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Optimal Location and Sizing of Thyristor Controlled Series Compensation on Nigerian Longitudinal Transmission System Using Dragonfly Algorithm

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ABSTRACT

Enhancement of longitudinal transmission system through voltage profile and line flow control is achievable through Thyristor Controlled Series Compensator (TCSC) incorporation in power systems. The use of an existing method such as arbitrary placement of TCSC was found to be ineffective for these purposes compared to the optimal placement approach. Power flow equations of the power system were linearized with the use of the Newton-Raphson (NR) iterative technique at the steady state. Dragonfly Algorithm (DA) was adopted for optimal placement of the TCSC and simulated in MATLAB R2018b environment. The DA was implemented on the Nigerian 28-bus power system for normal loading and at 25% overload. The voltage profile deviations of buses 9, 16, and 22 that were more than ±5% were controlled to fall within the acceptable ranges and the heavily loaded transmission lines were redirected. The optimized placement of TCSC gave a better result when compared with the conventional TCSC placement.

INTRODUCTION

Power system networks have continued to expand significantly due to the continuous rise in energy demand. This has reduced the efficiency of existing power transmission networks as more power is now being transmitted through them which resulted in instability in system voltage, inadequate power quality, reliability problems, and voltage profile deviation (Ahmad and Sirjani, 2018). Construction of new transmission networks and utilization of traditional devices such as tap changing transformers, and series capacitors, among others, have been used to solve these problems but the high cost of equipment expansion, slow response, and inefficiency in handling high power transmission networks are the banes of these solution methods (Tijani *et al*, 2018; Nguyen and Mohammadi, 2020).

Flexible Alternating Current Transmission System (FACTS) devices are known as useful alternative solutions to most of the transmission system problems. The FACTS technology has been employed for the reduction of power loss, regulation of voltages, planning of reactive power, management of congestion, control of power flow, and quality improvement. Popular FACTS devices include Thyristor- Controlled Series Capacitor (TCSC), Static Synchronous Series Compensator (SSSC), Static Var Compensator (SVC), Unified Power Flow Controller (UPFC), and Static Synchronous Compensator (STATCOM) (Khan *et al*, 2021).

TCSC is an effective device used to enhance the performance of power transmission networks. It was developed by merging a conventional series capacitor with power electronic technology. It has the intelligence to increase or decrease transfer capability for power flow, existing transmission network maximization, and system net loss reduction (Adepoju and Tijani, 2014). To maximize the many advantages of a TCSC device on a power transmission network, it is imperative to optimize the numbers, positions, and settings of this device. The determination of the most desirable position and its settings in the transmission network is highly complex because of the non-linearity in the power flow equations.

Optimal placement and settings of TCSC have been carried out using many approaches. Some of these approaches include conventional optimization methods like analytic approach and arithmetic programming methods. The other method is meta-heuristic optimization techniques that include Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC), and Dragonfly Algorithm (DA) (Vanishree and Ramesh, 2018). Dragonfly Algorithm (DA) is an effective approach applied to many real-time optimization problems because it attains optimum solutions in a shorter time and produces near-global optimal solutions. This algorithm is grounded on the imitation of the swamped performance of dragonflies. Dragonflies stream only for hunting and migration. These two characteristics make it easy to attain global optimal solutions with relative ease (Rejula and Stephen, 2019).

Like many longitudinal transmission grids, transmission grids in Nigeria are characterized by voltage profile deviation and line flow violations (Adepoju *et al*, 2017). Combating these system transmission problems is still based on traditional conventional devices (mechanical switching, tap changers, reactors, and inductors) and the construction of more generation stations and lines (Tijani *et al*, 2018; Nwohu *et a*l, 2016). Adebayo *et al* (2013) presented the application of TCSC for power flow analysis and voltage control of a Nigerian 330kV system using the conventional method. Nwohu et al (2016) deployed a Genetic Algorithm (GA) optimization algorithm for placing TCSC on the Nigerian 330kV grid. The aim was to control the system's power flow, improve its voltage profile, and reduce its overall loss. Ajenikoko *et al*, (2017) carried out a comparative performance evaluation analysis of Static VAR Compensator (SVC) and TCSC for transmission loss reduction of the Nigerian 330kV network using a self-adaptive firefly algorithm. Nkan *et al* (2021) deployed TCSC to maintain the voltage profile and reduce the loss on the Nigerian 48-bus 330kV system. Abubakar *et al* (2021) presented the application of DA for optimal sizing and siting of Static Synchronous Compensator (STATCOM) to enhance voltage stability in Nigerian power systems.

The FACTS devices are still under-utilized to solve voltage and power flow control problems on the Nigerian power networks (Tijani *et al*, 2018; Adepoju and Tijani, 2014). This paper, therefore, aimed at improving the present Nigerian transmission system by optimally locating and sizing TCSC devices for voltage profile and line power flow enhancement on the 28-bus system using the Dragonfly Algorithm.

METHODOLOGY

Steady State Power Flow Analysis

The power flow solution provides nodal voltage and phase angles and hence, power flow through interconnected power transmission lines. Newton-Raphson (NR) power flow analysis is carried out to find out the initial operating condition of the system and to solve the resulting power flow analysis problem of electrical transmission systems. The NR technique is faster with convergence guaranteed (Sekhar and Devi, 2016). The NR method starts by assuming the initial for all unknown variables (voltage magnitude and angles at Load Buses and voltage angles at Generator Buses). A Taylor Series, ignoring higher order terms, is then written for every power balance equation contained in the system of equations. This results in a linear system of equations expressed in equation (1) (Adepoju *et al*, 2013):

$$\begin{bmatrix} \Delta\theta \\ \Delta|V| \end{bmatrix} = -J^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{1}$$

where ΔP and ΔQ are referred to as mismatch

$$\Delta P_i = P_i + \sum_{k=1}^{N} |V_i||V_k|(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}) \tag{2}$$

$$\Delta Q_i = Q_i + \sum_{k=1}^{N} |V_i||V_k|(G_{ik}\cos\theta_{ik} - B_{ik}\sin\theta_{ik}) \tag{3}$$

and J = matrix of partial derivatives known as a Jacobian:

$$J = \begin{bmatrix} \dfrac{\partial \Delta P}{\partial \theta} & \dfrac{\partial \Delta P}{\partial |V|} \\ \dfrac{\partial \Delta Q}{\partial \theta} & \dfrac{\partial \Delta Q}{\partial |V|} \end{bmatrix} \tag{4}$$

The linearized system of equations is resolved to decide the next guess (m + 1) of voltage magnitude and angles based on:

$$\theta^{m+1} = \theta^m + \Delta\theta \tag{5}$$

$$|V|^{m+1} = |V|^m + \Delta|V| \tag{6}$$

This process is continued till a stopping criterion is met. A common stopping criterion is terminated if the norm of the mismatch equations is below a specified tolerance.

TCSC with Newton-Raphson Load Flow

The TCSC controller firing angle representation was executed in Newton–Raphson (NR) power flow algorithm to develop a new set of equations. However, the use of TCSC in the NR load flow requires several alterations in the usual power flow algorithm. The representation of the TCSC firing angle for its incorporation in the power flow algorithm is derived from its equivalent circuit in Figure 1.

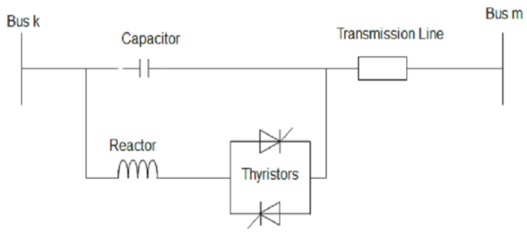

Figure 1: Diagram of TCSC between bus two buses (Adebayo *et al*, 2013)

Active and reactive power equations for TCSC at node k are given in the equation:

$$P_k = V_k \sum_{\substack{i=1 \\ i\neq k \\ i\neq m}}^{N} (G_{ki}\cos\partial_{ki} + B_{ki}\sin\partial_{ki})V_i - V_k^2 \sum_{\substack{j=1 \\ j\neq m}} (G_{kj} - P_{km}) \tag{7}$$

$$Q_k = V_k \sum_{\substack{i=1 \\ i\neq k \\ i\neq m}}^{N} (G_{ki}\sin\partial_{ki} + B_{ki}\cos\partial_{ki})V_i - V_k^2 \sum_{\substack{j=1 \\ j\neq m}} (G_{kj} - Q_{km}) \tag{8}$$

Linearized power equations concerning the firing angle of TCSC are given in equations (9) and (10). The TCSC firing angle representation for linearized NR power flow is given in equation (11).

$$\frac{\partial P_k}{\partial \alpha} = -\frac{\partial P_{km}}{\partial \alpha} = -V_k^2 \frac{\partial}{\partial \alpha} G_{km} + V_k V_m (\cos\partial_{km} \frac{\partial}{\partial \alpha} G_{km} + \sin\partial_{km} \frac{\partial}{\partial \alpha} B_{km}) \tag{9}$$

$$\frac{\partial Q_k}{\partial \alpha} = -\frac{\partial Q_{km}}{\partial \alpha} = -V_k^2 \frac{\partial}{\partial \alpha} B_{km} + V_k V_m (\cos\partial_{km} \frac{\partial}{\partial \alpha} G_{km} - \sin\partial_{km} \frac{\partial}{\partial \alpha} B_{km}) \tag{10}$$

$$\begin{bmatrix} \Delta P_k \\ \Delta P_m \\ \Delta Q_k \\ \Delta Q_m \\ \Delta P_{km} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial \delta_k} & \frac{\partial P_k}{\partial \delta_m} & \frac{\Delta P_k}{\partial V_k} V_k & \frac{\Delta P_k}{\partial V_m} V_m & \frac{\partial P_k}{\partial X_{TCSC}} X_{TCSC} \\ \frac{\Delta P_m}{\partial \delta_k} & \frac{\Delta P_m}{\partial \delta_m} & \frac{\Delta Pm}{\partial V_k} V_k & \frac{\Delta P_m}{\partial V_m} V_m & \frac{\partial P_m}{\partial X_{TCSC}} X_{TCSC} \\ \frac{\partial Q_k}{\partial \delta_k} & \frac{\Delta Q_k}{\partial \delta_m} & \frac{\Delta Q_k}{\partial V_k} V_k & \frac{\Delta Q_k}{\partial V_m} V_m & \frac{\partial Q_k}{\partial X_{TCSC}} X_{TCSC} \\ \frac{\Delta Q_m}{\partial \delta_k} & \frac{\Delta Q_m}{\partial \delta_m} & \frac{\Delta Q_m}{\partial V_k} V_k & \frac{\Delta Q_m}{\partial V_m} Vm & \frac{\partial Q_m}{\partial X_{TCSC}} X_{TCSC} \\ \frac{\Delta P_{km}}{\partial \delta_k} & \frac{\Delta P_{km}}{\partial \delta_m} & \frac{\Delta P_{km}}{\partial V_k} V_k & \frac{\Delta P_{km}}{\partial V_m} V_m & \frac{\partial P_{km}}{\partial X_{TCSC}} X_{TCSC} \end{bmatrix} \begin{bmatrix} \Delta \delta_k \\ \Delta \delta_m \\ \frac{\Delta V_k}{V_k} \\ \frac{\Delta V_m}{V_m} \\ \frac{\Delta X_{TCSC}}{X_{TCSC}} \end{bmatrix} \tag{11}$$

The state variable X_{TCSC} of the TCSC series controller is updated according to equation (12):

$$X_{TCSC}^{(i)} = X_{TCSC}^{(i-1)} + \left(\frac{\Delta X_{TCSC}}{X_{TCSC}}\right)^{(i)} \cdot X_{TCSC}^{(i-1)} \tag{12}$$

The active power flow mismatch for the series reactance is given as in equation (13);

$$\Delta P_{km}^{X_{TCSC}} = P_{km}^{reg} - P_{km}^{X_{TCSC.CAL}} \tag{13}$$

Where;

X_{TCSC} = equivalent reactance of the TCSC
B_{km} = bus inductive operation between bus k and m
G_{km} = bus conductance between bus k and m
δ_k = calculated phase angle at bus k
$\Delta P_{km}^{X_{TCSC}}$ = active power flow mismatch for the series reactance
$P_{km}^{X_{TCSC.CAL}}$ = active power flow mismatch for the series reactance calculated
ΔX_{TCSC} = incremental change in series reactance

Dragonfly algorithm

The DA is a nature-inspired meta-heuristics optimization method. It treats Dragonflies as small hunters that attack nearly all other little insects in nature. Dragonflies flock for only two purposes: hunting and migration. Hunting is called a static (feeding) swarm, and migration is called a dynamic (migratory) swarm. The main purpose of any flock is existence, therefore, all of the individuals should be enticed toward food sources and diverted away from enemies (Çig˘dem and Hakan, 2019). The two swarming behaviors are similar to two main phases of PSO: exploration and exploitation. Dragonflies generate sub-swarms that fly over dissimilar territories in a static swarm. This is the main objective of the exploration phase. They fly in larger swarms and along the same direction as the dynamic swarm which is favorable in the exploitation phase (Çig˘dem and Hakan, 2019; Mirjalili, 2014).

Five main primitive principles utilized in updating the position of individuals in swarms; are separation, alignment, cohesion, attraction to food sources, and distraction from enemies. These five concepts are used to reproduce the behavior of dragonflies in both dynamic and static swarms (Mirjalili, 2014; Rahman and Rashid, 2019). These behaviors are mathematically represented as follows (Wang *et al*, 2021):

Separation

$$S_{ei} = -\sum_{j=1}^{N} X - X_j \tag{14}$$

Alignment

$$A_j = \frac{\sum_{j=1}^{N} V_j}{N} \tag{15}$$

Cohesion

$$C_j = \frac{\sum_{j=1}^{N} X_j}{N} - X \tag{16}$$

Attraction towards a food source

$$F_i = X^+ - X \tag{17}$$

Distraction outwards an enemy

$$E_i = X^- + X \tag{18}$$

$$\Delta X_{t+1} = (sS_{ei} + cC_i + fF_i + aA_i + eE_i) + w\Delta X_t \tag{19}$$

After calculating the step vector, the position vectors are calculated as in equation (20):

$$X_{t+1} = X_t + \Delta X_{t+1} \tag{20}$$

Improving randomness, stochastic behavior, and exploration of artificial dragonflies requires that they fly around the search space using a random walk (Levy flight) when there are no solutions in the neighborhood. The position of dragonflies is then updated using equation (21) (Mirjalili, 2014):

$$X_{t+1} = X_t + Levy(x) X_t \quad (21)$$

Where:

X = position of the current individual;

X_j = position j^{th}neighboring individual;

N = number of neighboring individuals;

V_j = velocity of $j^{th}$the neighboring individual;

X^+ = position of the food source;

X^-= position of the enemy;

s = separation weight;

S_{ei} = separation of the i^{th} individual;

a = alignment weight;

A_i = alignment of i^{th} individual;

c = cohesion weight'

C_i = cohesion of the i^{th} individual;

f = food factor;

F_i = food source of the i^{th} individual;

w = inertia weight;

t = iteration counter.

e = enemy factor;

E_i = position of an enemy of the i^{th} individual;

Dragonfly Algorithm Implementation for Optimal Solution of TCSC

The DA was populated based on the number of buses in the network. The purpose is to finalize TCSC's optimal location with its appropriate firing angle model to control voltage magnitudes and line flows. The fitness function is computed using the following equation (Abubakar *et al*, 2021):

$$FF = \max \sum_{i=1}^{n} f(V_b)\{TCSC(C_{TCSC}, N_{TCSC})\} \quad (22)$$

$$f(V_b) = 0 \; if \; 0.95 \leq V_i \leq 1.05 \quad (23)$$

Otherwise

$$f(V_b) = \log \emptyset(f(V_b) * abs\left[\frac{V_{i\,(nominal)} - V_i}{V_{i\,(nominal)}}\right] * \left[\frac{1}{lin}\right] \quad (24)$$

Where;

FF = fitness function to be optimized

$F(V_b)$ = violation function of bus voltage

N = number of buses in the system

C_{TCSC} = TCSC capacity

N_{TCSC} = bus location of TCSC

$V_{i\,(nominal)}$ = nominal bus voltage

$\emptyset(F(V_b)$ =index values percentage of bus voltage against the allowable limit

V_i = voltage magnitude at the bus I

lin = integer coefficient to regulate voltage variations

Equation (22) is subject to both equality and inequality constraints as follows:

$$P_{L=} P_G - P_D(V, \delta) \quad (25)$$

$$Q_{L=} Q_G - Q_D(V, \delta) \quad (26)$$

$$V_i^{min} \leq V_i \leq V_i^{max} \quad (27)$$

$$P_{ik} \leq P_{ik}^{max} \quad (28)$$

Where;

$P_{L=}$ = real power loss

P_G = real power generation

P_D = real power demand

$Q_{L=}$ = reactive power loss

Q_G = reactive power generation

Q_D = reactive power demand

V_i^{min} = minimum voltage on the bus I

V_i^{max} = maximum voltage on bus i

P_{ik} = power flow through line i-k

P_{ik}^{max} = maximum power flow limit through line i-k.

In Dragonfly Algorithm, each of the five main behaviors is mathematically modeled in equations (14) to (21). For the optimization process, the weight of dragonflies was adaptively changed to guarantee the convergence of individual dragonflies during the process of optimization. Then, the neighborhood area was expanded to adjust the flying path of the dragonflies. At the final stage of optimization, the swarm becomes one group to converge to a global optimum. The most excellent and the most awful solutions found are identified as the food source and enemy, respectively. This makes convergence and divergence towards promising and outward non-promising areas of the search space, respectively. The position vector of DA was determined using equation (20) and dragonflies' positions were updated using equation (21).

RESULT AND DISCUSSIONS

Tests were conducted on the system under the base load condition which describes the status of the system when supplying normal load, and the peak load condition which describes the status of the system when the load demand was increased by 25 % at the load buses. The parameters of DA for the optimization process are shown in Table 1. The voltage magnitude and the line flow were noted for analysis and comparison. The permissible limit of the bus voltages is set to± 0.05.

Base Load Condition

Case1 - Steady State: This describes the steady state of the Nigerian 28-bus system without the incorporation of a TCSC device at the base load

Case 2 – Manual Placement: The system is reinforced with multiple TCSC devices to regulate the system's active and reactive power flow.

Case 3 – Optimal Placement: DA was used for optimal placement and sizing of the TCSC device to further regulate system active and reactive power flow.

Results for the test cases showing the voltage magnitudes and line flows are presented in Figure 2 and Table 2, respectively. Results of test case 1 from Figure 2 revealed that the magnitude of the voltage at buses 9 and 16 (0.9260 p.u and 0.9040 p. u, respectively) are too close to the upper voltage limit while bust 22 voltage magnitude (0.8580 p.u) is out of the permissible limit. For case 2, multiple TCSC devices were installed on lines 5, 11, and 21 to reinforce the system and redirect the flow of power on these lines. It was observed that the voltage magnitudes recorded at buses 9, 16, and 22 have been regulated to 1.0080, 0.9950, and 1.0650, respectively which fall within the permissible limit. For case 3, two TCSC devices were optimally placed on lines 11 and 21. It was observed that the overall voltage profiles have been improved.

From Table 2, for test case 1, it can be observed that lines 5, 11, and 21 are heavily loaded. The lowest active power flow is observed on line 6 (0.57 MW), other lines with low active power flow are 18 and 31 (1.81 MW and 0.69 MW, respectively). The results of the line flow for case 2 also showed that power flow on the heavily loaded lines (5, 11, and 21) has been considerably redirected due to the compensation provided by the TCSC devices installed in the system. However, it was observed that line 3 is now heavily loaded as compared to test case 1. The lowest active power flow for case 2 is observed on line 31 (0.22 MW); others with low active power flow are lines 9 and 17 (0.71 MW and 2.36 MW, respectively). For case 3, the lowest active power is recorded on line 31 (1.22 MW); others with low active power flow are lines 16 and 26 (1.43 MW and 1.32 MW, respectively). Furthermore, the results of line flow showed that the active power flow on all the heavily loaded lines 3, 5, 11, and 21 before the optimal placement of the TCSC device has been further redistributed and is now less stressed. This is a result of the series compensation provided by the installed TCSC devices. A summary of the

TCSC location and size before and after optimization is presented in Table 3.

Table 1: Parameters of Dragonfly Algorithm

S/N	Parameter	Value
1	Maximum number of iterations	150
2	Number of dragonflies	60
3	Number of wavelengths	401
4	Separation, alignment, cohesion, food, and enemy factor	Adaptive tuning
5	Number of principal components	2
6	Number of folds of cross-validation	5
7	Number of variables	40

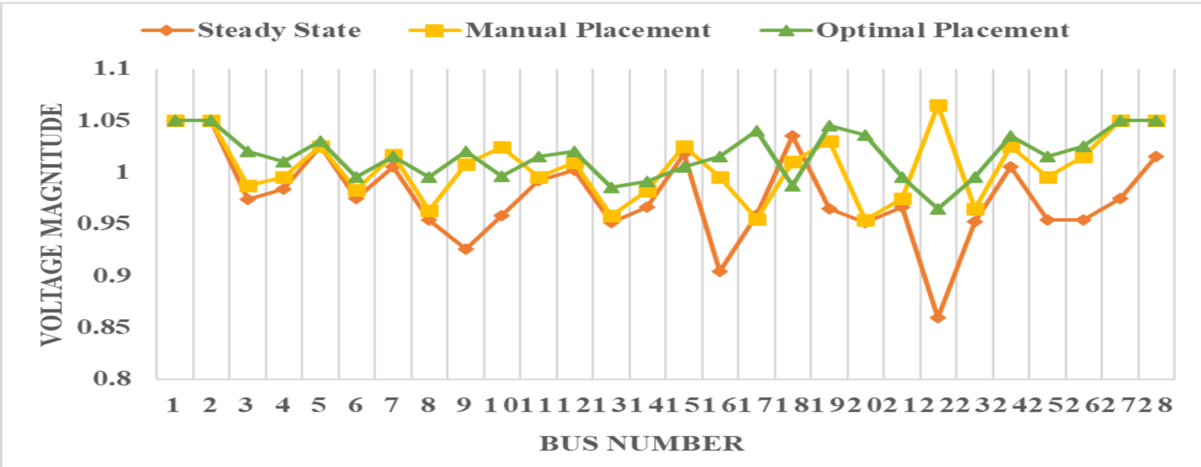

Figure 2: Comparison of Nigerian 28-bus test system voltage profile

Power System at 125 % Loading

Three test cases were also conducted. Test cases 4, 5, and 6 were equivalent to cases 1, 2, and 3, respectively. The summary of the result is presented in Figure 3 and Table 4, respectively. From the results of Figure 3: Results of Bus voltages of Nigerian 28-bus system at 25 % loading test case 4 in Table 4, it was revealed that the magnitudes of voltage at buses 9, 10, and 22 (0.8930 p.u, 0.8980 p.u and 0.8580 p.u, respectively) are out of the permissible limit, while the magnitudes of the voltage of buses 13 and 20 (0.9210 p.u and 0. 0.9210 p.u, respectively) are too close to the lower limit. This huge voltage limit violation can be attributed to the increase in energy demand, leading to increased system instability.

For case 5, multiple TCSC devices were installed on lines 4, 5,9 11 and 21 that are heavily loaded, in order to reinforce the system and to redirect the flow of power on these lines. It can be observed that the voltage magnitudes at buses 9, 10, 16, and 22 have been regulated and now fall within the permissible limit. Case 6 placed three TCSC devices on lines 11, 13, and 23. It was observed that the placement of the device on these lines leads to an improved overall system voltage profile. From Table 4, for test case 4, it can be observed that there were Many lines are now heavily loaded as compared to the system under normal loading conditions. Lines 4, 5, 9, 11, 19, and 21 are heavily loaded due to an increase in the load demand. The lowest active power flow is observed on line 31 (2.69 MW), other lines with low active

Table 2: Results of Active and Reactive line flows of the Nigerian 28-bus system

Branch Number	Bus Number From	To	Case 4 Active Power (MW)	Case 4 Reactive Power (MVar)	Case 5 Active Power (MW)	Case 5 Reactive Power (MVar)	Case 6 Active Power (MW)	Case 6 Reactive Power (MVar)
1	1	8	-6.91	21.74	-10.48	21.47	-11.63	25.07
2	1	20	-1.87	-5.78	-3.43	21.47	-6.12	25.07
3	**1**	**25**	**-20.71**	**-8.24**	**42.32**	**6.64**	**30.00**	**-11.37**
4	3	17	17.68	24.00	-21.85	4.64	-33.82	6.38
5	**2**	**24**	**37.08**	**-5.30**	**11.53**	**5.42**	**3.07**	**1.96**
6	**3**	**26**	**0.56**	**34.47**	**12.57**	**-3.42**	**4.05**	**-13.28**
7	3	12	-12.67	-8.20	-11.62	-0.20	-12.57	-0.38
8	4	27	-17.30	5.74	-11.62	4.83	-12.96	0.75
9	**4**	**12**	**16.75**	**-0.61**	**0.71**	**0.11**	**14.65**	**18.19**
10	4	14	9.58	-8.41	6.45	0.53	-6.08	5.79
11	**5**	**17**	**73.51**	**14.85**	**18.13**	**-8.09**	**18.95**	**-10.18**
12	5	24	-2.39	6.59	-12.47	7.954	2.53	1.58
13	6	12	29.39	2.83	19.99	2.75	1.47	0.06
14	7	23	-12.17	-7.38	-11.21	-5.76	6.65	-3.03
15	9	21	2.22	21.59	10.83	3.67	8.75	2.46
16	**10**	**23**	**-3.08**	**2.09**	**-2.42**	**-1.49**	**-1.43**	**2.19**
17	**11**	**13**	**-22.71**	**8.63**	**-2.36**	**5.45**	**-1.45**	**0.66**
18	**12**	**16**	**-1.81**	**12.65**	**-2.38**	**-1.97**	**7.52**	**-0.34**
19	13	27	35.94	-31.86	19.18	-4.99	13.55	3.04
20	15	16	-13.58	15.21	19.25	22.85	21.58	-4.66
21	**15**	**20**	**53.93**	**-21.10**	**-35.40**	**-26.89**	**-21.05**	**35.19**
22	16	17	8.73	-22.42	-32.35	-18.60	-19.84	-15.44
23	16	20	29.92	34.45	23.00	0.15	13.11	-5.26
24	17	18	-5.45	-2.21	-6.69	-4.43	-3.96	5.98
25	17	20	-31.45	-3.49	-6.55	-3.21	1.76	8.31
26	**17**	**21**	**1.83**	**-0.86**	**15.92**	**2.22**	**1.32**	**4.11**
27	19	20	9.20	0.59	20.86	0.76	4.31	3.67
28	21	22	-11.03	24.03	-9.65	0.71	-8.44	43.61
29	21	23	-15.05	-6.44	13.22	9.07	7.59	-5.37
30	22	23	-17.98	6.65	12.73	6.20	7.59	-5.37
31	**27**	**28**	**0.69**	**20.02**	**0.22**	**2.02**	**1.22**	**2.58**

	TCSC Location	TCSC Size (MVar)
Case 2	5	7.50
	11	6.55
	21	10.50
Case 3 (Optimal Placement)	**11**	**11.76**
	21	**5.56**

Table 3: Summary of TCSC Placement and size for the Nigerian 28-bus system

power flow are 2 and 18 (2.87 MW and 5.81 MW, respectively). Moreover, the results of the line flow presented in Table 4 for case 5 also show that the power flow on the heavily loaded lines (4, 5, 9, 11, 19, and 21) has been significantly redirected. This is due to the compensation provided by reinforcing the system with multiple TCSC devices on the heavily loaded lines. Nevertheless, it was observed that line 3 is now heavily loaded as compared to test case 4. The lowest active power flow for test case 5 is

Table 4: Results of Active and Reactive line flows of Nigerian 28-bus system at 25 % loading

Branch Number	**Bus Number From**	**To**	**Case 7 Active Power (MW)**	**Case 7 Reactive Power (MVar)**	**Case 8 Active Power (MW)**	**Case 8 Reactive Power (MVar)**	**Case 9 Active Power (MW)**	**Case 9 Reactive Power (MVar)**
1	1	8	-10.91	36.74	-12.56	51.47	-11.63	41.56
2	**1**	**20**	**-2.87**	**-17.78**	**-7.67**	**41.47**	**-12.12**	**35.89**
3	**1**	**25**	**-25.71**	**-19.24**	**51.32**	**26.64**	**45.00**	**-18.34**
4	**3**	**17**	**65.68**	**35.00**	**-48.85**	**24.64**	**-38.82**	**11.56**
5	**2**	**24**	**52.08**	**-15.30**	**34.61**	**15.42**	**7.07**	**5.89**
6	3	26	10.57	52.47	29.05	-13.42	5.05	-18.28
7	3	12	-15.67	-19.20	-11.62	-2.20	-18.57	-0.36
8	4	27	-19.30	18.74	-11.62	5.83	-16.96	3.19
9	**4**	**12**	**56.75**	**-6.61**	**0.71**	**2.11**	**25.65**	**26.10**
10	4	14	29.58	-12.41	6.45	2.53	-6.08	9.75
11	**5**	**17**	**93.51**	**21.85**	**49.20**	**-13.09**	**18.95**	**-15.17**
12	5	24	-22.39	12.59	-12.47	17.954	4.53	7.58
13	6	12	34.39	10.83	19.99	12.75	6.47	6.76
14	7	23	-12.17	-11.38	-11.21	-9.76	12.65	-13.23
15	9	21	12.22	42.59	10.83	8.67	18.75	7.46
16	**10**	**23**	**-7.08**	**31.09**	**-2.42**	**-4.49**	**-2.43**	**5.19**
17	**11**	**13**	**-22.71**	**18.63**	**-2.38**	**11.45**	**-4.45**	**1.90**
18	**12**	**16**	**-5.81**	**23.65**	**-2.36**	**-5.97**	**10.52**	**-2.51**
19	**13**	**27**	**65.94**	**-56.86**	**34.56**	**-8.99**	**28.65**	**9.056**
20	15	16	-13.58	31.21	19.25	32.85	32.24	-14.04
21	**15**	**20**	**81.93**	**-28.10**	**-49.40**	**-31.89**	**-21.05**	**45.45**
22	16	17	18.73	-25.42	-32.35	-22.60	-24.84	-25.32
23	16	20	45.92	54.45	32.40	9.15	34.11	-7.61
24	17	18	-9.45	-12.21	-6.69	-9.43	-6.96	9.08
25	17	20	-31.45	-13.49	-6.55	-7.21	6.76	14.04
26	17	21	18.83	-10.86	15.92	7.22	5.32	8.11
27	19	20	19.20	24.59	20.86	4.76	14.31	7.67
28	21	22	-16.03	35.03	-9.65	12.71	-8.44	55.61
29	21	23	-18.05	-16.44	13.22	10.07	15.53	-15.06
30	22	23	-19.98	16.65	12.73	16.20	15.40	-15.02
31	**27**	**28**	**2.69**	**20.02**	**2.22**	**3.71**	**1.72**	**2.58**

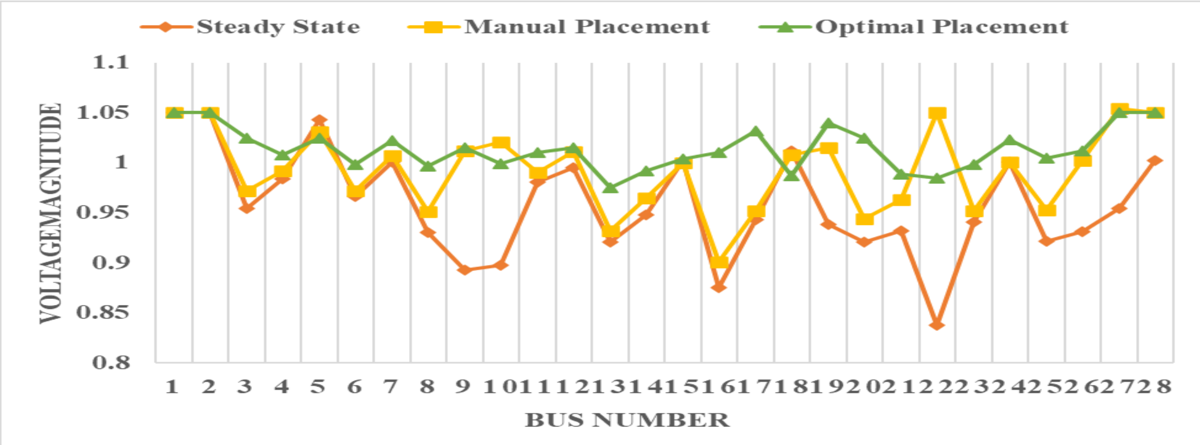

Figure 3: Comparison of Nigerian 28-bus test system voltage profile at 25 % loading

observed on line 9 (0.71 MW); others with low active power flow are lines 18 and 31 (2.36 MW and 2.22 MW, respectively).

Furthermore, the results of line flows presented in Table 4 showed that the active power flow on all the heavily loaded lines 4, 5, 9, 11, 19, and 21 before the optimal placement of the TCSC device has been further redistributed and is now less stressed. The lowest active power flow for test case 6 is recorded on line 31 (1.72 MW); others with low active power flow are lines 16 and 17 (2.43 MW and 4.45 MW, respectively). Results of line flow showed that the active power flow on all the heavily loaded lines before the optimal placement of the TCSC device has been further redistributed and is now less stressed as a result of the series compensation provided by the installed TCSC devices. A summary of the TCSC location and size for test case 5 and test 6, are presented in Table 5.

	TCSC Location	TCSC Size (MVar)
Test Case 5	4	7.50
	5	6.55
	9	10.50
	11	12.35
	21	8.40
Test Case 6 (Optimal Placement)	**11**	**11.75**
	13	**5.55**
	23	**9.60**

Table 5: Summary of TCSC Placement and size for Nigerian 28-bus system at 25 % loading

CONCLUSION

This work presented the optimal placement and sizing of TCSC. On a Nigerian 28-bus system for power voltage profile and line flow control using the Dragonfly Algorithm (DA). Power flow analysis on transmission systems without and with TCSC was performed using the Newton-Rapson (NR) iterative technique. TCSC firing angle model was implemented into the Newton-Raphson power flow algorithm. The optimal placement of the TCSC device on Nigerian 28-bus systems was done using DA. The results clearly showed that DA is a vigorous optimization approach for the placement of TCSC devices on an electric power system for regulation and control of voltage magnitudes and line flows.

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