

Research Article

Compensation of the Reactive Power Consumed by the Transformer of the Mamou Electrical Substation

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Abstract

The continuous growth in electricity demand imposes increasing constraints on power transmission and distribution infrastructures, particularly in developing electrical networks. Among the key components of these systems, power transformers play a central role, while simultaneously contributing to reactive power consumption that affects voltage regulation and network efficiency. This study focuses on the compensation of reactive power absorbed by the power transformer of the Mamou electrical substation in Guinea. The investigated transformer is an oil-immersed unit rated at 15 MVA with a voltage level of 110 kV/30 kV. An analytical approach based on transformer operating characteristics is adopted to evaluate the reactive power requirements associated with magnetizing and leakage reactances. Using these formulations, the required rating of a shunt capacitor bank is determined in order to fully compensate the reactive energy consumed by the transformer. The results indicate that a capacitor bank rated at 2422.5 kVAr allows a significant reduction in apparent power and line current on the high-voltage side. Consequently, copper losses, Joule losses in the transmission line, and associated greenhouse gas emissions are reduced, leading to an annual energy saving of approximately 36,104 kWh. The findings highlight the technical and economic relevance of reactive power compensation for improving the operational performance of substations in emerging power systems.

Keywords

Transformer, Reactive Power Compensation, Mamou Substation

1. Introduction

All induction devices and machines that operate on alternating current systems convert electrical energy supplied by generators in the power system into mechanical work and heat. This energy is measured in KWh, and is called active energy.

To perform this conversion, magnetic fields must be established in these machines. The most common of these machines are transformers, motors and discharge lamps with magnetic ballasts.

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The proportion of reactive power to active power for full load operation is 65 to 75% for asynchronous motors, and 5 to 10% for transformers [1, 17]. Reactive energy consumption in a transformer increases reactive power losses, which causes voltage drops in distribution networks. [8-10].

In a transformer, reactive energy is absorbed by both parallel reactance (magnetizing flux) and series reactance (magnetic leakage flux). Power factor compensation can be achieved by a bank of capacitors [11]. Complete compensation can be achieved by a bank of capacitors in parallel connected in LV. The power factor at the primary of the transformer is generally lower than that measured at the secondary due to the reactive power required by the transformer. If the metering is carried out at medium voltage, the additional reactive power consumed by the transformer will also be measured. In such cases, it is important to know the reactive power consumed by the transformer so that it can be subtracted from the reactive power demand of the load. Installing a capacitor bank can avoid changing the transformer during an extension.

An approach similar to that developed to reduce the subscribed power, increase the power factor of the load as described in previous work [2, 3], makes it possible to increase the capacity of a transformer, i.e. to increase the active power available [16, 18].

In this work, we study the compensation of the reactive energy absorbed by the transformer of the Mamou substation.

This work uses a simple and compact expression of the power of a bank of fixed capacitors for the compensation of the reactive power absorbed by the transformer itself, at different load conditions. It has been demonstrated that the installation of a bank of capacitors whose power corresponds to the nominal load, reduces the effective value of the current for all other loads without causing an overvoltage at no load.

2. Materials and Method

2.1. Materials

2.1.1. Presentation of the Study Area

The study is conducted in the prefecture of Mamou, which serves as the administrative capital of the Mamou region in the Republic of Guinea. The area is located between latitudes $9^{\circ}54'$ and $11^{\circ}10'$ North and longitudes $11^{\circ}25'$ and $12^{\circ}26'$ West, with an average altitude of approximately 700 m. Mamou occupies a strategic geographical position at the junction of major national transmission corridors, which makes it an important hub for electricity distribution in Middle Guinea [4]. It is limited: to the North by the Prefectures of Dalaba and Tougue; to the South by the Republic of Sierra Leone; to the East by the Prefectures of Dabola and Faranah; to the West by the Prefecture of Kindia. Its climate is Foutanian type, characterized by the alternation of two (2) seasons of equal duration: a dry season from November to April and a rainy season from May to October [15]. Its surface area is distributed between an urban commune which has 28 neighborhoods and 13 rural communities (CR), namely: Bouliwel, Dounet, Gongore, Kegneko, Konkoure, Niagara, Ourekaba, Poredaka, Saramoussaya, Soya, Tegueraya, Timbo and Tolo. The population is mainly rural, 79% of the population of Mamou is located in rural areas. Its average density is 43 inhabitants/km² and its climate is tropical [4]. According to the General Population and Housing Census, Mamou has 391,777 inhabitants in 2021 with an area of 2,350 km²; or a density of 167 inhabitants per km². Mamou includes 28 neighborhoods including 5 districts which represent its peri-urban zone. These 5 districts are Madina Km 15 (North of the city), Sere (Northeast of the city); Koumi (East of the city); Teliko (South of the city) and Hore Mamou (Northwest of the city).

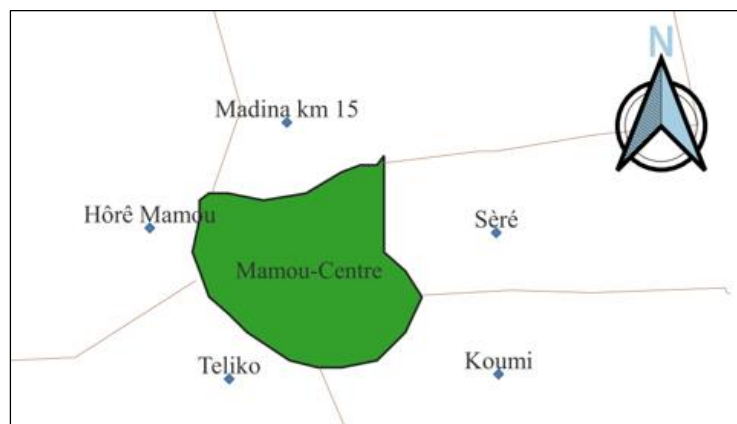


Figure 1. Map of the commune of Mamou.

2.1.2. Characteristics of the Mamou Substation Transformer

The Mamou electrical substation is a 110/30 kV distribution facility located approximately 6 km from the city center, in the S é é district along the Mamou–Dabola national road. The substation is supplied by the Linsan–Mamou transmission line, which forms part of the Garafiri power system.

The main transformer installed at the substation is a three-phase oil-immersed step-down transformer rated at 15 MVA,

with a nominal voltage of 110 kV on the high-voltage (HV) side and 30 kV on the low-voltage (LV) side. It operates under ONAN/ONAF cooling modes and is equipped with an on-load tap changer that allows secondary voltage regulation. This transformer supplies electrical energy to the city of Mamou as well as neighboring localities through several outgoing feeders. The single-line configuration of the substation illustrates the role of the transformer as the central element in power distribution (Figure 2).

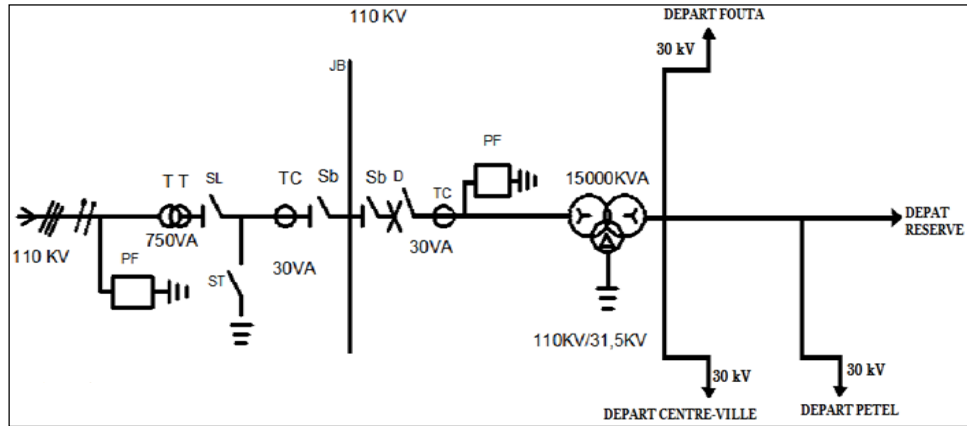


Figure 2. Single-line configuration of the Mamou substation.

2.1.3. Tools and Data Sources

The analysis is based on:

Nominal electrical parameters of the Mamou substation transformer,

Annual load statistics provided by the Electricity of Guinea (EDG) for the period 2018–2021,

Analytical expressions describing transformer reactive power consumption,

MATLAB software for numerical computation and simulation,

Microsoft Excel for data processing and graphical representation.

2.2. Method

The method used consists of determining the reactive energy consumed by the inductive components of the transformer from a mathematical expression, then defining the power of the bank of fixed capacitors to compensate for the reactive energy absorbed by the transformer itself [14]. For the collection of data on the transformer load, we extracted the statistics of the load peaks of the artery of the Mamou substation through the annual statistics of the EDG for the years 2018, 2019, 2020 and 2021 [3, 5]. Then we determined the total consumption of the different feeders supplied by the transformer at the Mamou substation.

2.2.1. Reactive Power Absorbed by a Transformer

Power transformers consume reactive energy during operation [10, 13, 14]. This is due to the reactive power requirements of two distinct branches of the transformer, namely: the shunt magnetization reactance and the series leakage reactance.

Considering that the reactive energy losses, the principal diagram of a transformer is defined in Figure 1. All the reactance is reported to the secondary of the transformer: the parallel reactance represents the magnetizing current circuit; the series reactance represents the magnetic losses.

The magnetizing current remains practically constant, at approximately 1.8% of the full load current whatever the load, in normal operation, that is to say with a constant primary voltage.

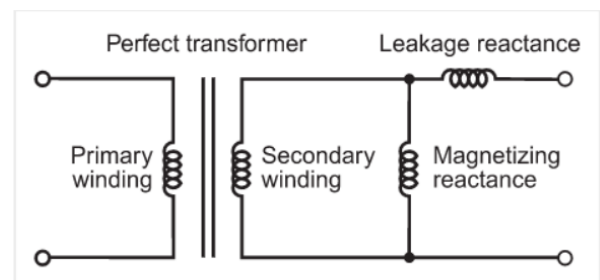


Figure 3. Schematic diagram of reactance per phase of a transformer.

(i). Reactive Power Absorbed in Leakage Reactance XL

The reactive power absorbed by a transformer cannot be neglected, and can be estimated at approximately 5% of the power of the transformer when it is operating at full load. The vector representation in Figure 2 illustrates this phenomenon.

The reactive component of the current in the load is: $I_r L = I \sin \phi$ hence:

$$Q_L = VI \sin \phi. \quad (1)$$

The reactive component of the current in the source is $I_r E = I \sin \phi'$ hence:

$$Q_E = EI \sin \phi'. \quad (2)$$

The difference between relation (1) and (2) determines the amount of reactive energy absorbed by the leakage reactance. From this representation, we deduce that the power linked to the magnetic leakage flux is given by:

$$P = I^2 X_L \quad (3)$$

From expression (3), we deduce the reactive leakage power dissipated for all the intensities of the load current of a transformer.

The vector representation in Figure 2 illustrates the reactive power dissipated by the series leakage inductance of a transformer.

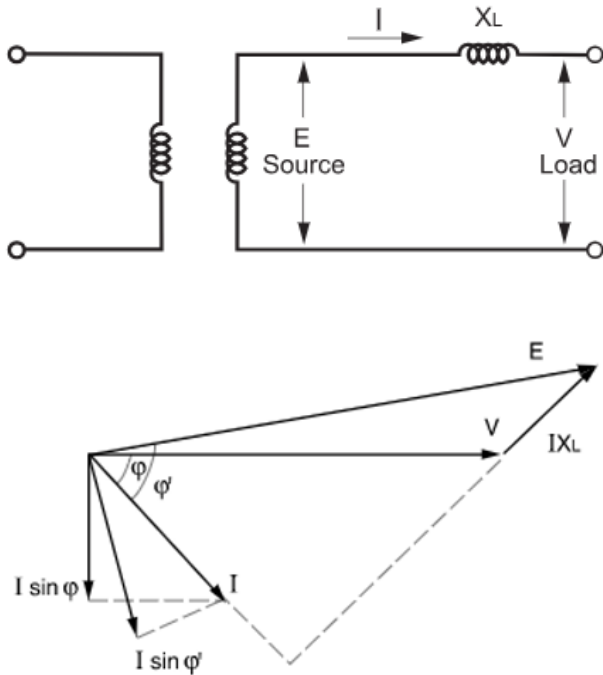


Figure 4. Reactive power dissipated by the series leakage inductance of a transformer.

To determine the total reactive losses of a transformer, it is necessary to add the losses due to constant magnetizing current to those previously calculated (reactive losses due to leakage flux).

(ii). Reactive Power Absorbed in the Shunt Magnetizing Reactance

The magnetizing shunt reactance is responsible for creating the magnetic flux in the transformer core. The current required to create this flow in the core is called excitation current and is relatively independent of the transformer load current. The excitation current is generally in the range of 0.25 to 2% of the transformer full load current. The actual value of excitation current can be obtained from the factory test report or can be measured in the field. To calculate the absorbed reactive power, one must first calculate the approximate shunt magnetizing impedance from the given excitation current. Excitation current is usually stated as a percentage of the transformer's full load current.

2.2.2. Power of the Fixed Capacitor Bank for Compensation of Reactive Energy Absorbed by a Transformer

The reactive losses of a transformer can be completely compensated by a bank of capacitors such that the power factor becomes very slightly ahead [11, 12].

In each operating mode of the transformer, the capacitor bank must provide reactive power Q_C to compensate for the reactive energy of magnetization of the transformer Q_μ and the reactive leakage energy Q_X [6, 7, 9]:

$$Q_C = Q_\mu + Q_X \quad (4)$$

In no-load operation, the apparent Power of transformer is:

$$S_0 = \sqrt{3}U_0 I_0 = \sqrt{3}U_r I_r = \sqrt{P_{Fe}^2 + Q_\mu^2} \quad (5)$$

Where: P_{Fe} is the loss in the iron of the transformer.

The reactive power for the magnetization of the transformer is:

$$Q_\mu = \sqrt{3U_r^2 I_0^2 - P_{Fe}^2} = \sqrt{(\sqrt{3}U_r I_r \frac{I_0}{I_r})^2 - P_{Fe}^2} \quad (6)$$

By introducing the value as a percentage of the no-load current: $i_0 = (I_0/I_r) \cdot 100$ expression (3) becomes:

$$Q_\mu = \sqrt{\left(\frac{i_0}{100} S_r\right)^2 - P_{Fe}^2} \quad (7)$$

Where S_r is the rated power of the transformer.

In Short-Circuit Operation, the apparent power is:

$$S_{SC} = \sqrt{3}U_{SC}I_r = \sqrt{P_{Cur}^2 + Q_{Xr}^2} \quad (8)$$

Where: I_r and P_{Cur} are respectively the nominal current and the copper losses of the transformer at nominal load. Therefore, the reactive power lost in the leakage reactance of the transformer is:

$$Q_{Xr} = \sqrt{(\sqrt{3}U_{SC}I_r)^2 - P_{Cur}^2} \quad (9)$$

As, by definition, the impedance voltage is:

$$u_{sc} = \frac{U_{SC}}{U_r} 100 \equiv \frac{X_{SC}I_r}{U_r} \cdot 100 \quad (10)$$

Expression (6) becomes:

$$Q_{Xr} = \sqrt{\left(\frac{u_{sc}}{100}\sqrt{3}U_rI_r\right)^2 - P_{Cur}^2} = \sqrt{\left(\frac{u_{sc}}{100}S_r\right)^2 - P_{Cur}^2} \quad (11)$$

For any other operating condition, when the transformer load is less than the nominal value, we have:

$$Q_x = x^2 Q_{Xr} = x^2 \sqrt{\left(\frac{u_{sc}}{100}S_r\right)^2 - P_{Cur}^2} \quad (12)$$

In general, for a load x , the power of the capacitor bank is:

$$Q_C = \sqrt{\left(\frac{i_0}{100}S_r\right)^2 - P_{Fe}^2} + x^2 \sqrt{\left(\frac{u_{sc}}{100}S_r\right)^2 - P_{Cur}^2} \quad (13)$$

When a quick and rough estimate of the power of the shunt capacitor banks is necessary, the following expression is used:

$$Q_C = \frac{i_0}{100}S_r + x^2 \left(\frac{u_{sc}}{100}S_r\right) \quad (14)$$

Where the losses in the transformer are neglected [11].

In the expression (14), appears the nominal apparent power of the transformer S_r , value as a percentage of impedance voltage u_{sc} , load x of the transformer and the value as a percentage of the no-load current, i_0 . When a transformer operates with its secondary open-circuited (no-load condition) and rated voltage applied to the primary, it draws a small no-load current i_0 . This current serves to:

Establish the magnetic flux in the transformer core (magnetizing component).

Supply core losses (hysteresis and eddy current losses).

The no-load current as a percentage of rated current decreases as the rated power of the transformer increases.

Mathematically, a correlation often used in power engineering is [2, 6, 10]:

$$i_0 = 0.0421 \cdot (\log S_r)^2 - 0.4384 \cdot \log S_r + 1.6064 \quad (15)$$

Where S_r is the nominal apparent power of the transformer in MVA and i_0 is the percentage value of the no-load current. Expression (15) conforms to the scaling laws of transformers.

$$\left(S_{r1}/S_{r0}\right)^{-0.25}$$

The active and reactive powers that the transformer absorbs on the high-voltage side are given by expressions (16) and (17).

$$P_{110KV} = P_L + P_{Fe} + P_{Cu} \quad (16)$$

$$Q_{110KV} = Q_L + Q_x + Q_\mu = Q_L + Q_C \quad (17)$$

Therefore, the apparent power and phase current on the 110 kV side are:

$$S = \sqrt{P_{110kv}^2 + Q_{110kv}^2} \quad (18)$$

$$I_{110kv} = \frac{S}{\sqrt{3}U} \quad (19)$$

3. Results and Discussions

After compensation for the reactive power consumed by the transformer, by a capacitor banks of 2422.5. KVar, the reactive power taken from the high voltage side (110kV) is equal to the reactive power of the load ($Q_{110kv} = Q_L$), so that the apparent power and the current on the high voltage side are $S = 11363.46$ kVA and $I = 60.76$ A. By full compensation in this operating condition, the input current is reduced by 5.5% and, therefore, the losses in the Linsan-Mamou cable under a voltage of 110 kV are reduced by 10.76%.

Table 1. Impact of compensation for reactive energy consumed by the transformer.

Sizes	Without compensation	With Compensation
Rated voltages [kV]	110/30	110/30
Active power P HV [kW]	11186.07	11186.07
Reactive power QHV [kVAr]	2000	4422.5
Apparent power SHV [kVA]	11363.46	12028.58

Sizes	Without compensation	With Compensation
The current I HV [A]	60.76	64.32
Active loss in the Linsan-Mamou line [KW]	72354, 46	81072,76

3.1. Evolution of Transformer Consumption Depending on the Load Rate

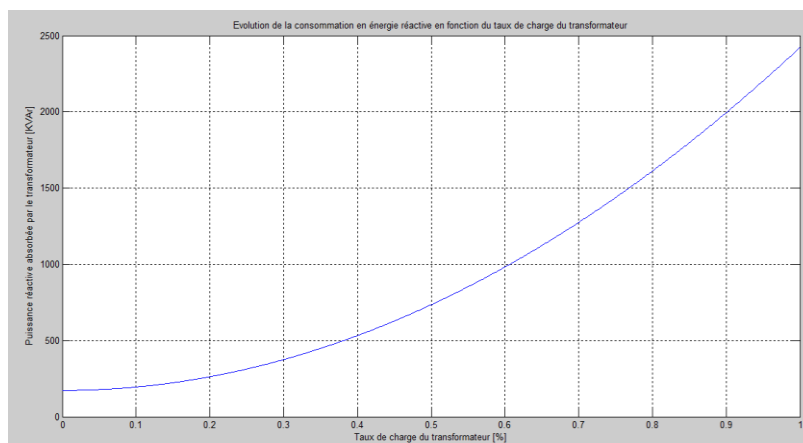


Figure 5. Evolution of transformer consumption as a function of load rate.

3.2. Evolution of the Reactive Energy Consumed at No Load Depending on the Power of the Transformer

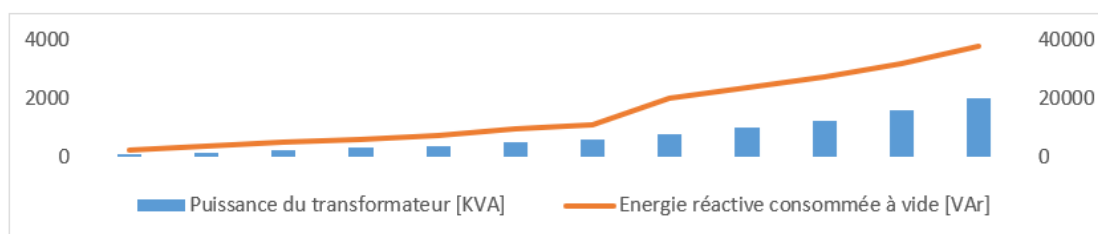


Figure 6. Evolution of reactive energy consumed at no load as a function of transformer power.

3.3. Evolution of the Reactive Energy Consumed at Full Load Depending on the Power of the Transformer

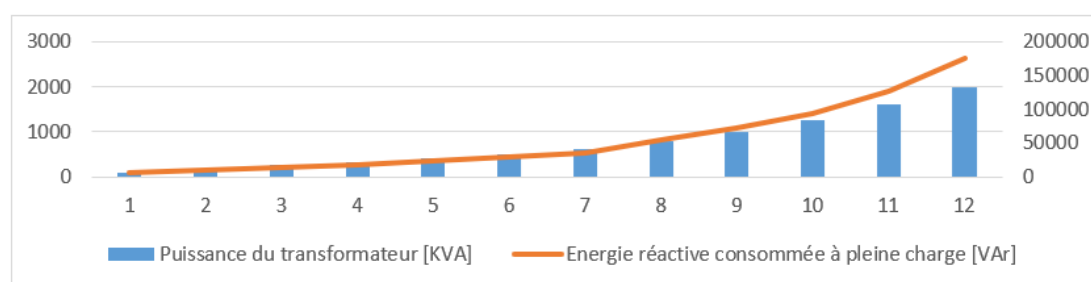


Figure 7. Evolution of reactive energy consumed at full load as a function of transformer power.

4. Conclusion

The research carried out is part of the compensation by a fixed capacitor bank, the reactive energy consumed by the transformer of the Mamou substation.

This study made it possible to determine the reactive power consumption elements (leakage reactance and magnetization reactance) of the transformer at the Mamou substation; and to determine the size of the capacitor bank required to compensate for the reactive power consumed by the transformer.

A mathematical expression was adopted and the simulation in MATLAB gave the following results (Figure 5). Before compensation, on the High Voltage side, we have an active power of 11186.07KW; a reactive power of 4422.5 KVAR; an apparent power of 12028.58KVA and a current of 64.32A. After compensation, we get a reduction in apparent power and current on the high voltage side (11363.46KVA, 60.76A). This reduction makes it possible to reduce Joule effect losses, losses in the copper of the transformer, an annual electrical energy saving of 36,104KWh and therefore a reduction in CO₂ and SO₂ emissions due to this energy saving.

Abbreviations

HV	High Voltage
EDG	Electricity of Guinea
ONAN	Oil Natural Circulation with Air Naturally Circulated for Cooling,
ONAF	Oil Natural Air Forced Cooling

Conflicts of Interest

The authors declare no conflicts of interest.

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