Parallel operation of transformers to optimize a 33 KV loop of power system

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ABSTRACT

This research investigates the viability of a perpetually scalable generation system to accommodate the anticipated growth in domestic load demands on the 33 kV loop network over the period from 2025 to 2040. This is achieved by analysis current situation of network through the voltages, loading lines, and transformers, within the permissible loading limits of the system. In this context, it is assumed that the loop is supplied by an ideal infinite power source. A numerical model utilizing the Gauss-Seidel (GS) method is developed and executed within the PSS/E simulator. The current operational state of the network will be simulated, with a focus on analyzing the voltage profile, which is expected to remain within the range of 0.095 to 1.05 per unit (p.u.). Demand forecasts are based on industrial growth projections for the cities interconnected with the 33 kV loop. The simulation results will demonstrate the feasibility of increasing active power transmission while maintaining effective control over reactive power by the year 2040. Furthermore, solutions will be proposed to address the identified critical path issues. To meet the projected demand, these solutions will involve doubling the capacity of the existing transformers. The proposed system will mitigate load imbalances and stabilize voltage fluctuations by effectively managing rapid variations in reactive power demand. As a result, it improves power quality for industrial consumers.

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1. INTRODUCTION

An effective power system management goes beyond ensuring that transmitted power remains within the transmission capacity. It also requires continuous monitoring of several technical parameters, with voltage level being a critical factor. Voltage must be maintained within an acceptable range across the entire grid, under all foreseeable operational and consumption scenarios.

In this context, it is also proposed to analyze the possibility of an infinite source generation system to meet the domestic demand of the 33 kV network [1]-[5]. The objective is to establish and sustain a voltage profile within the range of 0.95 to 1.05 per unit (p.u.). To reach this goal, we modeled the power grid through its transit capacities and analyzed the simulation results with PSSE and MATLAB [6]-[8].

This modeling is conducted to ensure the voltage profile remains within the limits defined by the grid operator. Another objective is to introduce a methodology for managing and controlling transit power and voltage, aimed at optimizing the system's performance under more favorable conditions. In this context, a reactive energy compensation system is proposed [9], [10].

To accomplish the set objectives, we undertake the following steps: Initially, a schematic diagram of the 33 kV loop network, along with its various parameters for the year 2022, is presented. This is followed by the calculation of the power system admittance matrix and the load flow analysis results. This is followed by the calculation of the power system admittance matrix and the load flow results, the forecasting demand between 2025 and 2040 years are provided in the second step. In the third step, a numerical model using the Gauss-Seidel (GS) method is implemented and programmed in the MATLAB environment and PSS/E simulator. The simulation results will be presented along with detailed discussions.

In the fourth step, the proposed solutions optimize the power flow and voltage profiles of the network [11]-[16]. The final phase involves drawing conclusions based on the proposed work. This ensures that the results are comprehensive and actionable. Increasing a transformer's capacity aims to stabilize the electrical network [17], [18]. This ensures reliable power delivery to consumers. Such upgrades are crucial during disturbances [19]-[22].

2. METHOD

Figure 1 illustrates the single-line diagram of the 33 kV loop network. The line data, as well as the injected powers at the buses and the loads, are provided in Tables 1 and 2, respectively. The electrical network comprises four transmission lines, four transformer substations fed by an infinite source, and four loads located at buses 1, 2, 3, and 4 (Figure 1). The generated active and reactive powers are provided in MW and MVAR, respectively. The active and reactive powers generated are given in MW and MVAR, respectively. The voltage at each bus(i) is given in per unit. The load bus is characterized by its active power P and reactive power Q. Therefore, (P, Q) are specified, while (V) is to be calculated. In this context, bus 3 (Kaedi) is proposed to serve as the slack bus. Additionally, it is important to note that each bus is numbered as (i) and is connected to (k) other buses, as illustrated in Figure 1.

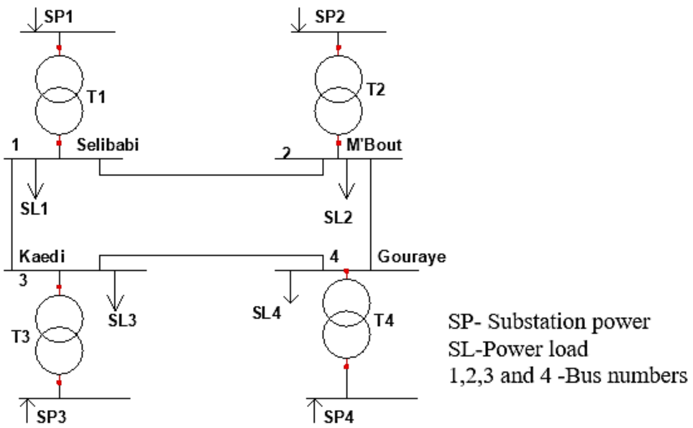

Figure 1. Schematic diagram of the 33 kV loop system

2.1. Line parameters

Table 1 provides the data, including the active resistances, reactances of the lines in per unit, node voltages, and the respective lengths of each line. This information is crucial for analyzing the electrical characteristics of the network. It provides key information needed to evaluate the network's performance, as shown below.

Table 1. Line parameters

Bus (i–k)	Resistance (Ω)	$Rpu=R/Z_B$	Reactance (Ω)	$Xpu=X/Z_B$	Voltage (kV)	Length (km)
1-2	2.147	0.0015	2.9380	0.00215	33	113
2-3	2.0805	0.00152	2.847	0.00207	33	109.5
3-4	3.8247	0.00281	5.2338	0.00384	33	201.3
4-1	0.84816	0.00061	1.16064	0.000852	33	44.64

2.2. Calculation of base values

To convert all the quantities in per unit (p.u.) listed in Table 1, it is necessary to arbitrarily select two independent base quantities at a given point in the electrical system, typically V_B and S_B. These base quantities are used to determine the base impedance, which is introduced via Ohm's law. The base impedance is given by the following expression:

$$Z_B = \frac{U_B^2}{S_B} = \frac{33^2}{800} = 1361\ \Omega\ with\ U_B = 33\ KV\ and\ S_B = 800\ KVA$$

Table 2 presents the given data of the initial voltages and their angles, the injected powers, and power demand in 2022. This data is essential for evaluating system performance and efficiency. Analyzing it helps ensure network reliability.

Table 3 provides the projected system demand from 2025 to 2040 based on extrapolation. This forecast is crucial for effective strategic planning and resource allocation. It allows for anticipating future needs and making informed preparations. Table 4 displays the simulation results for the admittance matrix of buses 1, 2, 3, and 4. This data underscores the interactions and performance of these buses within the system. Analyzing these results is essential for grasping system dynamics.

Table 2. Initial data of the system

Bus No.	Bus voltage		Injected power		Load	
	Voltage magnitude (p.u.)	Angle (deg)	P (kW)	Q (kVAr)	P (kW)	Q (kVAr)
1	1.05	0	634.5	310.2	564	423
2	1	0	333	162.8	296	222
3	1	0	720	352	640	480
4	1	0	288	140.8	256	192

Table 3. Forecasted system demand from 2022 to 2040

Country	2025-2030		2030-2035		2035-2040	
	P_D (Mw)	Q_D (Mvar)	P_D (Mw)	Q_D (Mvar)	P_D (Mw)	Q_D (Mvar)
Sélibabi	10.33	7.524	11.537	8.653	13.268	9.951
M'Bout	4.751	4.345	5.464	4.997	6.284	5.746
Kaédi	11.385	8.538	13.09	9.819	15.056	11.292
Gouray	4.109	3.42	4.726	3.93	5.435	4.523

Table 4. System's admittance matrix in p.u.

Bus No.	1	2	3	4
1	0.7807 - j1.0695	-0.2206 + j0.3016	0	-0.5601 + j0.7679
2	-0.2206 + j0.3016	0.4472 - j0.6127	-0.2206 + j0.3016	0
3	0	-0.2267 + j0.3111	0.3507 - j0,4807	-0.1241 + j0.1696
4	-0.5601 + j0.7679	0	-0.1241 + j0.1696	0.6842 - j0.9375

2.3. Numerical model of resolution

Load flow studies are one of the most important aspects of power system planning and operation. The main objective of the load flow is to find the voltage magnitude at each bus and its angle when the powers generated and loads are pre-specified. To solve the problem of load flow, we use the iterative method of Gauss-Seidel because the size of the studied system. The simulation was carried out on MATLAB and PSSE.

2.3.1. Gauss-Seidel resolution

Using Kirchhoff current law (KCL) from Figure 1, we obtain. Using Y_{Bus}, we can write a nodal equation for power system as (1).

$$I = Y_B V \tag{1}$$

Where (I) is the (n) column vector of source currents injected into each bus and (V) is the (n) column vector of bus voltages. For bus (k), the kth in (2) is:

$$I_i = \sum_{k=1}^{n} Y_{ik} V_k \tag{2}$$

the conjugate complex power delivered to bus(i) is given by (3).

$$P_i - jQ_i = V_i^* I_i \quad (3)$$

Putting in (2) in (3), we obtain, the voltage at bus(i) is defined by (4).

$$V_i = \frac{1}{Y_{ii}}\left[\frac{P_i - jQ_i}{V_i^*} - \sum_{k=1}^{n} V_{ik} V_k\right] \quad (4)$$

Hence, the following current between bus(i) and bus (k) is defined by (5).

$$I_{ik} = -Y_{ik}(V_i - V_k)\,,\ i \neq k \quad (5)$$

Where $V_i = |V_i|\angle\delta_i$ is the voltage magnitude and it angle injected at bus(i); $V_k = |V_k|\angle\delta_k$ is a voltage magnitude and it angle at bus(k); $Y_{ii} = |Y_{ii}|\angle\theta_{ii}$ is self-admittance; and $Y_{ik} = |Y_{ik}|\angle\theta_{ik}$ is admittance between bus(i) and (k).

$$V_i = |V_i|\angle\delta_i, V_k = |V_k|\angle\delta_k, Y_{ii} = |Y_{ii}|\angle\theta_{ii}, Y_{ik} = |Y_{ik}|\angle\theta_{ik} \quad (6)$$

Extended in (3), we find (7).

$$P_i - jQ_i = V_i^* I_i = V_i^* \sum_{k=1}^{n} Y_{ik} V_k = \sum_{k=1}^{n} |Y_{ik} V_i V_k| \left(\cos(\theta_{ik} + \delta_k - \delta_i) - j\sin(\theta_{ik} + \delta_k - \delta_i)\right) \quad (7)$$

The injected powers at bus(i) are defined by (8) and (9) in rectangular coordinates.

$$P_i = \sum_{k=1}^{n} |Y_{ik} V_i V_k| \cos(\theta_{ik} + \delta_k - \delta_i) \quad (8)$$

$$Q_i = -\sum_{k=1}^{n} |Y_{ik} V_i V_k| \sin(\theta_{ik} + \delta_k - \delta_i) \quad (9)$$

Since the voltage at the buses must be maintained within certain specified statutory limit. Hence, the voltage bound constraint limit at bus(i) is then defined by (10).

$$V_{i(\min)} \leq V_i \leq V_{i(\max)} \quad (10)$$

Where Vi (min) and Vi (max) are minimum and maximum voltage values at bus i. The reactive power supply constraint at bus(i) is specified by (11).

$$Q_{gi(\min)} \leq Q_{gi} \leq Q_{gi(\max)} \quad (11)$$

With Qgi(min) and Qgi(max) are the minimum and maximum reactive power values generated at bus(i).

3. RESULTS AND DISCUSSION

Table 5 presents the simulation results in PSS/E simulator at year 2040. Case before insertion the reactive power compensator in the system. We can observe the voltage magnitude profile and the voltage angles. The results show that the voltage magnitude values are below the stability range (0.95 and 1.05 p.u.) for all systems except the slack bus.

Table 5. PSSE simulation outcomes for the year 2040

Bus name	N°	Type	Vpu	ϕ°
Selibabi	1	PQ	0.9	-1.55
M'Bout	2	PQ	0.93	-0.89
Kaedi	3	Slack	1	0
Gouray	4	PQ	0.91	-1.37

3.1. Model of reactive power compensation

Table 5 presents the simulation results from the PSS/E simulator without reactive power compensation. The voltage magnitude profile and voltage angles fall outside the stability margin. To address this issue, we have proposed in (12).

$$Q_C = 3 * \omega * U^2 * C \; hence \; \omega = 2\pi f \quad (12)$$

Where Qc is a reactive power in MVAr, U is a bus bar voltage, C is a capacitance in µF, ω is a pulse, and F is a network frequency. Given that C = 20 µF, U = 33 kV, and F = 50 Hz, the reactive power required to maintain the system within the voltage constraints (0.95 and 1.05 p.u.), as preset in (10), is calculated using (13).

$$Q_C = 3 * 314 * 33^2 \, 10^6 * 20 * 10^{-6} = 20.51 \; MVAR \; with \; \omega = 314 \; rad/s \quad (13)$$

The injected reactive power at the Selibabi bus bar (1) is Qc = 20.51 MVAr. A shunt FACTS device, such as an SVC or STATCOM, is connected to bus (1). This device can absorb or inject reactive power as needed.

3.2. Analysis of simulation results

Table 6 presents the simulation results for the voltage profile and angles after the insertion of the reactive power compensation system. It also demonstrates that the voltage values are within the stability constraints (0.95 to 1.05 p.u.). That means we have performed one goal.

Figure 2 illustrates the voltage profile before and after the reactive power compensation, showing an increase in voltage magnitudes. For bus 1, the voltage rises from 0.90 (outside the limit of [0.95; 1.05 p.u.]) to 1 p.u., for bus 2 from 0.93 to 0.98 p.u., and for bus 4 from 0.93 to 0.99 p.u. It is noteworthy that the voltage and angle for slack bus 3 remain unchanged (1 p.u.; 0°). Figure 3 displays the voltage angle before and after the reactive power compensation, indicating an improvement in voltage angles. For bus 1, the angle improves from -1.55° to -5.15°, for bus 2 from -0.89° to 2.69°, and for bus 4 from -1.37° to -4.33°.

Table 7 presents the simulation results for the total active and reactive power before and after the insertion of the reactive power compensation system at Selibabi bus (1). A reduction in total power losses was observed, highlighting the effectiveness of the compensation system. As shown in Figure 4, there was a decrease in the total active power loss of the system, from 1.8 MW to 1.5 MW, thereby improving the active power transmission through the lines. These results demonstrate the reactive power compensation system's ability to enhance the voltage at buses and reduce active power losses in the power system.

Similarly, Figure 5 shows a reduction in the total reactive power loss of the system, from 2.5 MVAR to 2 MVAR. This results in lower reactive power losses in the transmission lines. These findings further illustrate the reactive power compensation system's effectiveness in improving voltage at buses and reducing reactive power losses across the power system.

Table 6. Simulation results after injected reactive power at bus 1

Bus N°	Type	Vpu	ϕ°
Selibabi 1	PQ	1	-5.15
M'Bout 2	PQ	0.985	-2.69
Kaedi 3	Slack	1	0
Gouray 4	PQ	0.99	-4.33

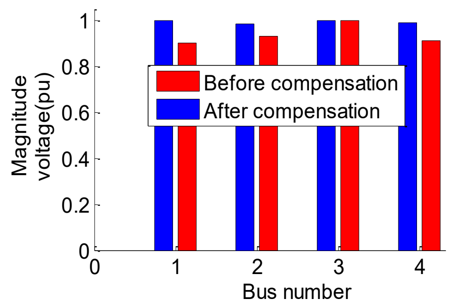

Figure 2. Voltage magnitude curve in per unit (pu)

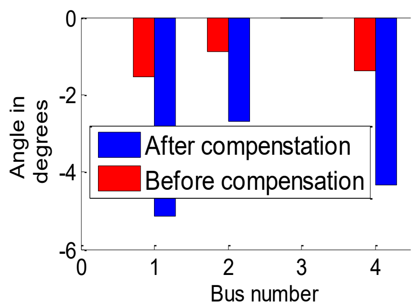

Figure 3. Voltage angle curve in degrees

Table 7. Total active and reactive power losses in the system

Connection state	Active power losses	Reactive power losses
Before compensation	1.8	2.5
After compensation	1.5	2

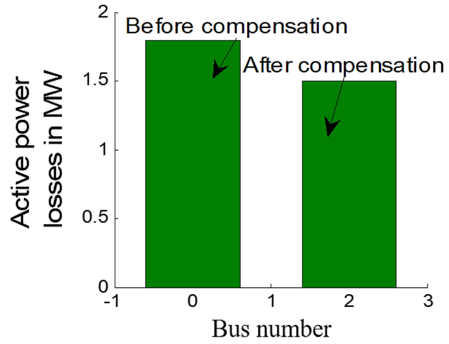

Figure 4. Total active power losses in the system

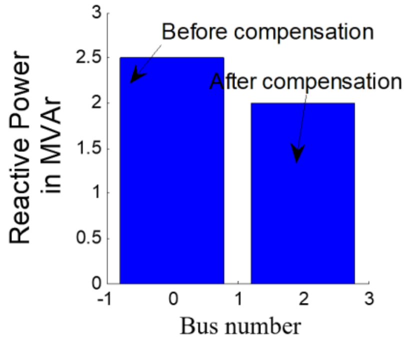

Figure 5. Total reactive power losses in the system

3.3. Model of transformer

To address the load growth of the 33 kV loop by the year 2040, we propose enhancing the capacity of the transformers connected to the various buses in the system. This can be achieved by connecting one or more transformers in parallel with the existing ones. Parallel connection of transformers is used when the load on one transformer exceeds its capacity. By connecting transformers in parallel, we can increase the available power without altering the voltage and distribute the power demand between the two transformers. The reliability of the system is enhanced with parallel operation compared to using a single larger unit [23], [24]. Additionally, the cost of maintaining spares is lower when two transformers are connected in parallel. This setup ensures that at least half of the load can be supplied even if one transformer is out of service. The advantages of parallel transformer operation include meeting load demand, improving reliability, facilitating switching operations, and providing an uninterrupted power supply in case of a unit outage.

The conditions for parallel operation of transformers are [25]-[30]: For parallel connection of transformers, primary windings of the transformers are connected to source bus-bars and secondary windings are connected to the load bus-bars. Several conditions must be met for the successful parallel operation of transformers:
- Both the primary and secondary voltage ratings must be the same (i.e., the same voltage ratio and turns ratio).
- The transformation ratio (k) should be identical.
- The short circuit voltage should be equal to or less than 10%.
- The phase angle shift must be the same (i.e., the vector groups should be the same or compatible).

3.3.1. Model parallel operation of transformers

To share the total load between two connected transformers in parallel, we must know certain key parameters. These include:
- The transformer power T1(MVA1) and their per cent impedance(%Z1)
- The transformer power T2(MVA2) and their per cent impedance(%Z2)
- The total(load) demand power (MVA)

Load sharing by T1 is given by (14), and that by T2 is given by (15).

$$T1 = \frac{\frac{MVA1}{Z1}}{\frac{MVA1}{Z1}+\frac{MVA2}{Z2}} * MVA \quad (14)$$

$$T2 = \frac{\frac{MVA2}{Z2}}{\frac{MVA1}{Z1}+\frac{MVA2}{Z2}} * MVA \quad (15)$$

The (14) and (15) allow us to calculate the power values shared between the connected transformers in parallel at bus 3 (Kaedi) for the year 2040. Note that one of these transformers already exists in the system, with a rating of T1 = 10 MVA. Theoretically, the total load demand (MVA) minus the power of the existing transformer (MVA1) gives the load to be shared by the second transformer (MVA2). To perform this calculation, we analyze two cases: the first is determined by simulating the total load demand of the system in the PSS/E software, and the second uses in (14) and (15) to calculate the shared load between transformers T1 and T2, as shown in Table 8.

Table 8. Simulation and calculation outcomes for the load distribution at bus (3)

Bus	Total load (T) (MVA) in 2045	Existing load (T1) (MVA1) for < 2030	Load shared by (T2) (MVA2) for > 2030	Impedances of T1 and T2		Calculation results MVA		Simulation results MVA	
				%Z1	%Z2	T1	T2	T1	T2
3	41	10	31	8	10	15.25	25.62	20.5	20.5

4. CONCLUSION

In this paper, we examined the state of a 33 kV loop network over two periods. The first period reflects the network parameters (voltages and powers) for the year 2022, where the system is stable and the parameters meet the required standards. In the second period, we projected the demand from 2025 to 2040. The results indicated that the system falls outside the stability constraints. To address the increasing demand, we injected reactive power (via a capacitor bank) at the Selibabi bus (1), which helped maintain the system within the voltage stability margin (0.95 to 1.05 p.u.) and reduced power mismatches. As a result, the system remained stable in terms of both voltage and power at each bus.

In the second case, the existing transformers became overloaded. It was found to be more economical to operate the transformers in parallel, which would accommodate the increased load rather than replacing the transformers. This approach ensured the system remained stable in voltage and power. Additionally, when the load decreased, one of the two transformers could be deactivated, preventing low-efficiency operation at reduced loads

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Ethmane Isselem Arbih Mahmoud	✓	✓	✓		✓	✓			✓					
Ahmed Abbou	✓	✓		✓		✓				✓		✓	✓	
Abdel Kader Mahmoud	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	

C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest in this manuscript.

INFORMED CONSENT

Informed consent has been obtained from all individuals included in this study.

ETHICAL APPROVAL

This research was reviewed and approved by the reviewers of this journal. Ethical approval for this study was obtained through the review process of journal, following its guidelines and policies. This research also was approved by the scientific committee of the Higher Institute of Educational and Technology, Rosso, Mauritania.

DATA AVAILABILITY

The system data used in this study are included within the manuscript and are available in the supplementary materials. The data supporting the findings of this study are provided in Figure 1, Table 1, Table 2, Table 3, and Table 4, respectively. All relevant data are included in the manuscript for review and further reference.

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