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Power Transmission Enhancement of the North Central Nigeria 330 kV Network through Optimal Placement and Sizing of TCSC and UPFC Using Whale Optimization Algorithm.

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***Abstract**: Load flow analysis is an important tool used in detecting challenges in a power system network such as voltage instability and losses. In this research, Newton - Raphson method is used on the MATLAB platform for modeling and analysis of the North Central Nigeria 330 kV network consisting of 8 load buses, 4 generating stations and 14 transmission lines. The result of the load flow analysis shows that bus 2 (0.8834) and bus 5 (0.8835) are outside the tolerance level of 0.95 pu to 1.05 pu. The total line losses of the real power and reactive power are 1402.889MW and 723.788MVAr respectively. TCSC and the UPFC devices were introduced to enhance the voltage level and reduce the losses on the network. A line stability index was carried out to obtain the optimal placement. Line 3 (bus 2 to 5) at 1.0104 and line 8 (bus 5 to 7) at 0.6968 have values close to 1.0 making them the most vulnerable branches, thus optimal positions. The best optimal value of objective function found by WOA is $860621.37 for UPFC and $959708.27 for TCSC. The optimal size of the UPFC and the TCSC obtained by WOA is 100KVAr and 10KVAr respectively. The introduction of TCSC and the UPFC indicate that, bus 2 improved from 0.8834 pu to 0.9613 pu by 8.8182% and 0.8834 pu to 1.0000 pu by 13.1990% respectively, while bus 5 improved from 0.8835 pu to 0.9714 pu by 9.9491% and 0.8835 pu to 1.0024 pu by 13.4578% respectively. The average voltage-profile improvement of the network with TCSC is 1.6778% while UPFC is 4.1666%. The real and reactive power losses reduced to 1217.1MW and 714.50MVAr with TCSC and to 1091.4MW and 701.3MVAr with UPFC. With this, it is our recommendation that UPFC be installed on the network to enhance network stability across the buses and lines.*

***Keywords:** Load flow, Newton-Raphson, FACTS Devices, optimization, Line stability index*

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I. Introduction

Reactive power is the power that maintains the voltage to deliver active power on transmission lines. Active power lights up the bulbs in our homes and its stability is regulated by the reactive power such that when the reactive power is high, the voltage drops or fluctuates leaving the current high. This high current leads to constant blackouts in Nigeria. On the contrast, a balanced reactive power results togood efficiency in power systems. In Nigeria however, and on the North Central 330 kV transmission network in particular, a good efficiency is difficult to achieve regardless of increased power generation. The generating stations are far from the transmitting stations leading to line losses. In addition, the Nigerian power system is stressed because of an increasing population that places increasing demands on power supply, lack of maintenance of power infrastructure, inadequate resources, and environmental challenges amongst other factors that affect transmission and distribution networks. This leads to losses in the power system that require compensation. A reactive power compensation technique, like the Flexible Alternating Current Transmission System (FACTS) device, can reduce such losses. FACTS is based on the use of high-speed power electronics to facilitate power control, enhance the capacity to transfer power, improve the system stability and provide security of supply, decrease line losses and generation cost[1]. FACTS uses various electronics-based power controllers to simultaneously regulate power flow, transmission voltages, and mitigate dynamic disturbances[2]. It controls efficiency, flexibility and reliability, hence the most efficient reactive power control method[3]. It uses existing resources, a cost-effective alternative to the construction of new transmission lines. It rather enhances existing transmission infrastructure with minimal investment, time, and environmental impact compared to the traditional upgrading of the line4. FACTS solves the problem of uncontrolled loop-flows and removes congestion by modifying the power flow5. However, this can be effectively achieved by optimal placement and sizing of the devices6.The continualincrease in population increases demand on electrical power for commercial and household uses and ultimately overloads the network beyond thermal stability limits that reduces the stability of the network. Hence, the need to improve the system to ensure continuity of power supply. The North Central 330 kV transmission network is experiencing several power outages and voltage instability. FACTS devices can provide reactive power compensation, transmission capability and voltage stability improvement. With the introduction of FACTS device, improvement in power supply is possible for the North-Central 330 kV power transmission line. However, sizing and optimal placement of these devices for enhanced efficiency remains a challenge.

Several methods used to enhance the performance of transmission lines include installation of new transmission lines, re-conducting transmission cables, replacement of transmission lines and terminal equipment, conversion from single circuits to double circuits, voltage upgrades, phase shifting and reactive power compensation. The reactive power compensation is known to be the most optimal enhancers of transmission lines, which requires simulation for optimal placement[7]. Reactive power compensation, usingespecially FACTS devices, is classified into Series controllers such as SSSC, TCSC, thyristor-controlled series reactor (TCSR), thyristor switched series reactor (TSSR), and Shunt controllers, which include STATCOM, SVC, thyristor-controlled reactor (TCR), thyristor switched reactor (TSR), thyristor switched capacitor (TSC), Combined series-series controllers – these comprise separate series controllers controlled in a coordinated manner like IPFC and Combined series-shunt controllers, which is the combination of separate series and shunt controllers, operated in a coordinated manner like the UPFC[8]. This study, a first of its kind, provides information needed for enhancing the Nigeria North Central 330kV network.

II. Materials and Methods

Materials Used

The materials used for the simulation of the 330kV North Central Nigeria grid system include the following:The single line diagram and network data (line, load and generator) obtained from Transmission Company of Nigeria (TCN) Maitama Abuja, together with MATLAB R2018b.

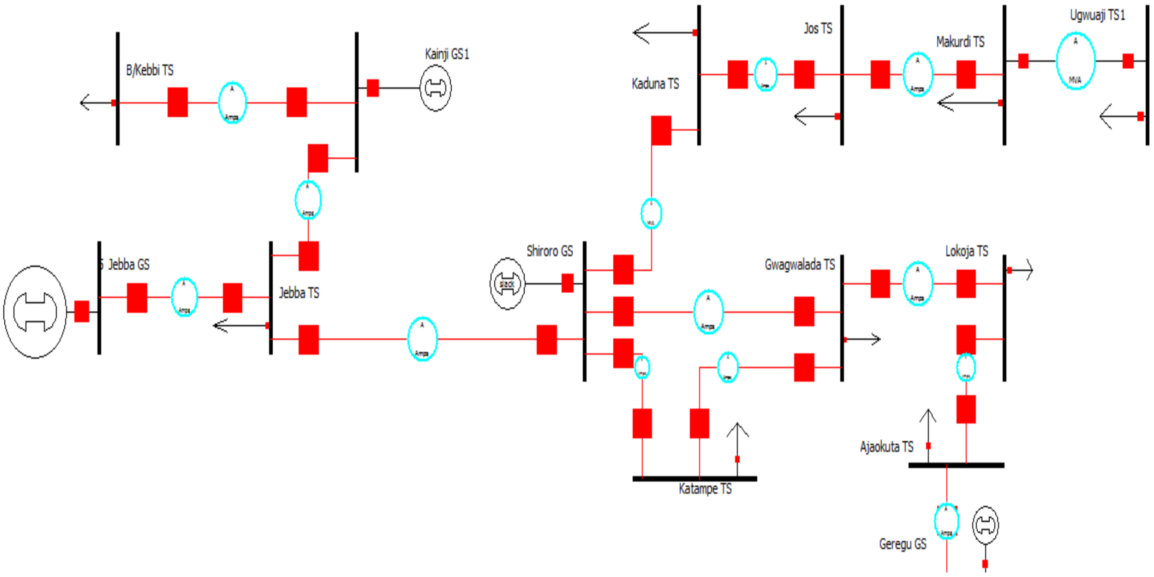

Figure1: Single Line Diagram of the Nigeria North Central 330 kV Grid

Modeling of TCSC

Depending on the firing angles of thyristors, TCSCs can provide both capacitive or inductivecompensations. They are positioned in series with the line and can influence impedance of transmissionline. Thus, a TCSC can modify transmission line power carrying capabilities. The mathematicalmodel of TCSC is presented in Figure 2.

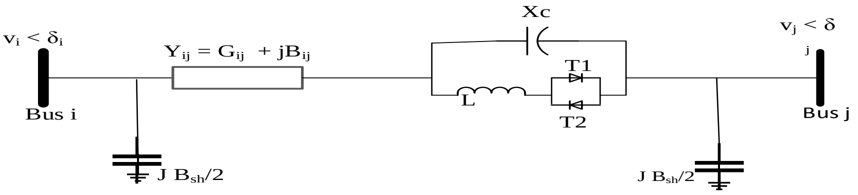

Figure 2: Static Model of TCSC[6]

In the presence of TCSCs, the real and reactive power flow equations from the respective buses can be given in equations 1 and 2 as:

$P_{ij} = V_i^2 G_{ij} - V_i V_j \left(G_{ij} cos\delta_{ij} + B_{ij} sin\delta_{ij}\right)$ 1

$Q_{ij} = -V_i^2 (B_{ij} - B_{sh}) - V_i V_j \left(G_{ij} sin\delta_{ij} + B_{ij} cos\delta_{ij}\right)$ 2

Here V_i and V_j are voltages of sending and receiving end buses, δ_{ij} is bus angle differences between sending and receiving end, T1 and T2 are thyristors and B_{sh} is the shunt admittance of the line.

Modeling of UPFC

The UPFC can change all parameters of power system like angle, impedance and voltage between the buses, thus modifying power flow in transmission lines. UPFCs are connected in series as well as parallel,thereby possessing qualities of both series and parallel compensators. Although, UPFC can control all parameters, but cost constraint limits its applications. If only voltage compensation is necessary, the shunt compensator will be more economicalinstead of UPFC.Similarly, if the control of line impedances is required, then series compensator can be a better choiceinstead of UPFC[6.]

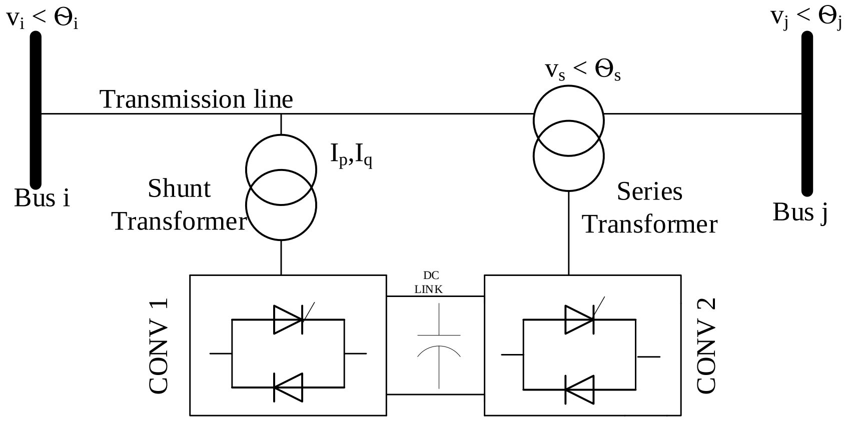

Figure3: Static Model of UPFC[6]

Real and reactive power flows between the buses are controlled through series and shunt transformers. CONV 1 and 2 aretwo, three phase controllable bridges. The active and reactive power flow equations between the respective buses where UPFC are connected is given in equations 3 and 4 as:

$P_j - V_j V_s\left[G_{ij} sin\left(\theta_s - \theta_j\right) - B_{ij}\, cos(\theta_s - \theta_i)\right] = 0$ 3

$Q_j - V_j V_s\left[G_{ij} sin\left(\theta_s - \theta_j\right) - B_{ij}\, cos(\theta_s - \theta_i)\right] = 0$ 4

Optimal placement of TCSC and UPFC

TCSC’s are placed at weak lines, which are determined using Lmn index, Lmn index is a very good indicator, which shows how much the line is close to instability. For a line to be stable, its value must be less than 1 as having the index number close to 1 indicates that the line is critical. The formula for calculating the Lmn is shown in equation (5).

$Lmn = \frac{4XQ_r}{[V_s sin\,(\theta - \delta)]^2}$ 5

where,

X is the reactance of Q_r.Q_r is the VAr demand at receiving bus,V_S is the magnitude of the bus voltage at sending end, θ is the difference in bus angles and δ is the impedance angle.For optimal placement of the UPFC, those lines carrying higher active power are determined, and UPFC are placed at the starting buses of these lines because their voltage magnitude and corresponding phase angles need to be controlled.

Problem Formulation for System Operation Cost and Sizing of FACTS.

Optimal sizing of FACTS devices is determined with an objective to minimize operating cost (OC) of the power system, OC consist of active power loss cost and FACTS device installation cost. The total objective function that needs to be minimized is as follows:

$min[C_{PL} + C_{FACTS}]$

where,

$$C_{PL} = (Active\ Power\ Loss) \times (0.09\$/Kwh) \times 365 \times 24 \qquad 6$$

$$C_{FACTS} = C_{UPFC} + C_{TCSC} \qquad 7$$

$$C_{TCSC} = 0.0015t^2 - 0.7130t + 153.75\left(\frac{\$}{kVAr}\right) \qquad 8$$

$$C_{UPFC} = 0.0003u^2 - 0.2961u + 188.22\left(\frac{\$}{kVAr}\right) \qquad 9$$

Cost function of TCSC and UPFC based on Siemens database are given else where[6,9], where t and u are the sizes of TCSC and UPFC in kVAr respectively.

Constraints that need to be satisfied are as follows;

Bus voltages should be in their appropriate limits as

$$0.95 \le V_j \le 1.05 \qquad 10$$

Thermal limits of transmission lines

$$S_{min} \le S_L \le S_{max} \qquad 11$$

where S_L is the apparent power flowing through the line in Mega Volt Ampere (MVA).

Generator's reactive power supply limits

$$Q_{g,min} \le Q_g \le Q_{g,max} \qquad 12$$

Whale Optimization Algorithm (WOA)

The whale optimization algorithm was first presented by Lewis and Mirjalil in 2016[6]. WOA is stimulated by Humpback–whale special hunting technique called the bubble-net feeding method. A group of humpback-whales encircle the prey in a specific pattern; initially, they create sound and dive deep to push small krills and fishes to the surface while releasing bubbles in circles to make a trap, after this, all whales come up with mouth open and hunt down their prey. The optimization algorithm inspired by this special hunting technique can be mathematically modeled using the following three main steps:

i. Encircling prey
ii. Exploitation phase
iii. Exploration phase

Details of each step and their respective modeling are discussed below. Humpback-whales encircle the prey because they know the location of prey. The position of each humpback whales or search agents is updated according to the current optimal candidate solution. This prey encircling behavior can be expressed mathematically as shown in equation 13 and 14

$$G = \left|K \times X_{B(t)} - X_t\right| \qquad 13$$

$$X(t+1) = X_{B(t)} - A \times G \qquad 14$$

Wheret is the current iteration, $X_{B(t)}$represent position-vector of best-solution at each iteration, G represents absolute value, X_t represents the location of the search agent, and coefficient vectors 'K' and 'A' are defined in equation 15 and 16

$$A = 2a \times r_1 - a \quad 15$$

$$K = 2 \times r_2 \qquad 16$$

As iterations proceed, 'a' is linearly decreased from [2, 0], whereas values of $r_2$and r_1 range from [0, 1].

Humpback-whales hunt their prey by bubble net mechanism. In this technique, bubbles are released around the prey to make a trap, then Humpback-whale moves around the prey in the shrinking circle as well as come up and update its position in the spiral shape. This strategy can be mathematically modeled as follows:

Shrinking-encircling technique

To achieve this, the value of 'a' in Equation (15) is decreased from 2 to 0 as the iteration proceeds. Thus 'A' will have a random value of$[-a, a]$. From Figure 4, it can be seen that different positions are available by moving from $(X^*, Y^*)$to $(X, Y)$by changing values of A.

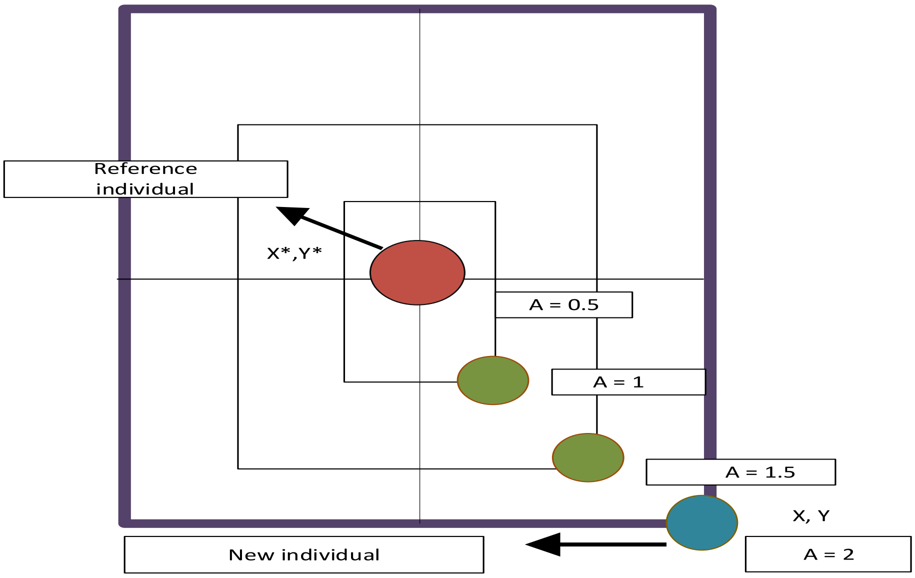

Figure 4: Shrinking-encircling Technique

Spiral-Updating Position Technique

Here the total distance from prey to humpback-whales is determined, and a helix-shape movement equation for search agent is created, which is written as equation 17.

$$X_{(t+1)} = G^* \times e^{bl} \times cos(2\pi l) \times X_{B(t)} \qquad 17$$

where *'l'* ranges from [−1, 1], 'b' is a constant and 'G' represent distance between jth whale and the prey (best-solution) as shown in equation 18.

$$G = \left| X_{B(t)} - X_t \right| \qquad 18$$

There is a 50% probability that the Humpback-whale will follow either shrinking circular or a helix-shaped movement as it moves around its prey. Thus, its total swim around the prey during its hunt down can be mathematically modeled as in equation 19.

$$X_{(t+1)} = \begin{cases} X_{B_{(t)}} - A \times G & if\ P < 0.5 \\ G^* \times e^{bl} \times cos(2\pi l) \times X_{B_{(t)}} & if\ P \geq 0.5 \end{cases} \qquad 19$$

'P' represents a random value ranging from [0, 1].

Searching for Prey (Exploration-Phase)

In order to provide a global search, the search-agent or Humpback-whale explores the best-solution and updates its position based on another randomly selected search-agent. This behavior can be mathematically expressed as in equation 20 and 21

$$G = |KX_r - X| \qquad 20$$

$$X(t+1) = X_r - A \times G \qquad 21$$

This makes WOA a global search optimization algorithm. $X_r$representsthe position vector of randomly selected search agent/whale.

In Summary, the WOA starts with random particle havingrespective fitness function values. As the iteration proceeds, each humpback-whale/search-agent upgrades its position in two different ways, either with regards to randomly selected particle or overall best particle present. A random particle is chosen when the magnitude of A>1, while the best particle/solution is selected when the magnitude of A< 1. To switch between different phases (exploration or exploitation), values of parameter 'a', which ranges from [2, 0], are varied. Finally,WOA comes to an end.

Finding optimal sizes of multiple FACTS devices (TCSC and UPFC) as well as settings of power system components (transformers and generators) by the WOA, fixing dimensions of search-agent/whale are major decisions.

Whale Optimization Algorithm Steps

i. Initialize population for n search agent.
ii. Calculate the fitness value for each search agent.

```
iii.   Choose best search agent.
iv.    While $(t < MaxT)$do
v.     Update a, A, K,$l$ and P for each search agent.
vi.    If $(P < 0.5)$thenselect random agent and
vii.   If $(|A| > 1)$then update position
           $X(t+1) = X_{rand}(t) - A.G$
viii.  Else if$(|A| < 1)$ – update position of agent.
           $X(t+1) = \begin{cases} X_{B_{(t)}} - A \times G & if\ P < 0.5 \\ G^* \times e^{bt} \times cos(2\pi l) \times X_{B_{(t)}} & if\ P \geq 0.5 \end{cases}$
ix.    Else if $(P >= 0.5)$ Update position of the agent.
x.     Calculate fitness value for each search agent
xi.    Update optimal solution.
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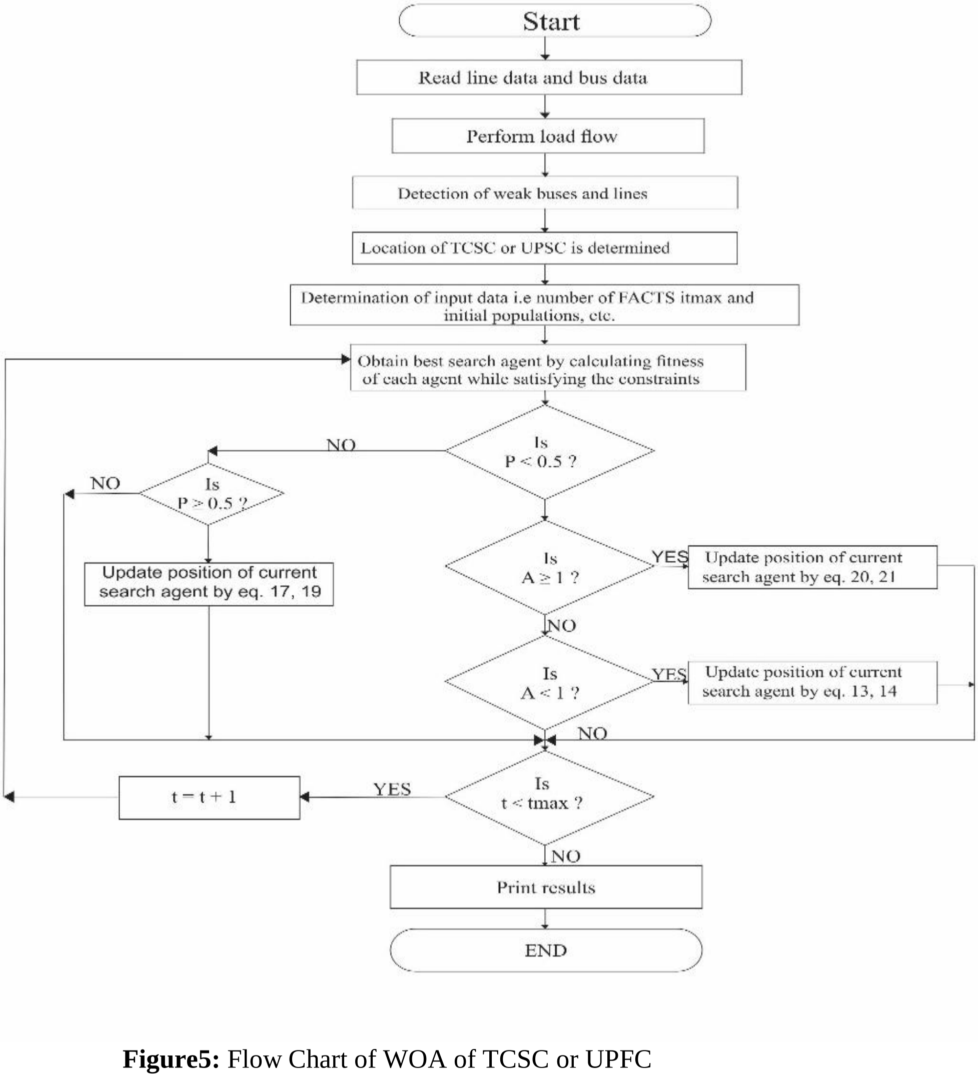

Figure5: Flow Chart of WOA of TCSC or UPFC

III. Result

The Simulation of the Nigerian 330kV North Central network on MATLAB software using Newton Raphson load flow method revealed the steady state solution of the network. After the simulation, some buses violated the voltage profile range limit of 0.95pu – 1.05pu, above and below which instability and or weakness exists. The Whale Optimization Algorithm and line stability index was employed afterwards to find an ideal optimal size and location for the UPFC and TCSC devices. The TCSC or UPFC Device Placement on the Network is shown in Figure 6.

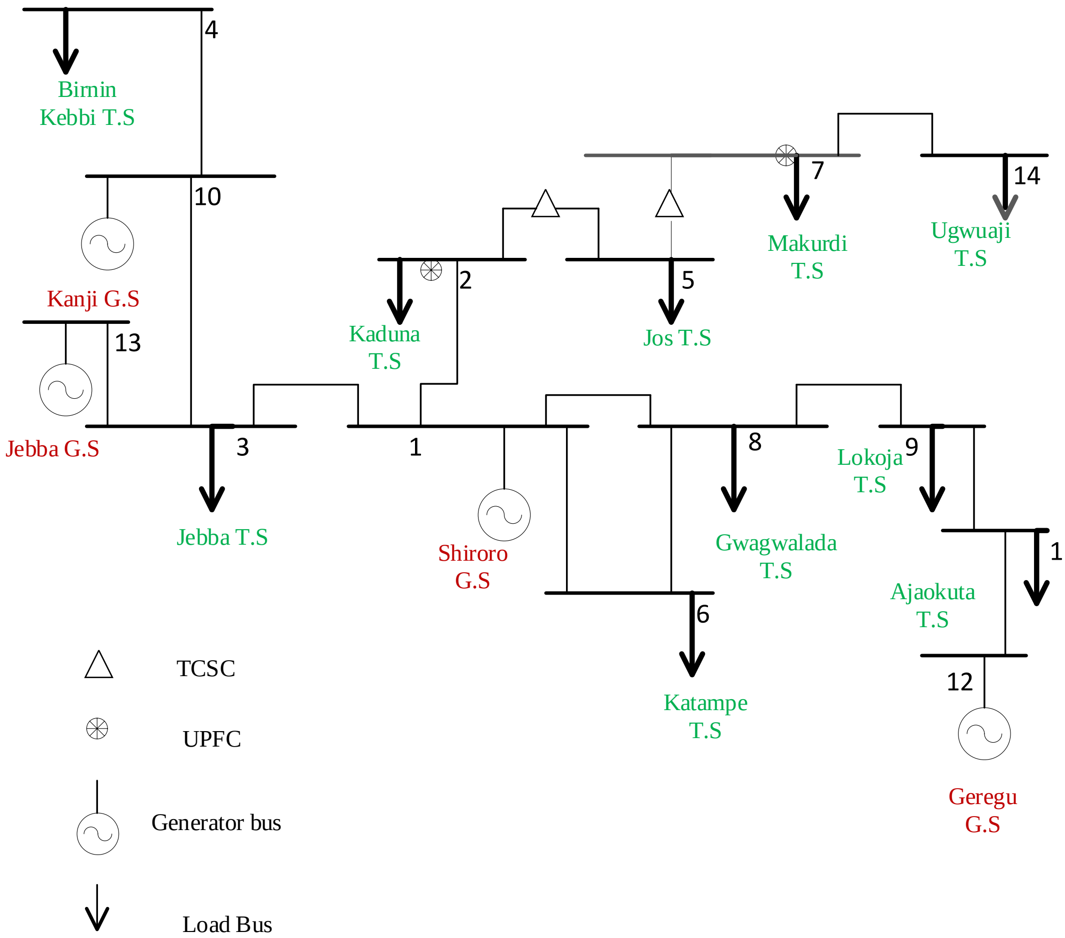

Figure6: TCSC or UPFC Device Placement on the Network

Table 1: Load Flow Analysis

Bus No	Voltage (pu)	Angle in Degree	Injection		Generation		Load	
			MW	MVAr	MW	MVAr	MW	MVAr
1	1.000	0.0000	933.00	247.02	933.80	247.02	0.00	0.00
2	0.8834	-16.7190	-275.00	-133.00	-0.00	0.00	275.00	133.00
3	1.0001	10.7785	-412.00	-199.00	-0.00	0.00	412.00	199.00
4	1.0335	8.7355	-112.00	-114.00	-0.00	0.00	112.00	114.00
5	0.8835	-44.0475	-489.00	-23.00	0.00	0.00	489.00	23.00
6	0.9753	-4.6571	-300.00	-127.00	0.00	0.00	300.00	127.00
7	0.9601	-49.3848	-50.00	-45.00	0.00	0.00	50.00	45.00
8	0.9838	-2.8803	-64.00	-45.00	0.00	0.00	60.00	45.00
9	0.9887	-0.0858	-95.00	-70.00	0.00	-0.00	95.00	70.00
10	1.0400	14.4398	400.00	-17.61	400.00	-17.61	0.00	0.00
11	0.994	1.4173	-96.00	-46.00	-0.00	-0.00	96.00	46.00
12	1.0000	1.5027	300.00	82.99	300.00	82.99	0.00	0.00
13	1.0000	11.2714	380.00	-53.73	380.00	-53.78	0.00	0.00
14	0.9580	-50.4247	-35.00	-50.00	0.00	0.00	35.00	50.00
Total			85.798	-593.303	2013.798	258.697	1928.000	852.000

Table2: Line Flow and Losses

From Bus	To Bus	P (MW)	Q (MVAr)	From Bus	To Bus	P (MW)	Q (MVAr)	Line losses	
								P (MW)	Q (MVAr)
1	2	956.86	419.12	2	1	-856.73	-120.71	100.07	298.41
1	8	26.56	26.56	8	1	-65.63	-19.91	120.13	6.65
2	5	668.27	74.25	5	2	-518.11	214.18	150.16	288.43
3	1	344.17	-5.76	1	3	-153.31	52.69	190.86	46.93

3	10	-253.16	-120.16	10	3	319.95	143.35	66.79	23.40
3	13	-376.26	53.66	13	3	383.31	-50.39	7.05	3.27
4	10	13.75	11.75	10	4	240.65	-0.59	254.40	11.19
5	7	174.52	-91.77	7	5	108.11	192.56	192.56	16.34
6	1	-46.94	-17.18	1	6	224.51	28.61	177.57	11.43
6	8	-167.16	-23.93	8	6	167.92	29.36	60.76	5.43
7	14	85.50	0.43	14	7	15.20	0.20	100.70	0.64
8	9	-107.42	-23.93	9	8	108.33	0.84	0.91	5.25
9	11	-183.95	-51.46	11	9	223.60	57.39	39.65	5.93
12	11	300.62	83.61	11	12	-299.33	-83.12	1.29	0.49
Total Loss								1402.889	723.788

It can be deduced from Table 1 that buses 2 and 5 are outside the tolerance level of 0.95 pu to 1.05 pu. Bus 2 has the voltage profile of 0.8834 pu while bus 5 has 0.8835 pu. The steady state solution of the system shows that there is need for a source of compensation. This study used TCSC and UPFC as reactive power compensation sources. A summary of the network line flow and losses associated with the network before compensation shown in Table 2 details the total line losses of the real and reactive power as 1402.889MW and 723.788MVAr respectively. Bus1 to 2 have the highest line power flow of 956.86MW and 419.12MVAr.

Table 3: Line Stability Index

Line No.	From Bus	To Bus	Lmn
1	1	2	0.2190
2	1	8	0.0511
3	2	5	1.0164
4	3	1	0.2429
5	3	10	0.2197
6	3	13	0.0071
7	4	10	0.0031
8	5	7	0.6968
9	6	1	0.1153
10	6	8	0.0347
11	7	14	0.0007
12	8	9	0.0024
13	9	11	0.0489
14	12	11	0.0026

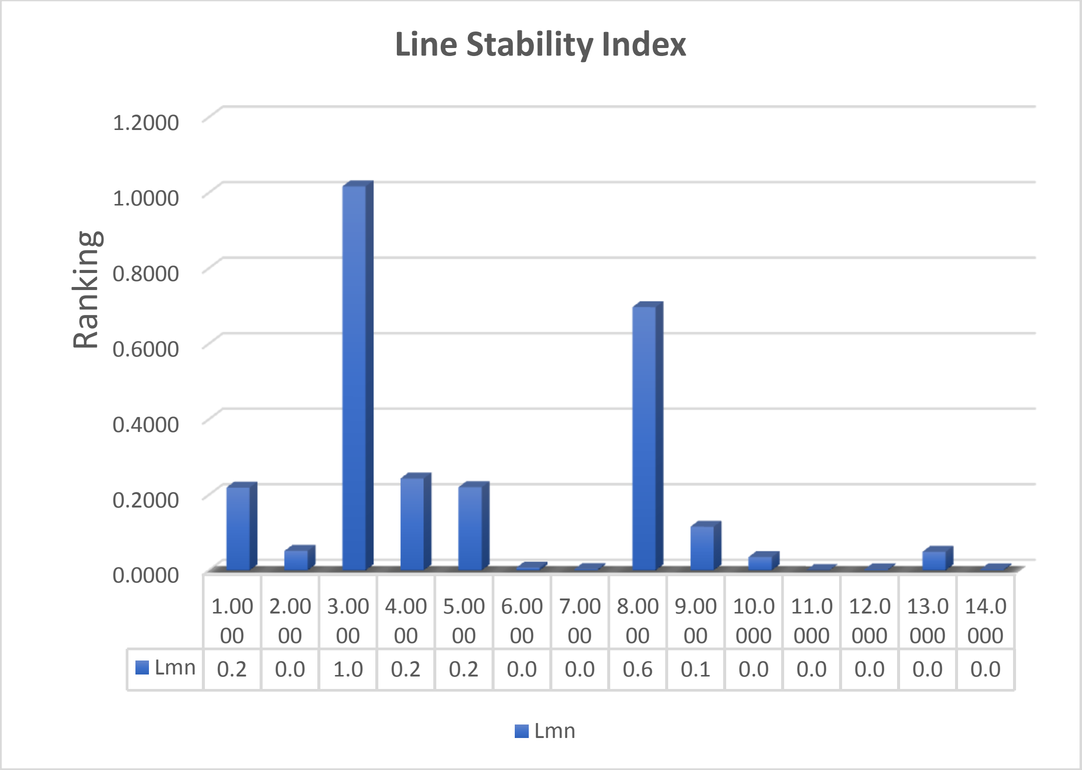

Figure 7: Line Stability Index

The line stability index of the network calculated to determine the most critical line is shown in Table 3. For a line or branch to be stable, its value must be less than 1. Line 3 (bus 2 to 5) with a value of 1.0164 and line 8 (bus 5 to 7) with 0.6968 are the most vulnerable branches since their values are close to or above 1.0. Critical lines for the placement of the FACTS devices in this case, are lines 3 and 8. The graphical representation of line stability index in Figure 7 shows that bus 3 has a value greater than 1.0 and thus highly vulnerable to system collapse. To appreciate the challenges of under voltage and losses recorded in the network, there is need for reactive power compensation preferably using UPFC to improve the voltage profile of the network and reduce losses.

Table 4: Voltage Profile of the Buses for Base Case, TCSC and UPFC

Bus No.	Voltage Profile (pu)		
	Base Case	With TCSC	With UPFC
1	1.0000	1.0000	1.0000
2	0.8834	0.9613	1.0000
3	1.0001	1.0002	1.0455
4	1.0335	1.0340	1.0437
5	0.8835	0.9714	1.0024
6	0.9753	0.9815	1.0134
7	0.9601	0.9640	1.0000
8	0.9838	0.9913	1.0268
9	0.9887	0.9916	1.0325
10	1.0400	1.0410	1.0500
11	0.9994	1.0100	1.0491
12	1.0000	1.0000	1.0000
13	1.0000	1.0000	1.0000
14	0.9580	0.9715	0.9901

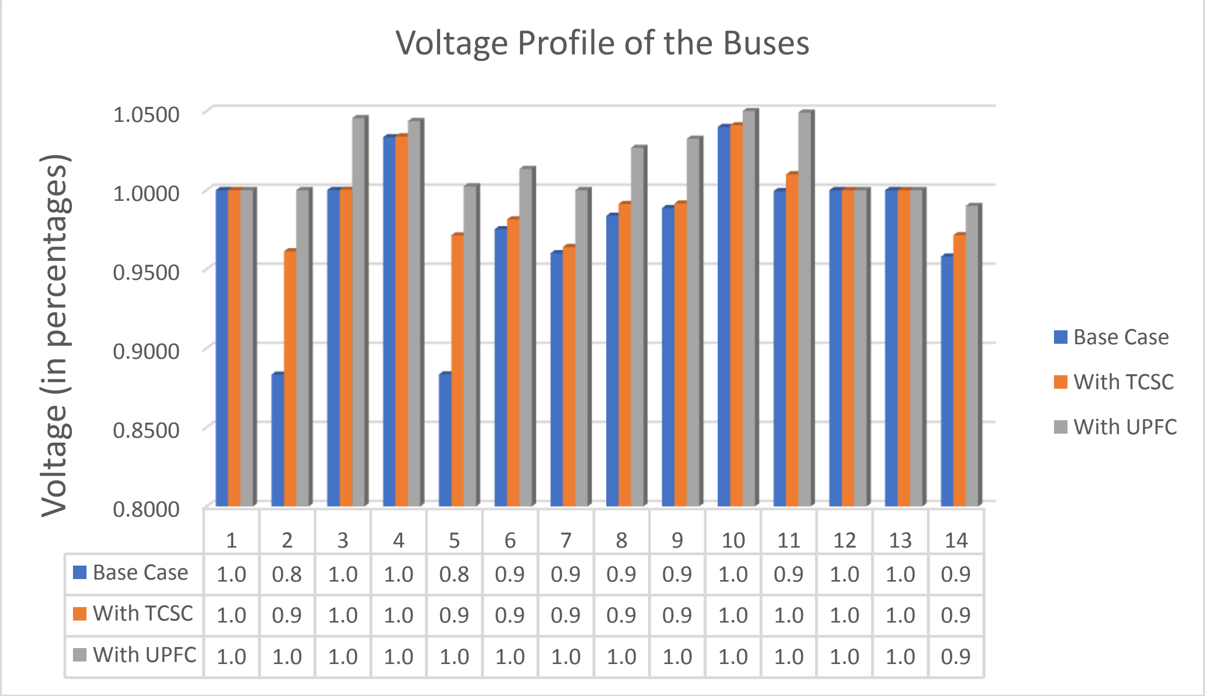

Figure 8: Voltage Profile of the Buses with and without Compensation

Table 4 shows the comparison of the voltage level before compensation of the network. The base case study shows under voltage in bus 2 and 5. After compensation, there is an improvement on bus 2 and 5. Improvements on bus 2 achieved 8.8182% and 13.1990% while bus 5 is 9.9491% and 13.4578% using TCSC and UPFC respectively. UPFC gives a better voltage profile improvement. On the average, the voltage profile improvement of the network with TCSC is 1.6778% while UPFC is 4.1666% (Figure 8). UPFC has a remarkable enhancement than TCSC, as is evidencedwith the voltage increase in percentage after compensation.

Table 5: System Loses for Base Case, with TCSC and UPFC

	Losses		
	Base Case	With TCSC	With UPFC
P	1402.889	1217.1	1091.4
Q	723.788	714.4999	701.3198

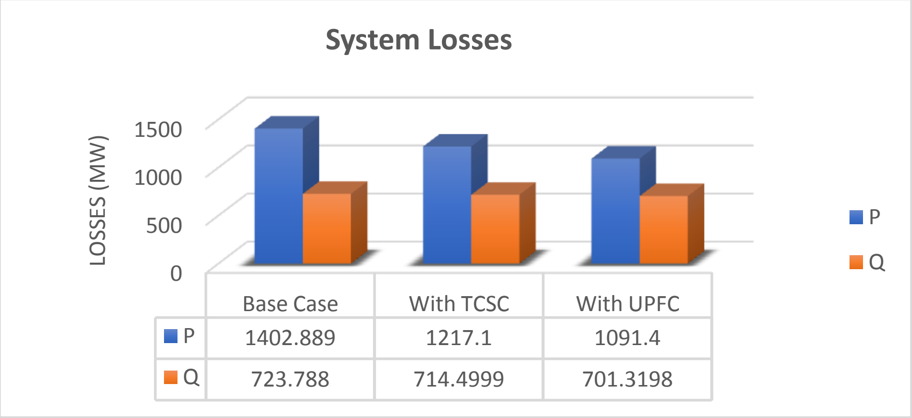

Figure 9: System Losses with and without Compensation

Table 5 displays system losses before and after compensation. For the base case, real and reactive power losses are recorded as 1402.889MW and 723.788MVAr respectively. After compensation, for TCSC and UPFC an improvement was recorded. The real and reactive power losses reduced to 1217.1MW and 714.50MVAr, and to 1091.4MW and 701.3MVAr with TCSC and UPFC respectively as shown in Figure 9. The Figure shows a reasonable reduction recorded by the network after applying a source of compensation to the network. With UPFC, there is significant improvement in loss minimization percentages as compared to TCSC. With TCSC, the real power (P) losses reduced by 13.2433% and the reactive power (Q) losses by 1.2833 % while with UPFC, P losses reduced by 22.2034% and Q by 3.1043%.

Table 6: Optimal Operating Cost and Size of the Power System with FACTS Devices

FACTS Devices	Cost ($)	Size (kVAr)
TCSC	959708.275	10
UPFC	860621.37	100

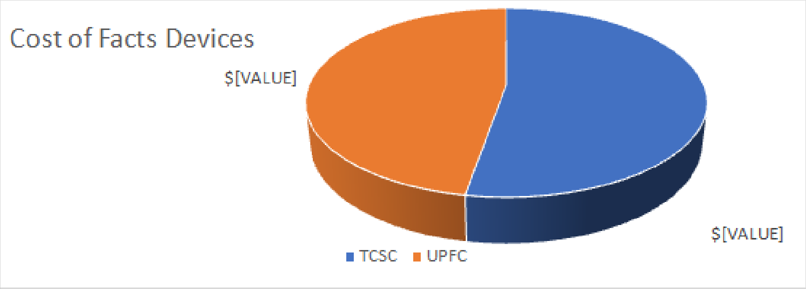

Figure 10: Cost of FACTS Devices

The objective function which is the cost function determines the size of the FACTS device to be used in the network. TCSC cost $959708.275 while UPFC cost $86062.37. The operating cost compose of active power loss cost and FACTS device installation cost. The cost of installing TCSC is higher than UPFC as shown in Table 6 and Figure 10. Therefore, UPFC with a minimum cost of $86062.37 is preferable. The optimal size of UPFC and TCSC device by WOA in MVAr is 100 and 10 respectively.

IV. Conclusion

This study is aimed at enhancing the power transmission of the Nigeria North Central 330 kV network consisting of 8 load buses, 4 generating stations and 14 transmission lines using TCSC and UPFC. Newton Raphson iteration technique is used to carry out the analysis, because of its fast convergence nature compared to other iterative techniques. The data used for this work is obtained from Transmission company of Nigeria (TCN). Simulations were carried out using MATLAB 18b software. It can be concluded that the objectives of the research work based on performance evaluation of load flow analysis of the power network using Newton

Raphson power flow solution, optimal sizing and placement of FACTS devices on the network using line stability index and whale optimization algorithm were achieved.This study recommends the optimal sizing and placement of UPFC device on the Nigerian North Central 330kV network for a more controllable, flexible and efficient network enhancement, using line stability index and whale optimization algorithm for optimal results. Comparison of different metaheuristic techniques may be considered in future to improve this study.

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