Int. j. adv. multidisc. res. stud. 2024; 4(4):926-933

Received: 27-06-2024
Accepted: 07-08-2024

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

Power Flow Analysis of 330 kV Nigerian Transmission Network Using Smell Agent Optimization Technique

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Abstract

The Nigerian 330 kV power transmission network is a crucial component of the nation's power sector, facilitating the efficient transfer of electrical energy across diverse regions. Operating at a voltage level of 330 kilovolts, it addresses the growing energy demands for industrial, commercial, and residential needs. This research explores the design, challenges, and opportunities of the network, emphasizing the need for addressing voltage profile issues, optimizing reactive power support, and enhancing overall resilience. Power flow studies are conducted to understand complex bus voltages, real and reactive power injection, and system behavior during operation. The work formulates the power flow problem as an optimization task, aiming to minimize mismatches between scheduled and calculated values. The traditional power flow equations are presented in polar form, providing a foundation for the subsequent application of the Smell Agent Optimization (SAO) technique. SAO, inspired by olfactory systems, operates in sniffing, trailing, and random modes. It simulates the dispersion of "smell molecules" representing optimal solutions. The algorithm dynamically adjusts agent positions based on the perceived smell strength, contributing to efficient optimization in power flow studies. The power flow analysis of the Nigerian 330 kV network using SAO reveals critical information such as bus voltages, phase angles, and power flows. The results, presented in tables 1 and 2 and figures 4 to 8 demonstrate that SAO effectively maintains voltage magnitudes of all buses within acceptable limits of ±5% (0.95 and 1.05 p. u) with the exception of only three buses and optimizes real and reactive power flows, and minimizes losses. In conclusion, the application of SAO in power flow studies proves effective in ensuring the secure and reliable operation of the Nigerian 330 kV power transmission network. By fine-tuning power flow parameters, SAO contributes to stability, efficiency, and optimal performance. The study emphasizes the importance of advanced optimization techniques in managing complex power systems and achieving a resilient, efficient, and sustainable energy infrastructure.

Keywords: Voltage Profile, Power Flow, Transmission Network Real and Reactive Power

Introduction

Nigerian 330 kV power transmission network stands as a critical infrastructure pillar, facilitating the seamless transfer of electrical energy across the nation. As a key component of the country's power sector, this network plays a pivotal role in meeting the increasing demands for electricity to support industrial, commercial, and residential needs. Characterized by a sophisticated and interconnected system, the 330 kV transmission network spans the diverse geographical landscape of Nigeria, linking power generation sources to distribution centers and ultimately to end-users (Ogbuehi and Madueme, 2015) [11].

Designed to operate at a voltage level of 330 kilovolts, this transmission network is integral to the efficient and reliable transfer of substantial electrical power over long distances. The high voltage is a testament to the network's capability to transmit large quantities of electricity, catering to the growing energy requirements of a nation striving for economic development and technological advancement.

The Nigerian 330 kV power transmission network faces unique challenges and opportunities. Challenges include addressing voltage profile issues in specific regions, optimizing reactive power support, overcoming limitations on power transport, and enhancing overall network resilience. In contrast, opportunities lie in the potential for expansion, technological advancements, and the integration of renewable energy sources, contributing to a more sustainable and robust power infrastructure (Gross and Kuruganti, 2017) [5].

This introduction sets the stage for a deeper exploration of the intricacies of the Nigerian 330 kV power transmission network, delving into its design, operational aspects, challenges, and the strategic initiatives undertaken to ensure a reliable and efficient supply of electricity across the nation.

The primary objective of power flow studies is to ascertain the complex bus voltages, as well as the real and reactive power injected into the transmission system. This analysis also includes the real and reactive power at the slack bus, with other specified parameters. power flow analysis finds application in power network design and planning, offering valuable insights into system behavior during operation. Furthermore, it aids in predicting the loading conditions of transmission lines and equipment within the system. The analysis assumes the system operates under a balanced condition, allowing for a comprehensive study using a balanced single-phase representation (Sen and Sen, 2017) [6].

Materials and Method

Power Flow Problem Formulation

In power flow studies, the principal information obtained is the magnitude and phase angle of the voltage at each bus and the real and reactive power flowing in each line. The starting point in obtaining the data required for the power flow analysis is the single line diagram of the system. Transmission line is represented by their per phase nominal – π equivalent circuits as shown in figure 1 (Akwukwuegbu, *et al*, 2022) [12].

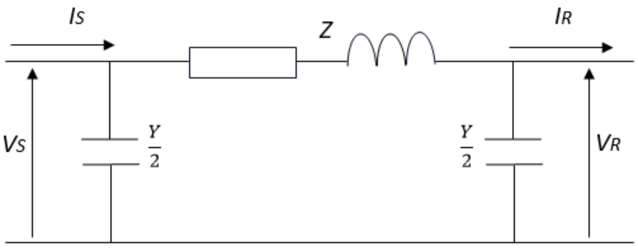

Fig 1: Nominal – π circuit of a medium length transmission line.

For each line the numerical values for the series impedance Z and the total line charging admittance Y are necessary so that we can determine all the elements of the $N \times N$ bus admittance matrix of which the typical element Y_{ij} is given by, (Uppal and Rao 2009) [13].

$$Y_{ij} = |Y_{ij}|\theta_{ij} = |Y_{ij}|\cos\theta_{ij} + j|Y_{ij}|sin\theta_{ij} = G_{ij} + B_{ij} \tag{1}$$

Other essential information includes transformer ratings and impedances, shunt capacitor ratings and transformer tap settings. In advance of each power flow study certain bus voltages and power injections must be given a known values as presented below (Srinivasa and Srinivasa, 2016) [7].

The voltage at a typical bus i of the system is given in polar coordinates by,

$$V_i = |V_i|\delta_i = |V_i|\,(\cos\delta_i + jsin\delta_i) \tag{2}$$

And the voltage at another bus j is similarly written by changing the subscript from i to j. The net current injected into the network at bus i in terms of the elements Y_{in} of Y_{bus} is given by the summation.

$$I_i = Y_{i1}V_1 + Y_{i2}V_2 + \cdots + Y_{iN}V_N = \sum_{n=1}^{N} Y_{in}V_n \tag{3}$$

Let $P_i \, and \, Q_i$ denotes the net real and reactive power entering the network at the bus i. Then the complex power conjugate of the power injected at bus i is

$$P_i - Q_i = V^*{}_i \sum_{i=1}^{N} Y_{in}V_n \tag{4}$$

$$P_i - Q_i = \sum_{i=1}^{N} |Y_{in}V_iV_n|\,(\theta_{ij} + \delta_n - \delta_n) \tag{5}$$

Expanding this equation and equating real and reactive parts, we obtain.

$$P_i = \sum_{i=1}^{N} |Y_{in}V_iV_n|\, cos(\theta_{ij} + \delta_n - \delta_n) \tag{6}$$

$$P_i - Q_i = -\sum_{i=1}^{N} |Y_{in}V_iV_n|\, sin(\theta_{ij} + \delta_n - \delta_n) \tag{7}$$

Equations (6) and (7) constitute the polar form of the power flow equations; they provide calculated values for the net real power *Pi* and reactive power *Qi* entering the network at typical bus *i*. Let *Pgi* denote the scheduled power being generated at bus *i*, and *Pdi* denote the scheduled power demand of the load at that bus.

Then $Pi, sch = Pgi - Pdi$ *is* the net scheduled power being injected into the network at bus *i*, as illustrated in figure 2 (a). Denoting the calculated value of *Pi* by *Pi, cal* leads to the definition of mismatch ΔP_i as the scheduled value *Pi, sch* minus the calculated value *Pi, cal* as shown in figure 2 (b).

$$\Delta P_i = Pi, sch - Pi, cal = (Pgi - Pdi) - Pi, cal \tag{8}$$

Likewise for reactive power at bus i, we have,

$$\Delta Q_i = Qi, sch - Qi, cal = (Qgi - Qdi) - Qi, cal \tag{9}$$

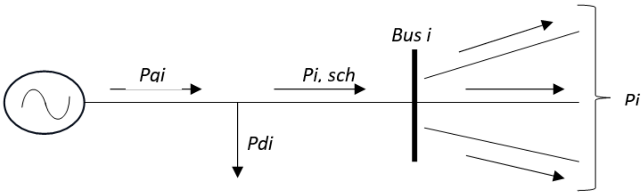

Fig 2: (a) Active power at typical Bus i in power flow studies

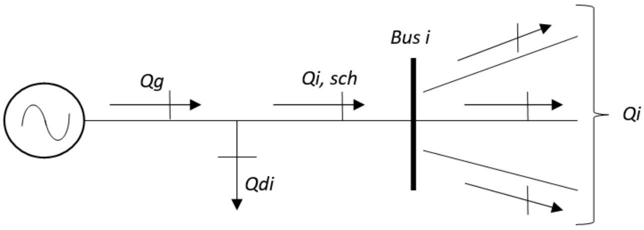

Fig 2: (b) Reactive power at typical bus i in power flow studies

From the above analysis, therefore, power flow problem is formulated as an optimization problem and the objective function is to, (Momoh and Zhu, 2015) [8], (Ezeruigbo *et al*, 2021) [10].

$$\text{Minimize } f = \sum_{k=1}^{N} \Delta P_k{}^2 + \sum_{k=1}^{N} \Delta Q_k{}^2 \tag{10}$$

Smell Agent Optimization

The Smell Agent Optimization (SAO) algorithm has recently emerged as a result of advancements in understanding how olfactory systems learn to detect the source of smells. According to the developers, organisms, including humans, can utilize their well-developed olfactory capacities to perceive smell substances and instinctively trace them back to their origin (Tamimi and Baiyat 2015) [3]. SAO, primarily designed for combinatorial optimization problems, operates through three distinct modes: Sniffing, trailing, and random modes (Okakwu *et al*, 2017) [9].

Sniffing mode – in this mode, an agent demonstrates its ability to detect the presence of a smell in its surroundings. Let q represent the quantity of smell molecules emanating from a source within a specified search space, and let n denote the dimension or size of the search space. Each constituent of these dissipating smell molecules can be allocated a vector position using the methodology described in (Singh and Kumar 2018) [4].

Furthermore, the algorithm simulates the expulsion of smell molecules from a source towards the agent within the search space (Monticelli and Ponci, 2016) [1].

$$X_i{}^t = \left[x_{q,1}{}^t, x_{q,2}{}^t, \dots\dots\dots x_{q,n}{}^t, \right] \tag{11}$$

Smell molecule expel in the browinian form, every smell molecule is designated a velocity using

$$V_i{}^t = \left[v_{q,1}{}^t, v_{q,2}{}^t, \dots\dots\dots v_{q,n}{}^t, \right] \tag{12}$$

Where $i = 1,2,3 \dots\dots\dots n$

The current position and the velocity of the agent which is the updated position of the smell molecule is given by equation (3) and (4) respectively:

$$X_i{}^{t+1} = X_j{}^t + \left[V_j{}^t + r^o \times \sqrt{\frac{3kT}{m}}\right] \tag{13}$$

Where;

$X_i{}^{t+1}$ is the current position of the molecule,

$X_j^{\,t}$ is the previous position of molecule and
r^o is a random number which stochastically guide velocity update.

$$V_i^{\,t+1} = \left[V_j^{\,t} + r^o \times \sqrt{\frac{3kT}{m}}\right] \tag{14}$$

Trailing mode - After the agent sniffs the smell, the agent will identify the source of the smell by following the smell molecules with highest strength through olfaction (olf) (Abido, 2004) [2].

$$olf = \frac{f(x_{agent})}{\sum_{i=1}^{N} \frac{f(x_i)}{N}} \tag{15}$$

Where:
olf is the olfaction capacity (which is the function of the fitness of the agent and the entire sniffing process),
$f(x_{agent})$ is the fitness of the agent,
$f(x_i)$ is the fitness of the individual smell molecules, and
N is number of smell molecules.
The trailing of the agent is modelled as shown in equation 6:

$$X_i^{\,t+1} = X_i^{\,t} + r_1 \times olf \times (X^t{}_{agent} - X^t{}_i) - r_2 \times olf \times (X^t{}_{worst} - X^t{}_i) \tag{16}$$

r_1 and r_2 are random numbers generated at different intervals.

Random Mode - When the agent fails to locate the source of the smell molecule, the agent maybe trapped into local minima leading to its inability to continue trailing, the agent will go into Random mode to look for the smell molecule source. The random mode is described mathematically as in equation (16):

$$X_i^{\,t+1} = X_i^{\,t} + r_3 \times SM \tag{17}$$

Where;
SM is a constant indicating the step movement, and
r_3 is random number which stochastically penalizes the value of the step movement [35-38].

SAO Algorithm Pseudo-code

```
Let N: Number of smell molecules;
D: Search space where the smell molecules evaporate
a.  Initialize SAO parameters ($k\ olf, T, m$)
b.  Randomly initialize smell molecules and its velocity
c.  For each molecule from 1 to N.
      i.   Update molecules velocity and position using equations (13) and (14)
      ii.  Evaluate fitness
      iii. Determine agent position and worst molecules position
      iv.  Evaluate the random mode and its fitness
      v.   If ii is better than iv move to vi else move to d
      vi.  Evaluate the random mode and its fitness.
d.  Repeat step c until maximum iteration is reach
e.  Sort all molecules and determine the smell source.
```

Description of the Study Area

The single line diagram of the 330 kV Nigerian power Transmission network used for this research is shown in Figure 4. The system consists of 25 buses load and controlled buses and 9 Generation Station making a total of 34 buses. Shiroro power station was chosen as slack bus. System data was collected from transmission company of Nigeria based on 2022 and 2023 reports.

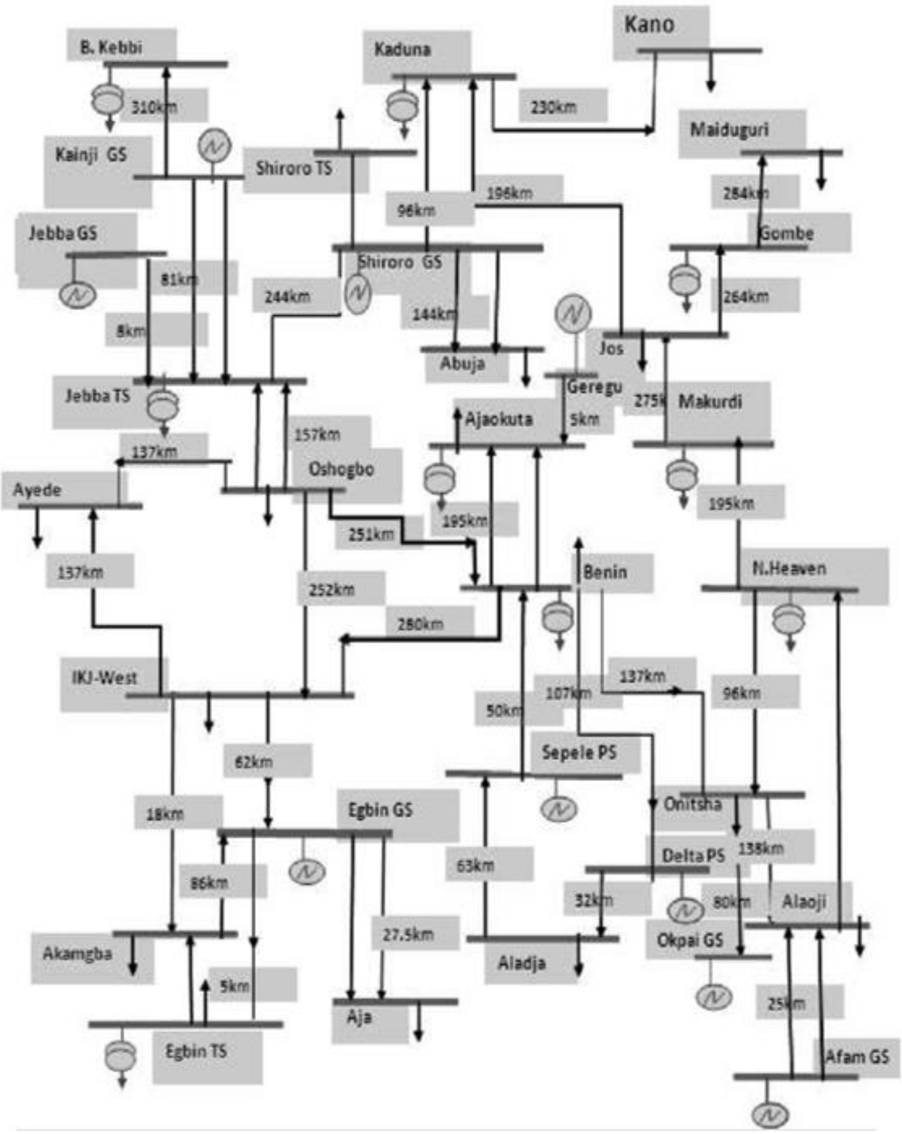

Fig 4: Single Line Diagram of 330 kV Nigerian Transmission Network

Results

In this work, efforts have been made to conduct power flow analysis of Nigerian 330 kV transmission network using smell agent optimization technique. The magnitude and phase angle of the voltage at each bus and the real and reactive power flowing in each line as obtained from the study are presented in tables 1 and 2 and also in figures 4 and 5.

Table 1: Bus Voltage and Phase Angle for 330kV Nigerian Transmission Network

Bus Number	Bus Name	Voltage (p.u)	Angle (Degree)
1	Egbin GS	1.04	0
2	Benin	1.0063	6.919
3	Ikeja West	0.9811	-4.726
4	Akangba	0.9735	-5.4148
5	Sakete	0.9623	-7.167
6	Aiyede	0.9471	-13.67
7	Olorunshogo GS	0.9833	-6.479
8	Omotosho	1.0224	6.816
9	Oshogbo	0.9578	-22.067
10	Gammo	0.9603	-27.63
11	Shiroro GS	0.9750	-55.71
12	Jebba TS	1.0026	-29.55
13	Jebbe GS	1.01	-29.52
14	Birnin Kebbi	1.0302	-29.13
15	Kainji GS	1.02	-26.13
16	Kano	0.976	-76.26
17	Kaduna	0.965	-67.37
18	Jos	0.932	-78.04
19	Gombe	0.981	-87.11

20	Yola	0.9709	-90.17
21	Damaturu	0.951	-89.76
22	Maiduguri	0.904	-90.12
23	Katampe	0.9167	-61.31
24	Ajaokuta	1.019	12.07
25	Geregu GS	1.02	12.1
26	Onitsha	1.003	9.08
27	Alaoji	1.014	12.93
28	New Haven	0.9673	5.233
29	Sapale GS	1.02	9.086
30	Delta GS	1.023	10.25
31	Okpai GS	1.021	10.96
32	Afam GS	1.02	13.73
33	Aja	1.0376	-0.235
34	Aladja	1.047	9.289

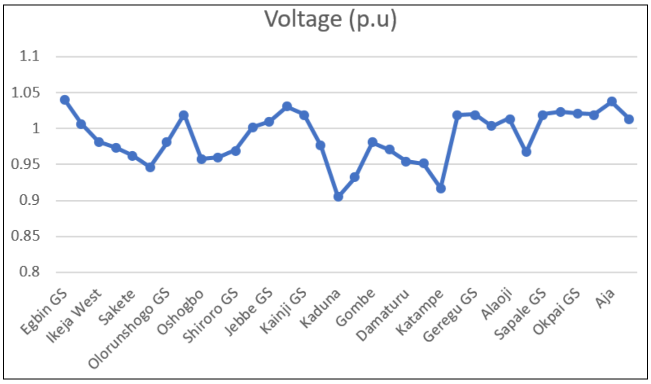

Fig 5: Voltage Profile at each Bus of the System

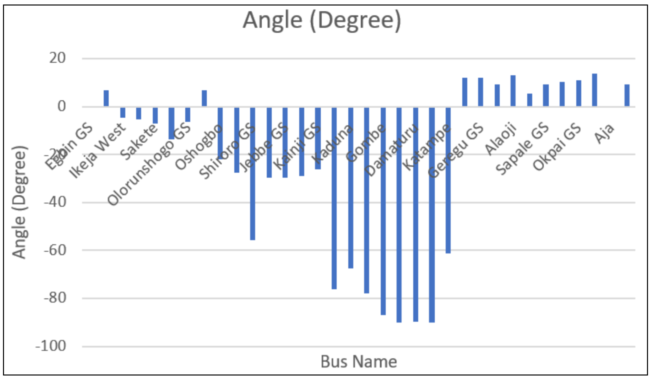

Fig 6: Voltage Phase Angle at each Bus of the System

Table 2: Transmission Line Power flows for the Nigerian 330 kV Network

From	To	Sending End		Receiving End		Line Losses	
		P	Q	P	Q	P	Q
1	3	1154.761	703.67	-999.56	-490.23	15.407	119.790
1	31	229.83	111.238	-219.010	-105.412	0.234	1.062
2	3	518.107	50.073	-504.556	54.144	13.551	104.217
2	8	2.5762	-88.934	-1.319	90.145	0.143	1.211
2	9	599.904	178.23	-592.734	167.236	37.17	315.466
2	22	-310.642	4.659	313.97	23.587	3.328	28.246
2	24	-180.692	26.694	181.5	-19.835	0.808	6.859
2	27	-572.9	-112.86	575.631	136.225	3.041	23.395
2	28	-483.549	-39.526	486.961	68.492	3.412	28.966
3	4	501.876	233.916	-471	-226.469	0.876	7.447
3	5	156.119	67.181	-195	-57.681	1.119	9.5
3	7	290.102	-21.358	-318.953	31.109	1.149	9.751
3	8	-328.292	9.128	336.319	58.995	8.027	68.123
3	9	373.791	42.331	-360.628	69.391	13.163	111.722
6	7	-643.946	-55.042	653.953	139.969	9.007	84.927
6	9	373.946	-45.13	-360.628	69.391	12.163	111.772
9	10	386.215	-37.426	-381.806	74.843	4.409	84.927
9	12	499.58	-204.486	-490.65	280.282	8.93	75.796

10	12	111.806	-177.678	-110.437	189.297	1.369	11.619
11	12	-1118.996	315.278	1181.754	217.385	52.758	532.663
11	17	1264.225	409.975	-1231.995	-136.07	27.27	273.897
11	21	304.771	144.672	-300	-107.986	4.771	36.686
12	13	-489.125	605.857	490	612.571	0.875	6.714
12	15	-503.542	-67.96	507.266	99.579	3.724	31.619
14	15	-112	38.52	112.734	-32.293	0.734	6.227
16	17	-350	-12.757	356.642	69.127	6.642	56.37
17	18	500.313	82.66	-489.284	10.941	11.029	93.601
18	19	298.284	-12.312	-292.757	59.224	5.527	46.912
19	20	112.757	26.852	-112	-20.429	0.757	6.423
19	21	180	24.56	178	12.06	2.04	11.06
21	22	120	30.6	110	10.06	1.02	9.02
22	23	-409.97	-50.208	410	50.436	0.03	0.228
24	25	-162.846	4.085	164.142	6.914	1.296	10.999
24	26	237.347	112.848	-235	-92.932	2.347	19.916
24	29	-418	-108.63	420	124.016	2.022	15.386
25	30	-430.142	-101.253	431	107.852	0.858	6.599
27	32	-15.631	30.191	15.656	-29.979	0.025	0.212
28	32	183.039	35.685	-182.656	-32.434	0.3883	3.251
Total Power Loss						**250.629**	**2137.23**

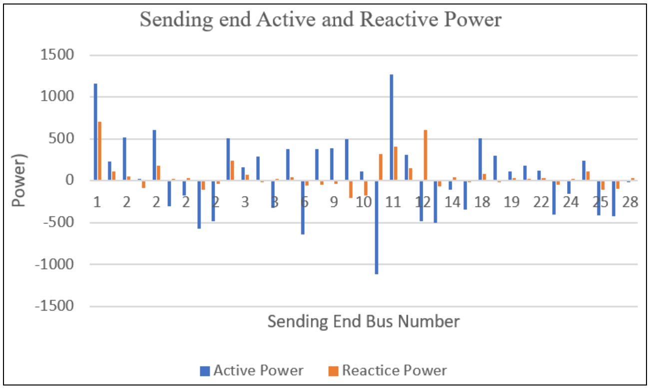

Fig 7: Sending End Active and Reactive Power

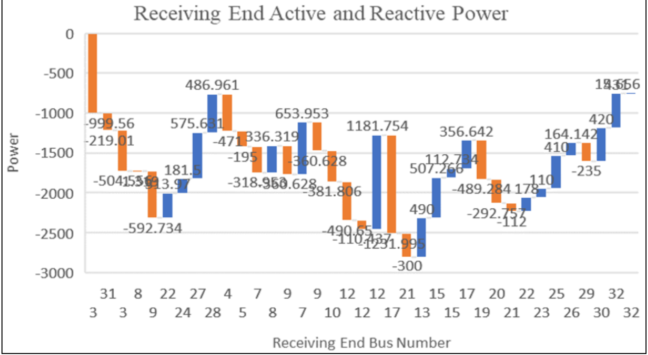

Fig 8: Receiving End Active and Reactive Power

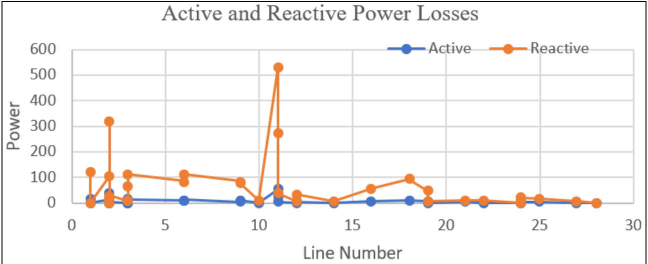

Fig 9: Active and Reactive Power losses along the lines

Discussion

Voltage Magnitude Phase Angle at Each Bus

The power flow study using smell agent optimization technique provides information on the voltage magnitude at each bus in the power system. Voltage magnitudes are crucial as they indicate the electrical potential at different points in the network. The voltage magnitudes for all the buses with the exception of bus 22 have fallen within acceptable limits of ±5%, thus ensuring the stability and reliability of the system as low voltage magnitudes can lead to voltage instability, while excessively high magnitudes can cause equipment damage. The highest voltage magnitude in per unit is 1.047 and the lowest is 0.904. The low voltage magnitude experienced at bus 22 was as a result of the long distance.

The phase angle of the voltage at each bus is another critical parameter. The phase angle represents the timing relationship between the sinusoidal waveforms of voltages at different buses. In this work as presented in the Table 1, the phase angles are within acceptable limits. Large phase angle differences between buses can indicate potential stability issues, and voltage collapse may occur if corrective measures are not taken.

Real and Reactive Power Flow between Lines

The power flow study provides insights into the real (active) power flow between transmission lines. Real power is the actual power consumed or generated in the system. In this research, the real power flows to ensure that power generation matches demand, and the transmission lines can handle the required power transfer. High real power flows can lead to line congestion and potential voltage stability issues.

Reactive power is essential for maintaining voltage levels in the power system. The power flow study revealed that the reactive power flows optimally between lines, indicating the exchange of reactive power between different buses of the system. Proper management of reactive power is crucial for maintaining voltage stability. Excessive reactive power flows can lead to voltage instability, while inadequate reactive power can result in voltage collapse.

Conclusions

In conclusion, the application of Smell Agent Optimization (SAO) technique in power flow studies has proven to be highly effective in ensuring the secure and reliable operation of the power system. Through the optimization process, the voltage magnitudes, phase angles, as well as real and reactive power values have been successfully maintained within the acceptable range. The utilization of SAO not only enhances the stability and efficiency of the power network but also contributes to minimizing losses and ensuring optimal performance.

This innovative approach provides a robust solution for managing complex power systems, addressing voltage stability concerns, and optimizing the utilization of network resources. The achieved results demonstrate the capability of the Smell Agent Optimization technique in fine-tuning power flow parameters, thereby meeting the stringent operational requirements and standards of the power industry.

As we navigate the evolving landscape of power systems, the integration of advanced optimization techniques like SAO becomes increasingly crucial. It not only assists in maintaining a balance between supply and demand but also aids in mitigating potential issues related to voltage deviations and power losses. In essence, the successful implementation of SAO in power flow studies represents a significant stride towards achieving a resilient, efficient, and sustainable energy infrastructure.

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