are detrimental to the maintenance of good voltage that the distributor owes to its customers. Thus, it is therefore technically preferable to produce them as close as possible to the places of consumption.

For active power, it is shown that it is more economical to produce it centrally and then distribute it to customers. The cost of transport is much lower than the additional cost of production carried out locally. On the other hand, for reactive power, it is economically more interesting to produce it, in whole or in part, locally by autonomous reactive energy generators.

Electrical distribution networks ensure the transfer of electrical energy to end users (industrial, residential and commercial). For a given line configuration and given that the active power demand is incompressible, the reduction of voltage drops and that of power losses can therefore only be achieved by reducing the transit of the strong reactive components of the line current. For this purpose, among strategies such as phase balancing, use of distributed generators, grid reconfiguration, and location of energy storage systems [4], reactive energy compensation is the most economical [5] [6] [7] [8]. However, it is not enough to place capacitor banks to say that the problem posed (circulation of strong reactive currents) is solved. By optimizing reactive energy compensation, we must understand the choice of the power of the compensation device, its location and even the time during which it will remain online if it is an adaptive compensation [2] [7] [9].

In recent decades, contemporary lifestyle, as well as economic and technological development, has increased household electricity consumption. Excessive electricity use has a negative impact on the environment, increasing the carbon footprint and contributing to climate change.

In recent years, the municipalities supplied by the Mamou substation have experienced an increase in their energy consumption due to the increase in their populations [10] and in the standard of living through the purchase of electronic devices, thus provoking an exorbitant call current in the network. This inrush current pushes the operators of this substation to perform manual voltage adjustment maneuvers using the adjustment taps provided for this purpose on the primary windings of the substation transformer.

The purpose of this study is to determine the optimum power of the capacitor bank for reactive energy compensation in order to increase the supply capacity and improve the voltage profile of the Mamou substation.

2. Material and Methods

2.1. Materials

2.1.1. Presentation of the Study Area

The prefecture of Mamou, capital of the administrative region of Mamou is between 9˚54' and 11˚10' North latitude and 11˚25' and 12˚26' West longitude with an average altitude of 700 m. It covers an area of 8000 km^2 with a population of 318981 inhabitants, an average density of 30 inhabitants per km^2. Its climate is of the Foutanian type, characterized by the alternation of two (2) seasons (dry and rainy) of equal duration. The Urban Commune of Mamou is located 270 km from the capital, Conakry, it has 28 districts. The highest temperatures are observed in March-April (37˚C and 38˚C), while the lowest are noted in December (11˚C) [10] (**Figure 1**).

2.1.2. Presentation of the Mamou Substation

The Mamou substation (110/30KV) is located 6 km from the city center in the Séré district on the Mamou-Dabola national road with an area of 100 m^2. It is a distribution station which is supplied by the Linsan-Maou line of the Garafiri system over a 43 km route on 110 pylons. This substation with an installed capacity of 15 MVA supplies the town of Mamou via the "Petel" and "Centre-ville" feeders and the towns of Dalaba, Pita and Labé via the "Fouta djallon" feeder. The substation transformer is a three-phase step-down transformer (11.25/15MVA, 110/30KV), ONAN/ONAF type, equipped with a 12-position UZERN 380/150 CAT type on-load tap changer which serves as a means of regulation manual secondary voltage. The transformer parameters are: HT: Nominal rated voltage 110000Y/63510 ± 15% volts; HT Shock withstand, line: 550 KV; neutral 325 KV; LV Shock withstand, line: 170 KV, neutral 170 KV; Apparent power S = 15 MVA; Current I = 274.9 A. The Mamou substation supplies three departures: the Fouta Djallon departure; the city center departure and the Petel departure. The Single-line diagram of the Mamou substation is shown in **Figure 2**.

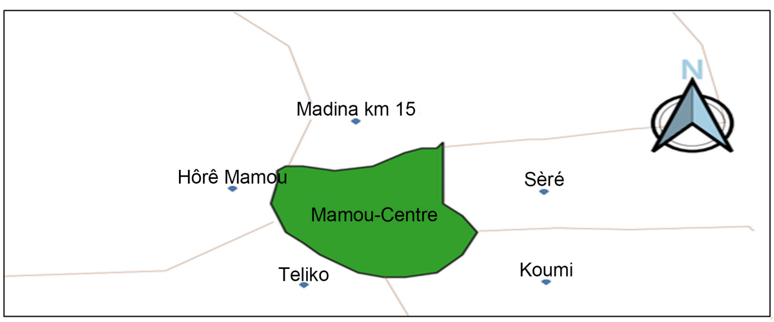

Figure 1. Map of the commune of Mamou.

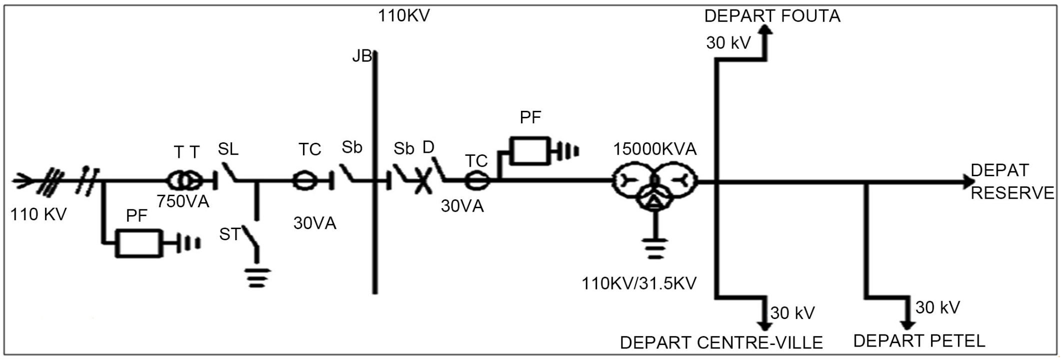

Figure 2. Single-line diagram of the Mamou substation.

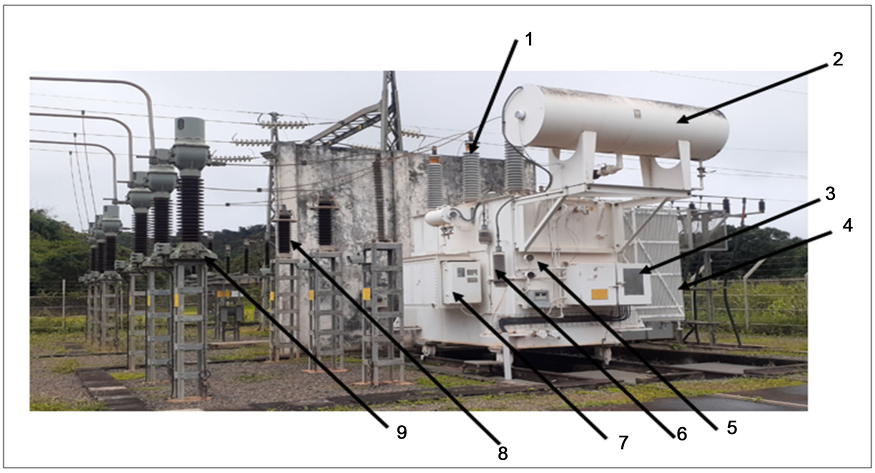

Photo of the electrical substation

Legend: 1-Insulators, 2-Oil conservator cylinder, 3-Nameplate, 4-Radiator, 5-Pressure gauges, 6-Siligazel, 7-Tap changer, 8-Lightning arresters, 9-Voltage transformer.

2.1.3. Materials Used

As part of this work we used the MATLAB environment, the Microsoft Excel software, the extract of the annual statistics of the peaks of load of the arteries of the Electricity of Guinea.

2.2. Method

The method used consists in finding or choosing a mathematical model linking the main electrical quantities to the power factor. Thus, we have chosen a model that takes into account the increase in the supply capacity of the substation (increase in the active power available at the secondaries of the substation transformer) [11]. For data collection, we extracted peak load statistics from the artery of the Mamou substation through the annual statistics of the EDG for the years 2018, 2019, 2020 and 2021 [12]. Then we determined the total consumption of the different departures from the Mamou substation. The analytical method was used for the optimization [13] [14]. The analytical method combined with the numerical method allowed us to do the simulation using MATLAB software.

The reactive energy compensation bank sizing optimization equation is given by Equation (1) [11].

$$\Delta KVA_S = S \cdot \left[\sqrt{1 - \left(Q_C^2 \cdot pf^2 / S^2 \right)} + \left(Q_C \cdot \sin\varphi / S \right) - 1 \right] \tag{1}$$

where: S: Apparent power of the transformer; pf: Desired power factor; $\sin\varphi$: Sinus of the uncorrected power factor angle, Q_c: reactive power of capacitors bank.

The equations used to determine the substation parameters before and after compensation optimization are as follows [14] [15] [16]:

The available power of the transformer is determined by Equation (2).

$$P_{disf} = S_T \cdot \cos\varphi \tag{2}$$

The demand or subscribed power is determined by Equation (3).

$$S' = \frac{P_P}{\cos\varphi} \tag{3}$$

The charging rate at the transformer is determined by Equation (4).

$$T_{XC} = \frac{S}{S_{Tn}} \tag{4}$$

The current in the installation downstream of the circuit breaker is determined by Equation (5).

$$I = P_P \Big/ \left(\sqrt{3} \cdot U_n \cdot \cos\varphi \right) \tag{5}$$

The amount of annual electrical energy saved is determined by Equation (6).

$$E_a = \left[R \cdot Q_C \cdot \left(2 \cdot S \cdot \sin\varphi - Q_C \right) 8760 \right] \Big/ \left(1000 \cdot U^2 \right) \tag{6}$$

The capacitance of capacitors is determined by Equation (7).

$$C = Q_C \Big/ \left(3 \cdot U^2 \cdot \omega \right) \tag{7}$$

The resonant frequency in capacitor banks is determined by Equation (8).

$$f_R = f \cdot \left(\sqrt{S_{CC}} \Big/ \sqrt{Q_C} \right) \tag{8}$$

The short-circuit power of the transformer is determined by Equation (9).

$$S_{CC} = \left(S / U_{CC} \right) \cdot 10 \tag{9}$$

The amplification of harmonics is determined by Equation (10).

$$F_a = \sqrt{Q_C S_{CC}} \Big/ P \tag{10}$$

The increase in voltage is determined by Equation (11).

$$U = \left(Q_C / S_T \right) \cdot X_T \tag{11}$$

The subscribed apparent power gain is determined by Equation (12).

$$G_S = S - S' \tag{12}$$

The annual gain on the fixed premium is determined by Equation (13).

$$G_A = G_p \cdot P_u / \text{kVA} \tag{13}$$

The reactive power gain is determined by Equation (14).

$$G_Q = Q - Q' \tag{14}$$

The cost of installing and purchasing the compensation system is determined by Equation (15).

$$C_T = P_u / \text{kvar} \cdot G_Q \tag{15}$$

The payback time of the amount invested for the installation is determined by Equation (16).

$$T = C_T / GA \tag{16}$$

where: *S*: Apparent power of the transformer; *pf*: Desired power factor; sinφ: Sinus of the uncorrected power factor angle; *R*: Electrical resistance in ohms; *U*: phase-to-phase voltage (voltage between phase); *Nh* = 8760: Number of hours per year.

3. Results and Discussions

3.1. Evolution of Consumption of Departures from the Mamou Substation

This **Figure 3** shows that in recent years, the urban municipalities supplied by the Mamou substation have experienced an increase in their energy consumption due to the increase in their populations and in the standard of living through the purchase of electronic devices, household appliances thus causing an exorbitant inrush of current in the network.

3.2. Electro-Energy Balance of the Various Departures from the Mamou Substation

The results of the electro-energy balance (active power, reactive power, apparent power, current and power factor) of the various departures from the Mamou substation for the year 2021 show that: A load peak around 7p.m.-8p.m. due to the massive use of electrical energy in households supplied by the various outgoing stations (**Figure 4**).

It appears from these graphs that the Fouta Djalon departure is the busiest, *i.e.* 58% of the Mamou substation load as shown in the diagram below (**Figure 5**).

A large variation in the reactive energy demand of the various substation feeders. This leads us to propose a dynamic compensation (**Figure 6**).

We note a bad power factor of the various departures during the night hours, this is due to the use for lighting of fluorescent lamps which have a bad power factor (0.48), Uncompensated discharge lamps (0.4 to 0.6); the use of induction furnaces with integrated compensation (0.85), resistance welding machines (0.3 to 0.8), static single-phase arc welding stations (0.5) (**Figure 7**).

The "Fouta Djalon" feeder represents the largest load of the Mamou substation with a current at peak times of 100 A, *i.e.* 57% of the substation outgoing current, 36.37% of the substation's nominal current (274.9 A). But this percentage does not give rise to a sectoral compensation (Compensation by sector) (**Figures 8-10**).

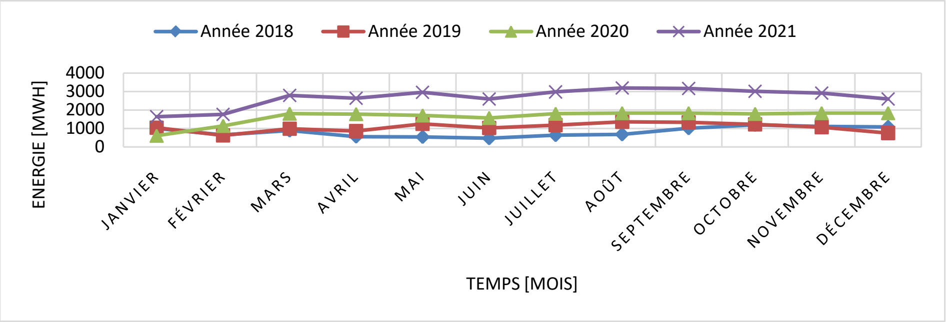

Figure 3. Evolution of consumption of departures from the Mamou substation [12].

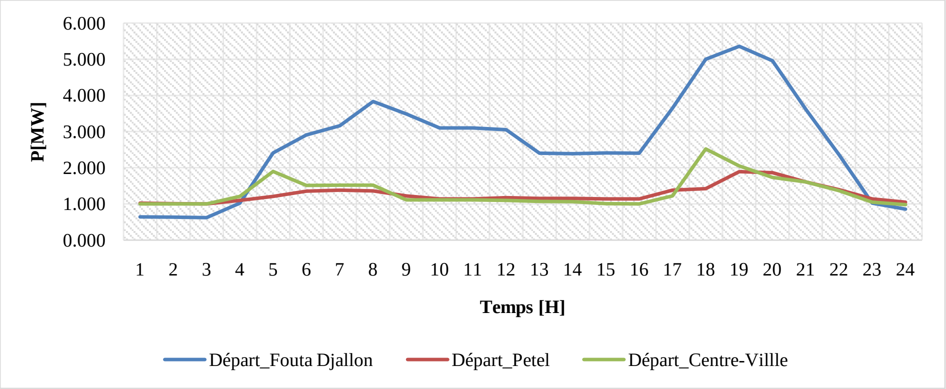

Figure 4. Active powers of the different departures from Mamou Post.

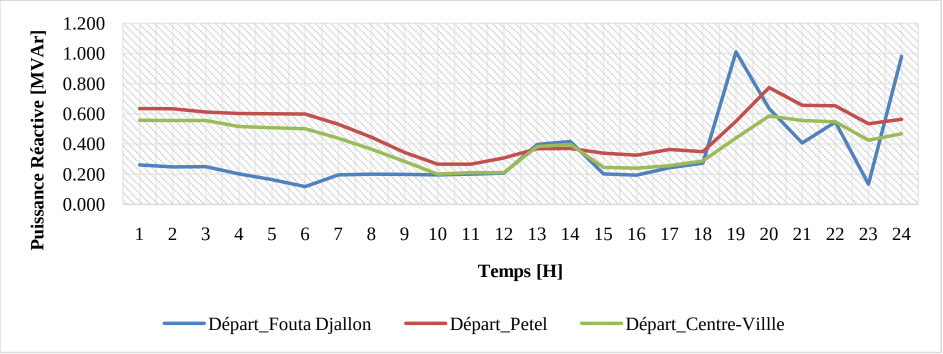

Figure 5. Reactive powers of the different feeders from the Mamou substation.

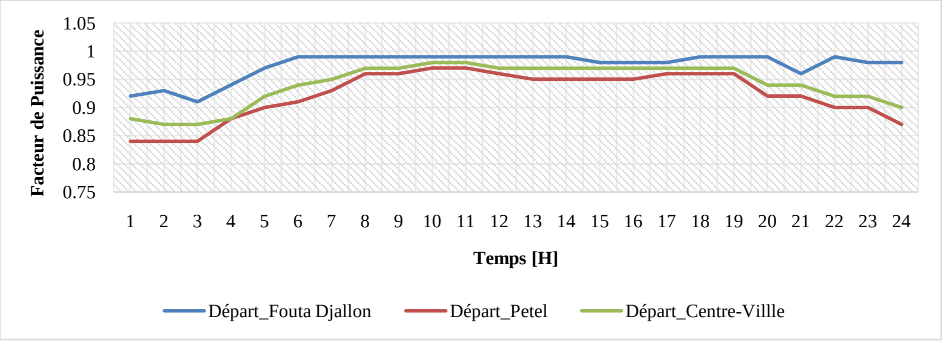

Figure 6. Variation in the power factor of the various substation feeders.

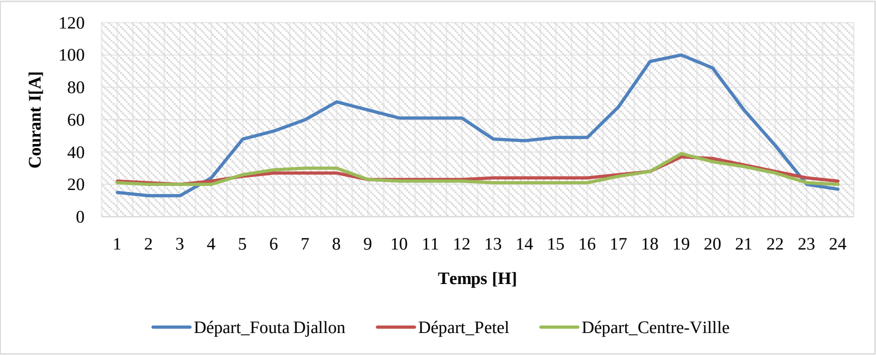

Figure 7. Currents from the different departures from Mamou substation.

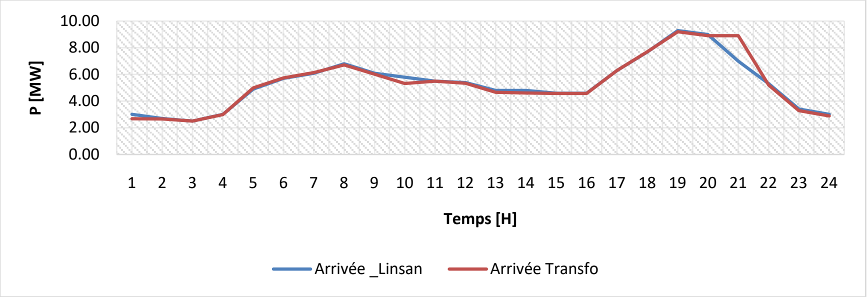

Figure 8. Active powers transmitted by the substation transformer.

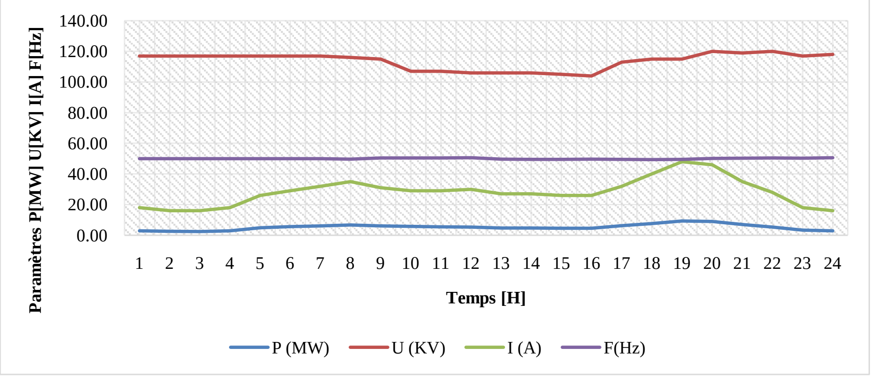

Figure 9. Substation primary electrical parameters.

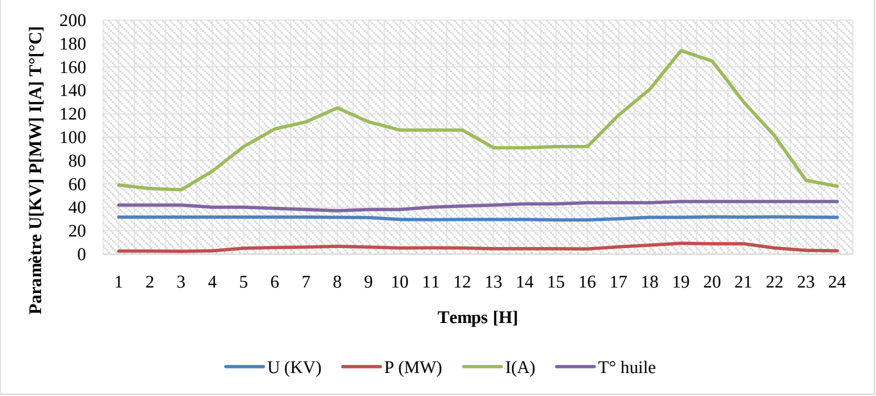

Figure 10. Electrical parameters at substation secondary.

3.3. Simulation of the Objective Function

The results of this simulation show us that with compensation, the apparent power available at the secondary of the transformers increases up to a certain value and then decreases to zero. For the case of the Mamou substation, we find that this transformer substation supply capacity reaches its maximum value (optimal value) for a reactive power Q_c = 5178.4 KVAr, therefore to optimize the reactive energy compensation at Mamou substation, a bank of capacitors with a power equal to 5000 KVAr must be installed. Thus, the supply capacity of the transformer station, *i.e.* the power available at the secondary of the transformer station, reaches an optimal (maximum) value, *i.e.* an increase of: ΔS = 961.049 KVA. Beyond this value we note a reduction, even a cancellation of this increase at approximately 9800 KVAr (**Figure 11**).

In electrical energy distribution networks, a certain reactive power is imposed according to the active power. This constraint is imposed by the tgφ function, that is to say Q/P, if the Q/P ratio is greater than the value of tgφ imposed, the substation requires a power capacitor bank Q_c, which will retreat to Q. This will decrease tgφ and approach the value imposed to satisfy the constraints of the production of electrical energy. However, when the reactive energy Q_c supplied by the capacitor bank becomes greater than that required by the installation, an overcompensation of the reactive power is obtained, *i.e.* the installation becomes a producer of reactive power on the network. This results in the fact that the overall installation will have its current ahead of its voltage. It will therefore have a "front" and not "rear" phase shift, and the installation will be likened to a capacitive receiver, and not an inductive one (**Figure 12**).

Determining the power of the capacitor bank allows us to choose the type of battery (fixed or automatic battery). So the Q_c/S_n ratio gives us: 15000/5000 = 0.3 or 30%. This allows us to choose an automatic compensation. As the demand for electrical energy from the various outlets of the substation is variable, we offer dynamic compensation which is gradually adjusted as needed (response time of less than a minute).

3.4. Power Absorbed by the Various Substation Feeders

Before the installation of the capacitor banks (without compensation), a large reactive current was drawn on the network by the feeders, *i.e.* a power of 14913.978 KVA. The installation of capacitor banks for optimization of reactive energy allowed a reduction in the current called therefore a reduction in the absorbed power: 14153.061 KVA, *i.e.* a reduction of 903.876 KVA (**Figure 13**, **Figure 14**).

The active power available at the secondary of a transformer is all the greater as the power factor of the installation is high. The efficiency of a transformer depends on its load and the power factor of the loads it supplies. The installation of a compensation device (capacitor battery) of 5000 KVAr at the secondary of the transformer will make it possible to transport an active power of 8962.323

KW. This power is greater than that transported by the transformer station, before the reactive energy compensation (8505.062 KW).

3.5. Effects of Reactive Energy Compensation [15]

Improving the power factor by installing a compensation device affects:

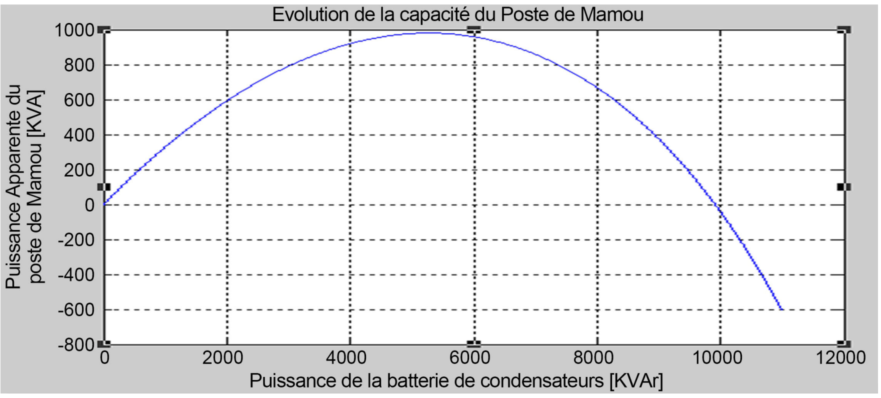

Figure 11. Evolution curve of Mamou substation supply capacity.

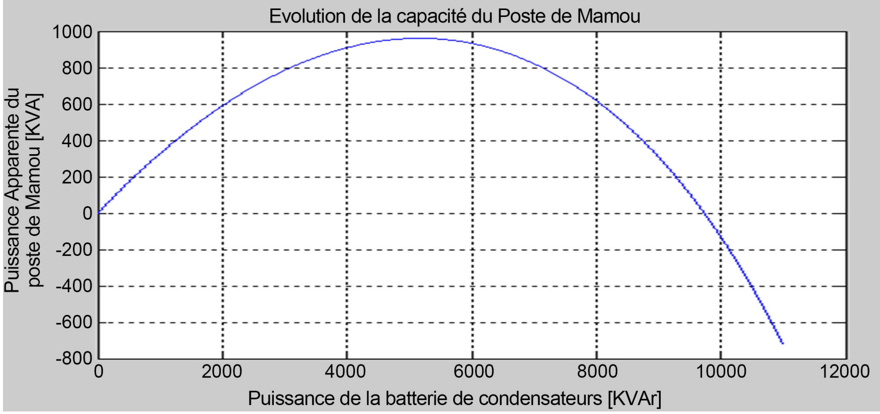

Figure 12. Evolution of feeding capacity for overcompensation.

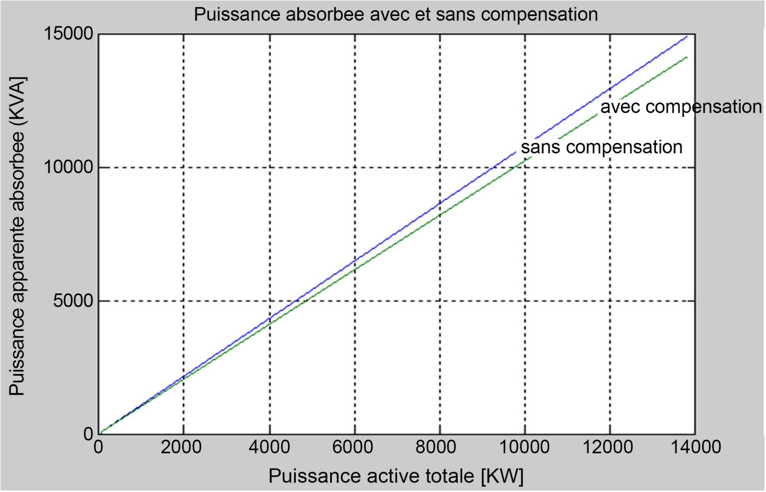

Figure 13. Power absorbed by feeders before and after compensation.

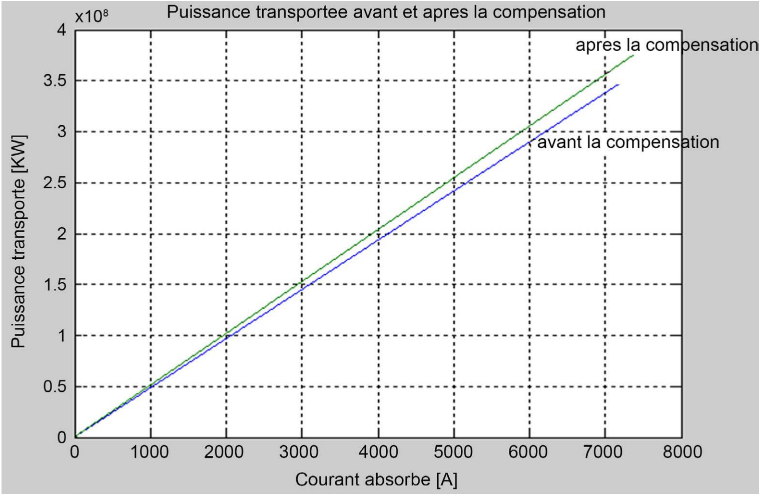

Figure 14. Active power transmitted before and after compensation.

- **The available power of the transformer**

With an improved power factor of 0.98, the power available at the Mamou substation (15000 KVA) would be:

$$P_{dis} = S_T \cdot \cos\varphi = 15000 \times 0.98$$

$$P_{dis} = 14700 \text{ kW}$$

- **The power demand**

With a load of 13.87 MW in March 2020 and a power factor of 0.98, the subscribed power would be:

$$S' = \frac{P_P}{\cos\varphi} = \frac{13870}{0.98} = 14153 \text{ KVA}$$

- **The load rate at the Post level**

For a subscription of 14153 kVA and a nominal power of 15000 kVA:

$$T_{XC} = \frac{S}{S_{Tn}} \cdot 100 = \frac{14153}{15000} \cdot 100 = 94.35\%$$

- **The current carried in the installation downstream of the circuit breaker**

For an active power peak of 13870 kW, U_{n2} = 30000 V and a $\cos\varphi$ = 0.98, the current passed through the installation downstream of the main circuit breaker would be:

$$I = \frac{P_P}{\sqrt{3} \cdot U_n \cdot \cos\varphi} = \frac{13870}{\sqrt{3} \cdot 30000 \cdot 0.98} = 272.37 \text{ A}$$

- **Reduced voltage drop**

The relative voltage drops in the Mamou substation transformer under a load of 13870 KW and 5481.729 KVAr, before and after compensation are given in Table 1 below. The compensation decreases the reactive power Q and therefore the voltage drop.

The installation of capacitor banks downstream of the transformers will reduce the voltage drop from 4.8% to 3.9%.

Table 1. Impact of reactive power compensation.

Sizes	Before Clearing	After clearing	Unit
Nominal voltages	110/30	110/30	kV
Total active power of feeders P	13870	13870	kW
Total reactive power of feeders Q	5481.729	481729	kVAr
Total active resistance of substation RTr	7431	7431	Ω
Total reactance of substation XTr	5076	5076	Ω
The voltage drop in the substation $\Delta U/U_n$	4.8	3.9	%
Active loss in the transformer	1836499.427	1590308.005	kW
Reactive loss in transformer	1254484.065	1086314.550	kW
Active loss in the Linsan-Mamou line	124797.671	108067.954	kW
Reactive loss in the Linsan-Mamou line	276654.140	239567.346	kVAr

At the terminals of the transformer station, reactive energy compensation allows an increase in voltage [17] [18].

$$\%U = \frac{Q_C}{S_T} \cdot X_T$$

Thus the installation of capacitor banks will give a voltage increase of 1.69% which is far from an overvoltage which could be harmful for the receivers.

With the reduction of losses due to the installation of capacitor banks, we obtain an annual saving of 339943.48 KWh of electrical energy. Therefore, fuel savings and a reduction in CO_2 and SO_2 emissions due to this energy saving will be obtained.

3.6. Synthesis after Power Factor Improvement

Before compensation, the installation consumed a reactive power of 5481.729 KVAr. After raising the power factor, the installation would consume a reactive power of 481.729 KVAr. The compensation device must provide a power of 5000 KVAr. Graphically, for an installed power of 13870 kW, the composition of the powers before and after power factor improvement gives:

$$S_1 = 14913.978\text{ KVA};\ Q_1 = 5481.729\text{ KVAr};\ S_2 = 14153.061\text{ KVA};$$
$$Q_2 = 481.729\text{ KVAr};\ \varphi_1 = 29.54;\ \varphi_2 = 18.19.$$

After compensation of the reactive energy by placement of the compensation device, the reactive power taken from the network is lower. Part of the reactive power shuttles between the compensation device and the load and therefore no longer constitutes a load for the network. The transformer, the cables are partly relieved.

We are therefore thinking of installing an automatic compensation system with a Q_c/S_n ratio = 30% > 15% (percentage authorized) (**Figure 15**).

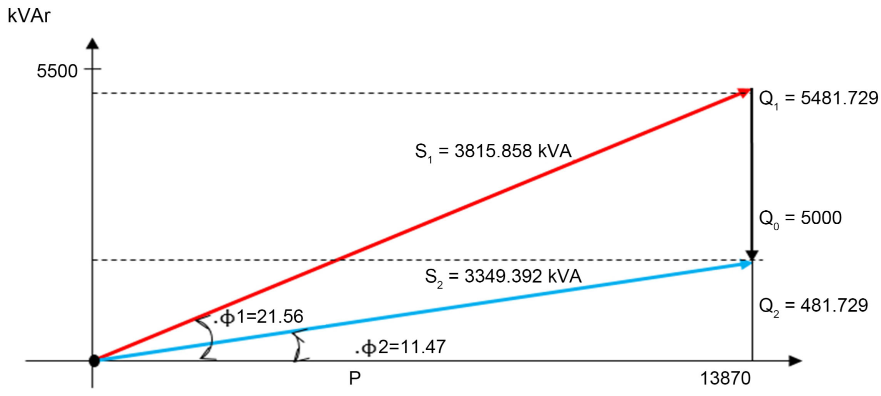

Figure 15. Composition of powers before and after compensation.

where:

S_1: Subscribed apparent power before reactive energy compensation;

S_2: Subscribed apparent power after reactive energy compensation;

Q_1: Reactive energy absorbed before reactive energy compensation;

Q_2: Reactive energy absorbed before reactive energy compensation;

P: Active power of the installation;

φ_1: Angle of phase shift before reactive energy compensation;

φ_2: Phase angle after reactive energy compensation.

3.7. Economic Parameters of the Compensation Scheme

The economic interest of raising the power factor is measured by composing the cost of installing capacitor banks with the savings they provide:

- **Gain in subscribed apparent power**

The difference between the apparent power subscription before and after power factor improvement is:

$$G_S = S_1 - S_2 = 14913.978 - 14010.100 = 903.878\ \text{kVA}$$

- **Annual gain on the fixed premium**

For an amount of \$39.2/kVA, including VAT, the annual gain on the fixed premium would be:

$$G_A = G_p \cdot P_u / \text{kVA}$$

$$G_A = 903.878 \times 39.2$$

$$G_A = \$35432.0176$$

- **Gain in reactive power and total cost**

The difference in the reactive powers consumed before and after raising the power factor is:

$$G_Q = Q - Q' = 5481.729 - 481.729$$

$$G_Q = 5000\ \text{kVAr}$$

For a reactive power to be compensated of 5000 kVAr and a unit price/kVar to be installed of $28, the cost of installing and purchasing the compensation system would be:

$$C_T = P_u / kvar \cdot G_Q$$

$$C_T = 28 \times 5000 = \$140000$$

➢ **Investment payback time**

The return time of the amount invested for the installation of the compensation system would be:

$$T = \frac{C_T}{G_A} = \frac{140000}{35432.0176} = 3.95 \text{ ans}$$

This gives four (4) years for the return on investment.

3.8. Observations after Compensation

By increasing the power factor from 0.93 to 0.98, the load on the secondary level of the supply transformer is further reduced and thus an apparent power of 903.878 kVA is freed up which can be used to supply energy to other users. This increases the power available at the secondary of the transformer, which improves access to electricity by reducing losses [3] [19].

For these reasons, it is therefore appropriate to reduce energy consumption as much as possible, that is to say to have the highest possible power factor. According to the pricing applied by the electricity supplier, the minimum average monthly power factor must be 0.95 to avoid invoicing the increase for reactive consumption.

Below is the summary table of the results of the parameters obtained after improving the power factor (**Table 2**).

Table 2. Summary of results after analysis.

Settings	Before Clearing	After compensation	Unit
Power factor	0.93	0.98	
Subscribed apparent power	14913.978	14010.100	KVA
Active power available	13950	14700	KW
Power reserve	−963978	689.9	KW
Reactive power consumed	5481.729	481729	kVAr
Tangent phi	0.39	0.20	
Phase shift	21.56˚	11.47˚	
Position load rate	99.4	93.4	%
Current drawn (carried)	287.019	272375	AT
Gain obtained on the fixed premium	0	3532.0176	$

4. Conclusions

This work made it possible to know the electrical energy consumption of the various departures from the Mamou substation and to propose solutions for the compensation of the reactive energy called by these departures in order to reduce voltage drops and energy losses. In the energy context of our country, optimizing energy consumption through reactive energy compensation, which results in an 8.78% reduction in reactive energy consumption for departures from the Mamou substation, should not leave the indifferent authorities. This compensation provides for an annual gain on the fixed premium of $35432.0176. The remarkable results of this study are: the reduction of the subscribed power from 14913.978 KVA to 14010.100 KVA; the increase in the active power transported by the transformer from 8505.062 kW to 8962.323 kW; the reduction of the post load rate from 99.4% to 93.4%; the decrease in the voltage drop from 4.8% to 3.9%, the increase in the power available at the secondary of the transformer station at full load from 13950 KW to 14700 KW; the annual electrical energy saving of 339943.480 kWh.

Reducing the power factor from 0.93 to 0.98 further reduces the load on the secondary level of the supply transformer and thus frees up an apparent power of 903.878 kVA which can be used to supply power to other users. This increases the power available at the secondary of the transformer, which improves access to electricity [11] [20] [21].

It is therefore essential that energy players are convinced of the need to install compensation devices to reduce or eliminate the negative impacts of the circulation of reactive energy on the networks [22].

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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