SSR Journal of Engineering and Technology (SSRJET)

Homepage: https://ssrpublisher.com/ssrjet/

Volume 3, Issue 7, 2026 ISSN: 3049-0383

Optimal Placement and Sizing of SVC, TCSC, and UPFC in the Nigerian 330KV Grid Using Particle Swarm Optimization

Ogbodo Ikechukwu Ogbodo, Nwaogaidu Simeon Obinna, Egbonwonu Emmanuel livinus, Asanya Onyebuchi Nduka

Electrical/Electronic Engineering Dept, State University of Medical and Applied Sciences, Igbo-Eno Enugu State Nigeria

Received: *11.06.2026* | ***Accepted:*** *25.06.2026* | ***Published:*** *16.07.2026*

***Corresponding author:** Ogbodo Ikechukwu Ogbodo

DOI: *10.5281/zenodo.21387666*

Abstract **Review Article**

The Nigerian 330 kV transmission network plays a critical role in bulk electric power delivery across the country, yet it continues to experience operational challenges such as weak voltage profiles, excessive transmission losses, congestion on key corridors, and limited loadability. These issues reduce the efficiency, reliability, and stability of the national grid. This study presents the optimal placement and sizing of Flexible Alternating Current Transmission System (FACTS) devices, namely the Static Var Compensator (SVC), Thyristor Controlled Series Capacitor (TCSC), and Unified Power Flow Controller (UPFC), in the Nigerian 330 kV 48-bus power system using Particle Swarm Optimization (PSO). The objective was to minimize voltage drop, reduce real power losses, and improve network performance through intelligent compensation planning. A base-case load flow analysis was carried out in MATLAB/PSAT to determine voltage magnitudes, line loading conditions, and weak buses in the network. Results identified Jos, Ugwuaji, and New Haven buses as the most voltage-deficient locations and were selected for SVC placement. The Ugwuaji–New Haven and Jos–Markurdi transmission lines were identified as suitable locations for TCSC installation, while UPFC devices were placed at the midpoint of the same lines. PSO was then applied to determine the optimal compensation size subject to network operating constraints. The optimization process converged successfully with a best objective function value of -5974.45942 and produced optimal decision variables of $x_1 = 0.018169, x_2 = 0.019036, and\ x_3 = 0.018392$. The corresponding equivalent FACTS impedance obtained was 37.5546 Ω. Comparative analysis showed that PSO-based placement significantly outperformed random placement, reducing transmission losses from 182.4 MW in the uncompensated system to 121.5 MW under optimized compensation. Compensation sensitivity analysis further showed that increasing compensation level from 0% to 60% progressively reduced losses, with 60% compensation providing the best operating condition within the tested range. Among the devices studied, the UPFC produced the best overall technical performance due to its simultaneous control of voltage magnitude, transmission impedance, and active/reactive power flow. The study concludes that PSO is a reliable and computationally efficient tool for solving the nonlinear FACTS placement and sizing problem. Strategic deployment of optimally sized FACTS devices offers a practical and cost-effective approach for improving the performance of the Nigerian 330 kV grid and reducing the need for immediate transmission expansion.

Keywords: Nigerian 330 kV grid, FACTS devices, Particle Swarm Optimization, SVC, TCSC, UPFC, transmission loss reduction, voltage stability, power system optimization.

1. Introduction

Electric power transmission networks are fundamental to the reliable delivery of electricity from generating stations to distribution centers and final consumers [11]-[13]. In developing countries such as Nigeria, the transmission grid plays an especially important role because it links geographically dispersed generation sources with rapidly growing urban, commercial, and industrial load centers. The Nigeria 330 kV transmission network serves as the principal backbone of bulk power transfer across the nation [17], [20], [22]. Despite its strategic importance, the grid continues to face several operational challenges, including weak bus voltages, high transmission losses, overloaded lines, inadequate reactive power support, poor voltage regulation, and restricted loadability [1]. These technical problems contribute to reduced system reliability, frequent disturbances, and an inability to meet increasing electricity demand efficiently. The growing population, urbanization, industrial expansion, and rising energy consumption in Nigeria have increased pressure on the existing transmission infrastructure [2]-[4]. Many parts of the network now operate close to their thermal and stability limits, while some substations experience persistent undervoltage conditions due to insufficient reactive power compensation and long transmission distances. In addition, network expansion through new transmission line construction often requires substantial capital investment, lengthy approval processes, environmental considerations, and right-of-way acquisition challenges [7], [10], [14]. Consequently, there is increasing need for cost-effective alternatives that can improve the performance of existing transmission assets without immediate large-scale infrastructure expansion. Flexible Alternating Current Transmission System (FACTS) technology has emerged as one of the most effective solutions for enhancing modern power system operation and controllability. FACTS devices are power-electronic-based controllers capable of regulating key transmission parameters such as voltage magnitude, line impedance, and phase angle in real time [16], [18], [21]. By dynamically controlling these variables, FACTS devices can increase power transfer capability, reduce losses, improve voltage stability, relieve congestion, and enhance both steady-state and transient system performance.

Among the numerous FACTS controllers available, the Static Var Compensator (SVC), Thyristor Controlled Series Capacitor (TCSC), and Unified Power Flow Controller (UPFC) are widely recognized because of their technical versatility and practical applications [15], [19]. The SVC is a shunt-connected device mainly used for reactive power compensation and voltage control. It supports weak buses by injecting or absorbing reactive power depending on network conditions. The TCSC is a series compensation device that modifies effective line reactance, thereby controlling power flow, reducing congestion, and improving transfer capability [6], [8], [9]. The UPFC is one of the most advanced FACTS controllers because it combines shunt and series compensation functions in a single device, allowing simultaneous control of voltage magnitude, line impedance, and active/reactive power flow. Although FACTS devices provide substantial technical benefits, they are capital-intensive assets whose effectiveness depends greatly on where they are installed and the size at which they are operated [5]-[8]. Arbitrary placement of FACTS controllers may lead to poor performance, underutilization, or unnecessary investment cost. Similarly, over-sizing may increase capital expenditure without proportional benefit, while under-sizing may fail to solve the intended network problem. Therefore, determining the optimal placement and sizing of FACTS devices is a critical planning problem in transmission system engineering.

The optimization of FACTS allocation is inherently complex because power systems are nonlinear, highly interconnected, and subject to multiple operating constraints [2], [7]. Traditional deterministic methods may struggle with local minima, computational burden, or poor scalability when applied to large transmission networks. For this reason, intelligent metaheuristic optimization techniques have become increasingly popular for solving such problems. Particle Swarm Optimization (PSO) is a population-based optimization algorithm inspired by the collective movement behavior of birds and fish schools. In PSO, a set of candidate solutions known as particles moves through the search space by updating positions according to personal experience and group best performance [11], [15], [16]. The method is simple to implement, computationally efficient, and highly effective for nonlinear constrained engineering problems. PSO has been successfully applied in economic dispatch, optimal power flow, reactive power planning, and FACTS allocation studies. Applying PSO to the Nigeria 330 kV transmission network offers a practical means of identifying the best buses and transmission corridors for FACTS installation while simultaneously determining the most suitable compensation size [20]-[22]. Such optimization can significantly reduce power losses, improve voltage profile, increase loadability, and enhance the operational security of the national grid.

This study therefore investigates the optimal placement and sizing of SVC, TCSC, and UPFC devices in the Nigeria 330 kV 48-bus transmission network using Particle Swarm Optimization. The network was modeled in MATLAB with the PSAT environment. Weak buses and critical transmission lines were first identified through load flow analysis, after which PSO was employed to determine optimal compensation parameters. The study evaluates the effectiveness of the proposed approach in minimizing losses and improving system performance. The findings are expected to provide valuable guidance for planners, operators, and policymakers seeking efficient strategies for strengthening the Nigeria national transmission grid.

2. Problem Formulation and System Modeling

2.1. Problem Statement

The Nigerian 330 kV transmission network is characterized by significant technical deficiencies that compromise its operational efficiency and reliability. These deficiencies include persistent voltage deviations below acceptable limits, high active power losses along transmission corridors, thermal overloading of critical lines, and reduced loadability margins. These problems arise primarily from inadequate reactive power support, long transmission distances, and the absence of effective power flow control mechanisms. The problem addressed in this study is therefore twofold: where to place FACTS devices (SVC, TCSC, and UPFC) in the Nigerian 330 kV 48-bus network, and what size (compensation magnitude) each device should be, such that the overall system performance is maximized while satisfying all network operating constraints. This is a non-linear, constrained optimization problem that cannot be solved efficiently by deterministic or trial-and-error methods.

2.2. Objective Functions

The primary objective of this study is to minimize the total active power losses in the transmission network while simultaneously improving the voltage profile. These two objectives are formulated as a single weighted objective function.

2.2.1. Minimization of Active Power Losses

The total real power loss in the transmission system is given by:

$$P_{\text{loss}} = \sum_{k=1}^{N_L} G_k\left[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)\right] \quad (1)$$

Where:

- $P_{loss} =$ $total\ active\ power\ loss\ (MW)$
- $N_L = number\ of\ transmission\ lines$
- $G_k =$ $conductance\ of\ line\ k\ (Siemens)$
- $V_i, V_j =$ $voltage\ magnitudes\ at\ buses\ i\ and\ j\ (pu)$
- $\delta_i, \delta_j = voltage\ angles\ at\ buses\ i\ and\ j\ (radians)$

2.2.2. Minimization of Voltage Deviation

The voltage deviati0n index quantifies how far bus voltages deviate from the nominal reference value (1.0 pu):

$$VD = \sum_{i=1}^{N_B} \left|V_i - V_{ref}\right|^2 \quad (2)$$

Where:

- $V_D = voltage\ deviation\ index$
- $N_B = number\ of\ buses$
- $V_i = voltage\ magnitude\ at\ bus\ i\ (pu)$
- $V_{ref} = reference\ voltage\ (1.0\ pu)$

2.2.3. Composite Objective Function

The two objectives are combined into a single composite objective function using weighting factors:

$$F = w_1 \cdot P_{\text{loss}} + w_2 \cdot VD \quad (3)$$

Where:

- $F = composite\ objective\ function\ to\ be\ minimized$
- $w_1,\ w_2 = weighting\ factors\ \left(w_1 = 0.6,\ w_2 = 0.4\ based\ on\ relative\ importance\right)$

For the PSO implementati0n, the objective was ref0rmulated as:

$$f(x) = Ax_1 + Bx_2 - Cx_3$$

Where $x_1,\ x_2, and\ x_3$ are decision variables representing compensation magnitudes, and A, B, C are coefficients derived from line parameters (Table 1).

Table 1. Line parameters used in the objective function coefficients

Parameter	Value	Description
A	966.1	Voltage drop coefficient (Ugwuaji–Markurdi line)
B	3.05 × 10⁵	Reference voltage coefficient
C	3.05 × 10⁵	Compensation benefit coefficient

2.3. Decision Variables

The decision variables represent the compensation magnitudes (sizes) of the FACTS devices. Three primary variables are defined:

- $x_1: Compensation\ factor\ for\ SVC\ (shunt\ reactive\ power\ injection)$
- $x_2: Compensation\ factor\ for\ TCSC\ (series\ reactance\ reduction)$
- $x_3: Compensation\ factor\ for\ UPFC\ \left(combined\ shunt\ and\ series\ compensation\right)$

Decision variable vector:

$\mathbf{x} = [x_1, x_2, x_3]$

Table 2. Decision variable bounds

Variable	Lower Bound	Upper Bound	Description
x_1	0	0.70	SVC compensation factor (0–70%)
x_2	0	0.70	TCSC compensation fact0r (0–70%)
x_3	0	0.70	UPFC compensation factor (0–70%)

2.4. Constraints

The optimization problem is subject to both equality and inequality constraints that ensure the system operates within safe and feasible limits.

2.4.1. Equality Constraints (Power Flow Equations)

For each bus i, the active and reactive power balance must be satisfied:

$$P_{Gi} - P_{Di} - \sum_{j=1}^{N_B} V_i V_j Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j) = 0$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{N_B} V_i V_j Y_{ij} \sin(\theta_{ij} - \delta_i + \delta_j) = 0$$

Where:

- $P_{Gi}, Q_{Gi} = active\ and\ reactive\ power\ generation\ at\ bus\ i$
- $P_{Di}, Q_{Di} = active\ and\ reactive\ power\ demand\ at\ bus\ i$
- $Y_{ij}, \theta_{ij} = admittance\ magnitude\ and\ angle\ between\ buses\ i\ and\ j$

2.4.2. Inequality Constraints

Voltage magnitude limits:

$$V_i^{min} \leq V_i \leq V_i^{max}$$

For the Nigerian 330 kV network:

$$0.90\ pu \leq V_i \leq 1.10\ pu$$

Line thermal limits:

$$S_{ij} \leq S_{ij}^{max}$$

Where S_{ij} is the apparent power flow on line j.

FACTS operating limits:

$0 \leq k_{SVC} \leq 0.70$
$0 \leq k_{TCSC} \leq 0.70$
$0 \leq k_{UPFC} \leq 0.70$

PSO-specific constraints:

$x_i \geq 0$
$x_i \leq 2 \times 10^6$

2.5. Mathematical Modeling of FACTS Devices

2.5.1. Static Var Compensator (SVC) Model

The SVC is modeled as a variable shunt susceptance B_{SVC} that injects or absorbs reactive power at the connected bus:

$$Q_{SVC} = V_i^2 \cdot B_{SVC}$$

Where:

- $Q_{SVC} = reactive\ power\ injected\ (positive) or\ absorbed\ (negative)$
- $V_i = voltage\ at\ the\ connected\ bus$

$B_{SVC} = variable\ susceptance,\ subject\ to: B_{min} \leq B_{SVC} \leq B_{max}$

2.5.2. Thyristor Controlled Series Capacitor (TCSC) Model

The TCSC is modeled as a variable series reactance that modifies the effective impedance of a transmission line:

$$X_{\text{line,new}} = X_{\text{line}} - X_{\text{TCSC}} \quad (4)$$

Or in percentage compensation form:

$$X_{\text{TCSC}} = k \cdot X_{\text{line}} \quad (5)$$

Thus:

$$X_{\text{line, new}} = (1 - k) X_{\text{line}} \quad (6)$$

Where:

- $k = compensation\ factor\ (0 \leq k \leq 0.70)$
- $X_{line} = original\ line\ reactance$

$X_{TCSC} = TCSC\ compensation\ reactance$

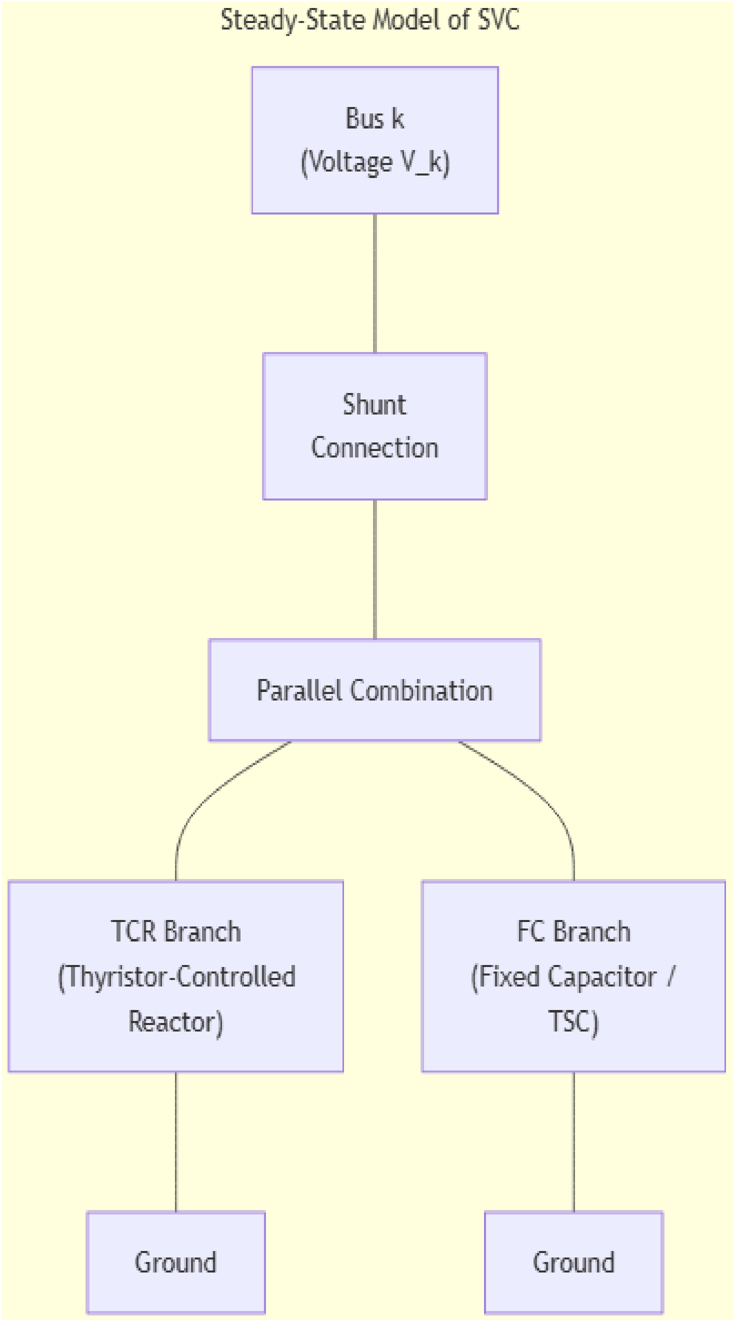


Figure 1. Steady-state model of SVC

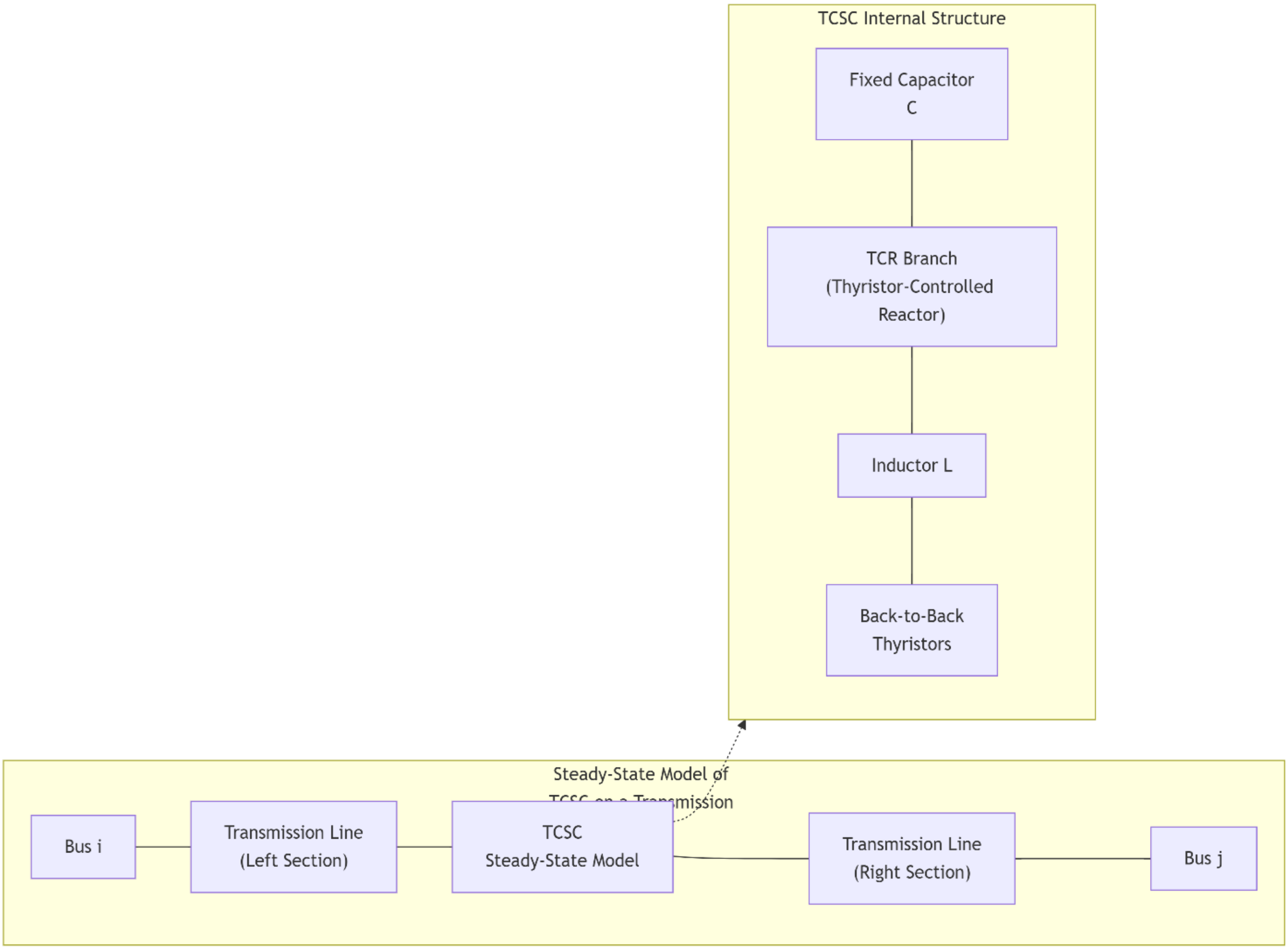


Figure 2. Steady-state model of TCSC on a transmission line

2.5.3. Unified Power Flow Controller (UPFC) Model

The UPFC combines shunt and series compensation. It is modeled as an ideal series voltage source V_{se} and a shunt current source I_{sh} :

$$V_{se} = rV_i e^{j\gamma} \quad (7)$$

Where:

- $r = magnitude\ control\ ratio\ (0 \leq r \leq 0.15)$
- $\gamma = phase\ shift\ angle\ (0° \leq \gamma \leq 360°)$
- $V_i = bus\ voltage\ magnitude$

The UPFC equivalent impedance is:

$$Z_{FACTS} = \frac{(1 - x_1)Z_L}{x_1} \quad (8)$$

Using the optimized values from this study:

- $Z_L = 137.7\,\Omega$
- $x_1 = 0.018169$

Theref0re:

$$Z_{FACTS} = \frac{(1 - 0.018169) \times 137.7}{0.018169} = 137.5546\Omega$$

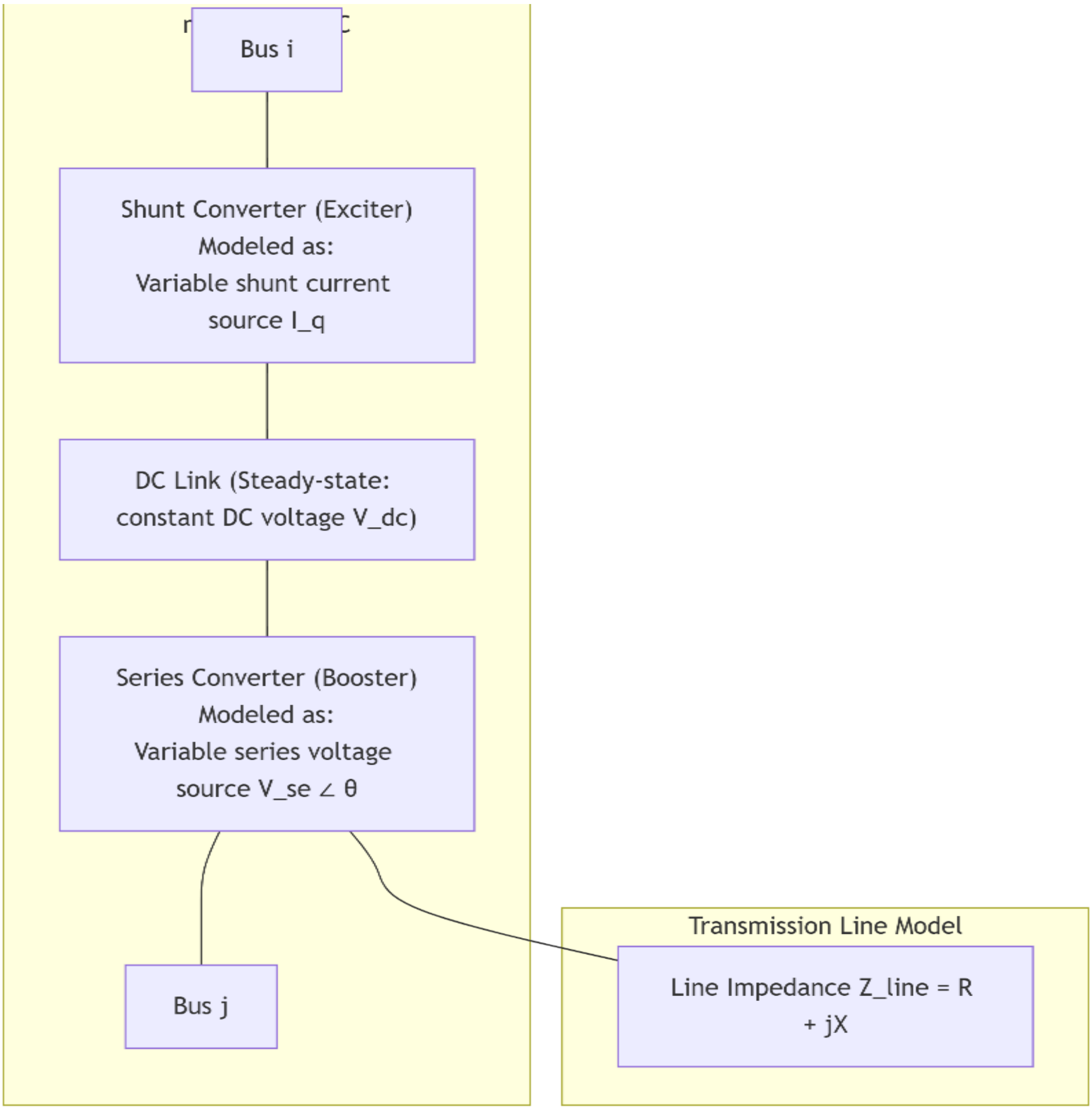


Figure 3. Steady-state model of UPFC

2.6. Summary of Problem Formulation

The complete optimization problem can be summarized as:

$$\text{Minimize } f(x) = Ax_1 + Bx_2 - Cx_3 \qquad (9)$$

Subject to:

Table 3. Constraints

Constraint Type	Mathematical Expression
Voltage limits	$0.90 \leq V_i \leq 1.10\ pu$

Line flow limits	$S_{ij} \leq S_{ij}^{\max}$
Power balance	$\sum P_G - \sum P_D - P_{loss} = 0$
Decision variable bounds	$0 \leq x_1, x_2, x_3 \leq 0.70$
Inequality constraints	$966.1x_1 + 3.05 \times 10^5 x_2 - 3.05 \times 10^5 x_3 \leq 71.144$

Table 4. Summary of the optimization problem components

Component	Description
Objective	Minimize transmission losses and voltage deviation
Decision variables	$x_1(SVC),\ x_2(TCSC),\ x_3(UPFC)$
Constraints	Voltage limits, line limits, power balance, device limits
Optimization method	Particle Swarm Optimization (PSO)
Test system	Nigerian 330 kV 48-bus network

3. Materials and Methods

3.1. Study Network Description

This study was carried out on the Nigerian 330 kV transmission network represented as a 48-bus interconnected power system. The network consists of major generating stations, switching substations, transmission corridors, and load centers distributed across the country. The 330 kV grid forms the backbone of bulk power transfer in Nigeria and is used for long-distance transmission of generated power to regional substations before further transformation to lower voltage levels. The selected 48-bus model includes important buses such as Jos, Ugwuaji, New Haven, Markurdi, Benin, Ajaokuta, Onitsha, Ikot-Ekpene, and other strategic substations. The buses are interconnected through high-voltage transmission lines characterized by resistance, reactance, charging susceptance, and thermal limits.

The network data used for simulation include bus voltage magnitudes, voltage angles, real and reactive power demand, generator outputs, and line parameters. These data were implemented in the Power System Analysis Toolbox (PSAT) environment in MATLAB/Simulink.

3.2. Research Methodology Framework

The methodology adopted in this study consists of base-case load flow analysis, weak bus identification, FACTS device location selection, optimal sizing using Particle Swarm Optimization (PSO), and post-compensation performance evaluation.

The major stages are summarized as follows:

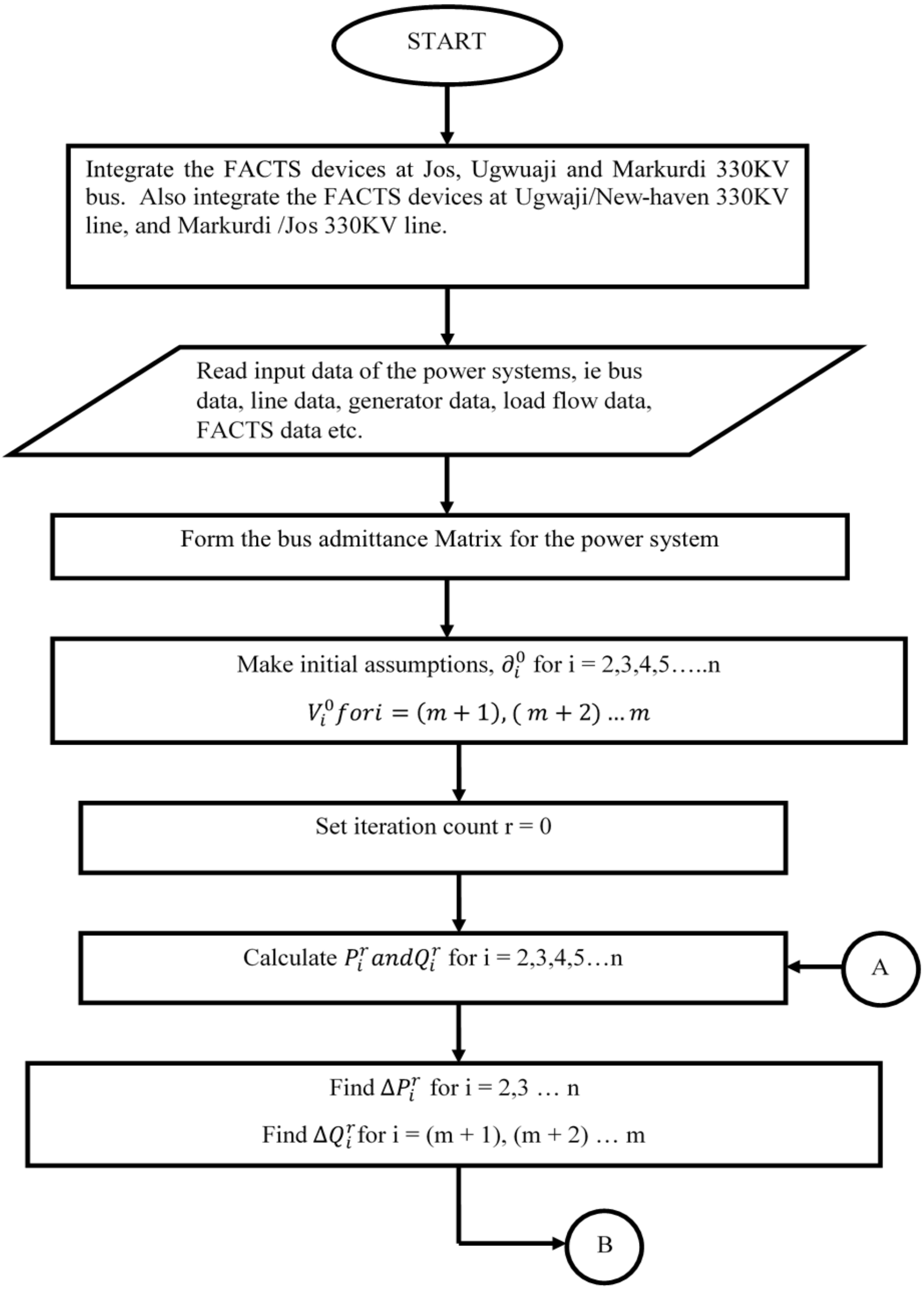
Base-case power flow analysis was first carried out on the uncompensated Nigerian 330 kV grid to determine bus voltages, line loading, active power losses, and reactive power flow.

Buses with the poorest voltage profile were identified from the load flow results.

Transmission lines connected to weak buses were selected as candidate locations for TCSC and UPFC installation.

Particle Swarm Optimization was then used to determine the optimal size (effective impedance/reactance compensation) of the FACTS devices.

The optimized devices were inserted into the PSAT model and a compensated load flow study was performed. The resulting network performance was compared with the base-case system.



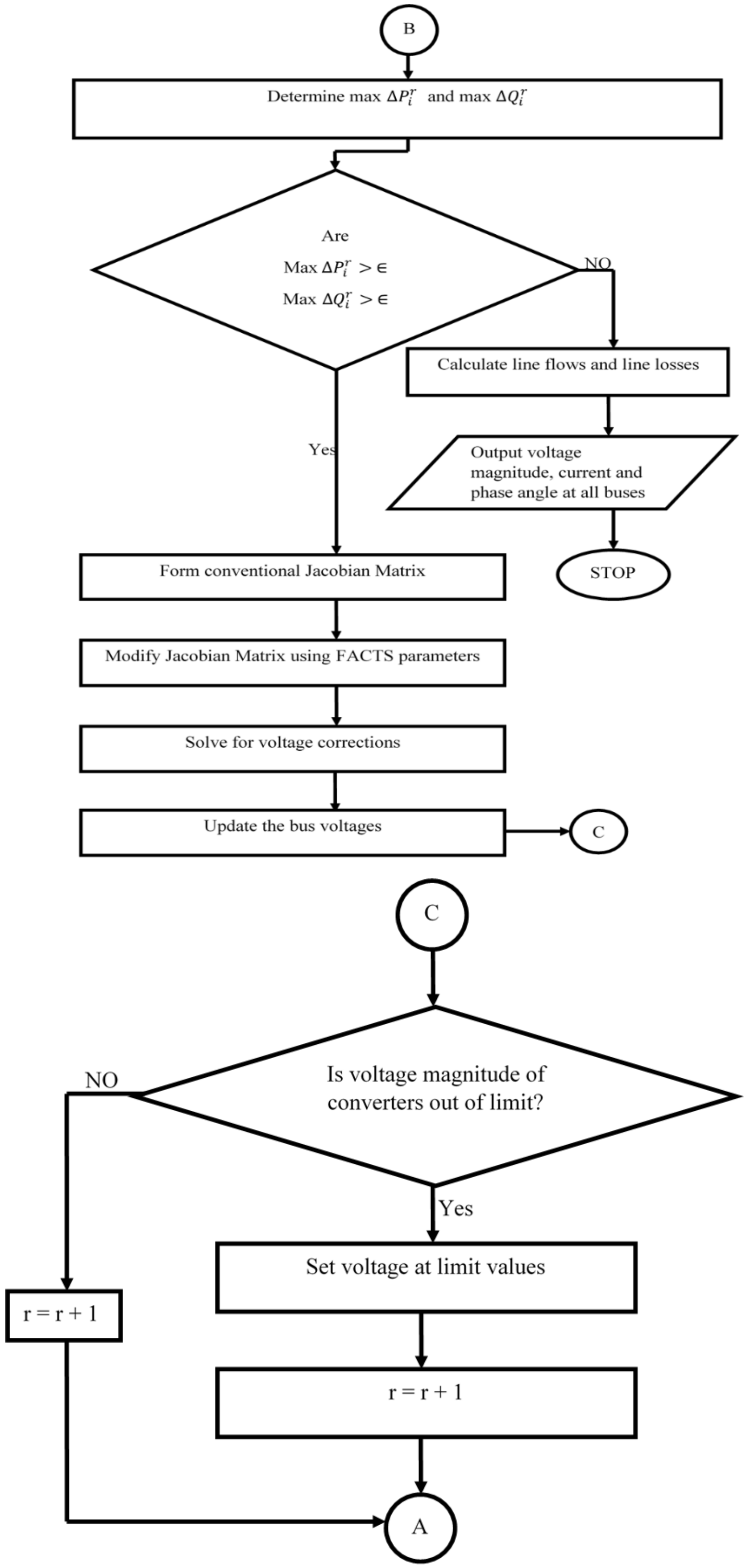


Figure 4. Flowchart of the proposed methodology for optimal placement and sizing of SVC, TCSC, and UPFC.

3.4. Identification of Weak Buses for SVC Placement

From the uncompensated power flow results, buses with the lowest voltage magnitudes were considered weak buses requiring reactive support.

The weakest buses identified were:

- Jos 330 kV Bus
- Ugwuaji 330 kV Bus
- New Haven 330 kV Bus

These buses were selected as optimal candidate locations for Static Var Compensator (SVC) installation because SVC is a shunt compensator used primarily for voltage support.

The reactive power injected by the SVC is expressed as:

$$Q_{\{s\,v\,c\}} = V^2 B_{\{s\,v\,c\}} \tag{10}$$

Where:

$Q_{\{s\,v\,c\}} = $ *reactive power injected /absorbed*
$V = $ *bus voltage magnitude*
$B_{\{s\,v\,c\}} = $ variable susceptance of SVC

3.5. Selection of Transmission Lines for TCSC Placement

The TCSC was placed on transmission lines feeding the weakest buses so as to reduce line reactance, improve power transfer, and support voltage stability.

Based on the weak bus locations, the candidate lines selected were:

- Ugwuaji – New Haven line
- Jos – Markurdi line

The compensated reactance of TCSC is given by:

$$X_{\text{line, new}} = X_{\text{line}} - X_{tcsc} \tag{11}$$

or in percentage compensation form:

$$X_{tcsc} = kX_{line} \tag{12}$$

Where:

$k = $ *compensation factor*
$0 < k < 0.70$

Thus:

$$X_{\text{line, new}} = (1-k)X_{\text{line}} \tag{13}$$

3.6. Selection of UPFC Placement

The UPFC was installed at the midpoint of the same transmission lines selected for TCSC because these corridors were critical power transfer routes.

Thus, UPFC devices were installed at:

- Midpoint of Ugwuaji – New Haven line
- Midpoint of Jos – Markurdi line

The UPFC combines series and shunt compensation simultaneously and can regulate voltage magnitude, line impedance, and phase angle.

Its injected series voltage is represented as:

$$V_{se} = rV_i e^{j\gamma} \tag{14}$$

Where:

$r = $ *magnitude control ratio*
$\gamma = $ *phase shift angle*

3.7. FACTS Device Optimization Model

The objective of optimization was to minimize voltage drop and improve transmission line performance.

The optimization variable was the FACTS equivalent impedance: Z_{FACTS}

Since all other network variables were known from load flow results, the unknown parameter optimized was Z_{FACTS}.

From the line model:

$$Z_{FACTS} = \frac{(1-x_1)Z_L}{x_1} \tag{15}$$

Where:

$Z_L = $ *line impedance*
$x_1 = $ *optimization decision variable*

Given:

$Z_L = 137.7\Omega$

After optimization:

$x_1 = 0.018169$

$$Z_{FACTS} = \frac{(1 - 0.018169)(137.7)}{0.018169}$$

Theref0re:

$$Z_{FACTS} = \frac{(1 - 0.018169)(137.7)}{0.018169}$$

$$Z_{FACTS} = 137.5546\Omega$$

3.8. Line Flow Data Used for Optimization

The optimization model was formulated using practical line-flow parameters extracted from load flow simulation.

Table 5. Line-flow parameters used for optimization of FACTS devices.

Transmission Line	From Bus Voltage (V)	To Bus Voltage (V)	Power Flow (W)	Current (A)	Voltage Drop (V)
Ikot-Ekpene/Ugwuaji	3.05E+05	3.06E+05	1.39E+07	45.6038	-454.2
Ajaokuta/Benin	3.29E+05	3.27E+05	8.18E+06	24.8510	1471.1
Ugwuaji/Markurdi	3.06E+05	3.05E+05	2.45E+07	79.9366	966.1
Benin/Onitsha	3.27E+05	3.17E+05	2.33E+07	71.0498	10714.4

3.9. Objective Function and Constraints

The optimization problem was formulated as a constrained minimization problem:

$$\text{Minimize } f(x) = Ax_1 + Bx_2 - Cx_3 \quad (16)$$

subject to:

$$966.1x_1 + 3.05 \times 10^5 x_2 - 3.05 \times 10^5 x_3 \leq 71.144$$
$$x_i \geq 0$$
$$x_i \leq 2 \times 10^6$$

where:

x_1, x_2, x_3 *are decision variables associated with compensation magnitude.*

3.10. Particle Swarm Optimizati0n (PSO)

Particle Swarm Optimization was employed because of its robustness in nonlinear constrained optimization.

Each particle updates velocity and position using:

$$v_i^{t+1} = wv_i^t + c_1 r_1(\text{pbest}_i - x_i^t) + c_2 r_2(\text{gbest} - x_i^t)$$
$$x_i^{t+1} = x_i^t + v_i^{t+1}$$

where:

w = *inertia weight*
c_1, c_2 = *acceleration coefficients*
r_1, r_2 = *random numbers in* $[0,1]$

PSO Parameters

Table 6. PSO control parameters used in the study.

Number of Variables	3
Number of Particles	2000
Minimum Inertia Weight	0.4

Maximum Inertia Weight	0.9
Lower Bound	0
Upper Bound	2×10^6
Cognitive Coefficient c_1	2
Social Coefficient c_2	2
Maximum Iteration	1000

3.11. Optimization Results Used for Device Sizing

The PSO algorithm converged successfully with runtime of:

$$32.724494\ seconds$$

Best solution occurred at:

- Run = 20
- Iteration = 2000
- Particle = 1063

Best objective function:

$$f(x) = -5974.45942$$

Optimal variables:

$$x_1 = 0.018169$$
$$x_2 = 0.019036$$
$$x_3 = 0.018392$$

3.12. Compensation Strategy

Total compensation level adopted was:

$$60\%$$

For standalone devices:

- $SVC = 60\%$
- $TCSC = 60\%$
- $UPFC = 60\%$

F0r combined FACTS arrangement:

- $SVC = 20\%$
- $TCSC = 20\%$
- $UPFC = 20\%$

Total:

$$20 + 20 + 20 = 60\%$$

3.13. UPFC Parameter Configuration

The UPFC was connected on the New Haven – Ugwuaji transmission line.

Voltage operating limits were:

$$V_{max} = 1.15pu$$
$$V_{min} = 0.85pu$$

Maximum current setting:

$$I_{max} = \frac{1.15 \times 330000}{137.5546}$$
$$I_{max} = 2758.9A$$

Minimum current setting:

$$I_{min} = \frac{0.85 \times 330000}{137.5546}$$
$$I_{min} = 2039.2A$$

These values were used for UPFC parameterization in PSAT.

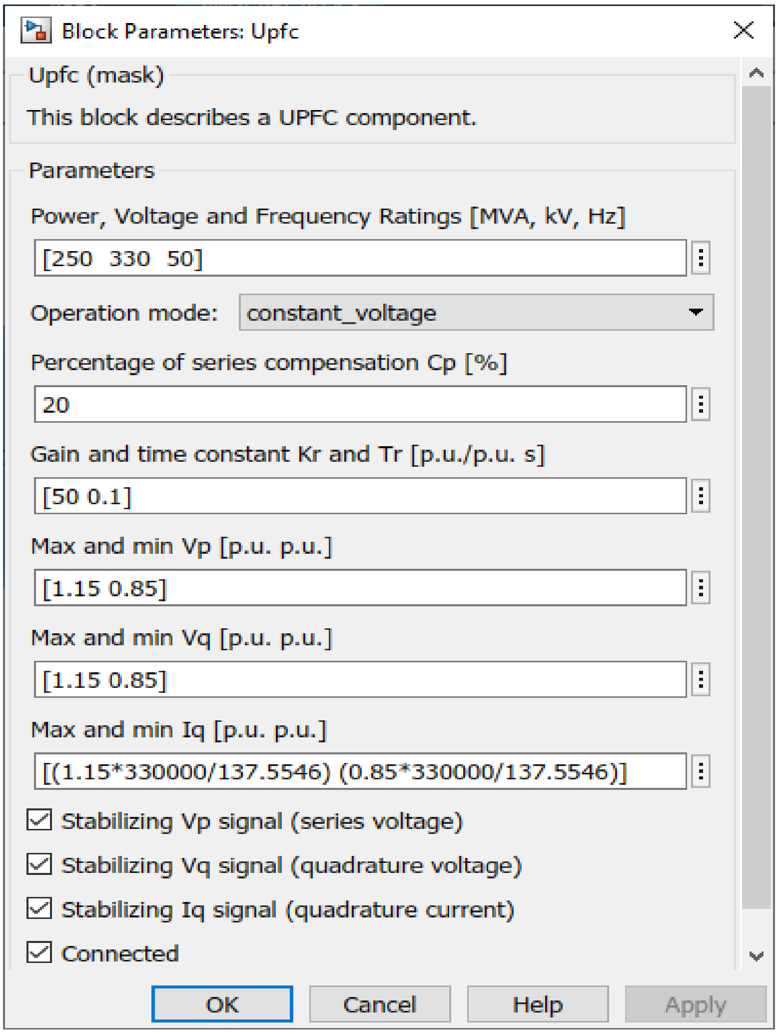
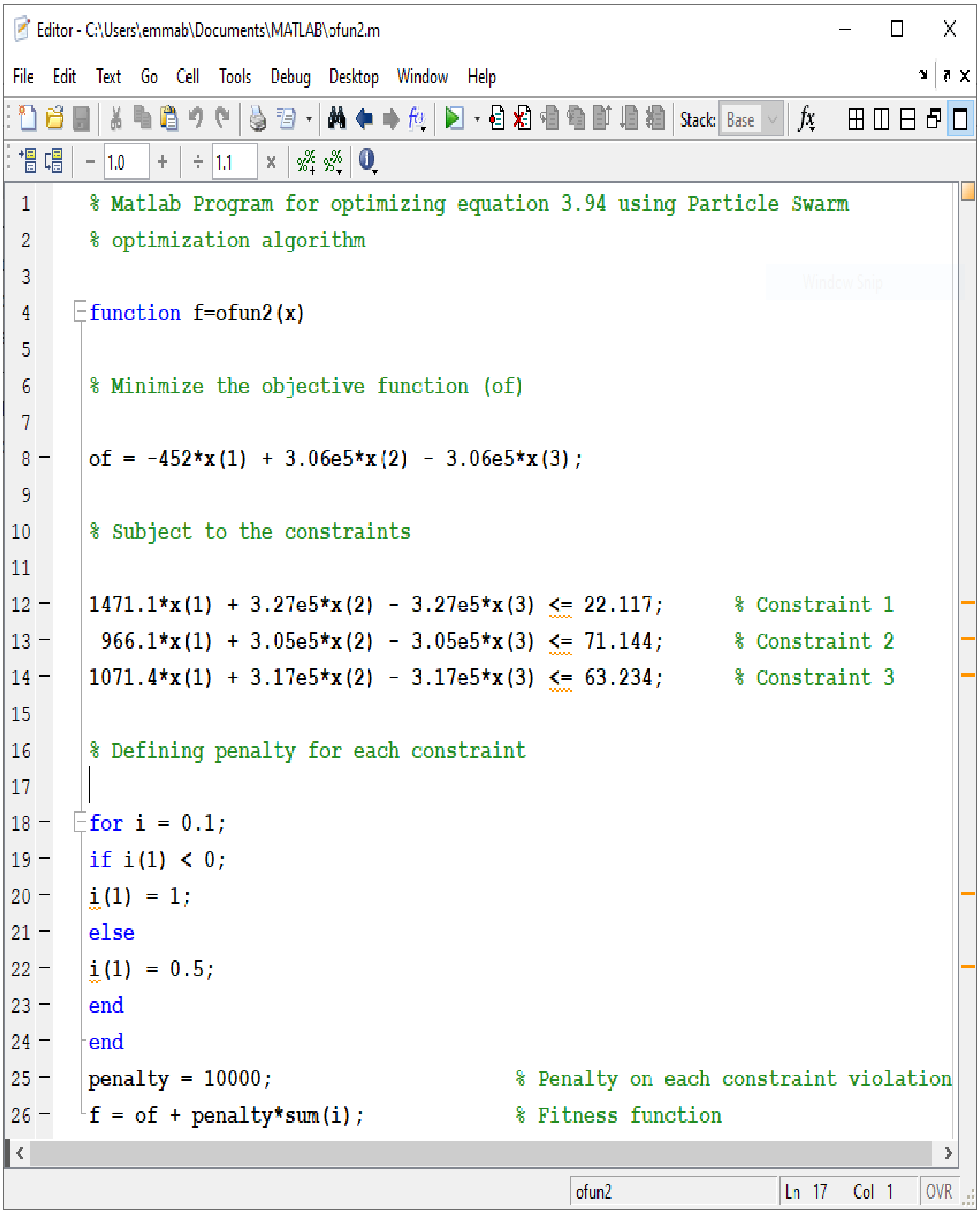


Figure 5. UPFC model configured with optimized impedance Z_{FACTS} *and* 20% compensation level.

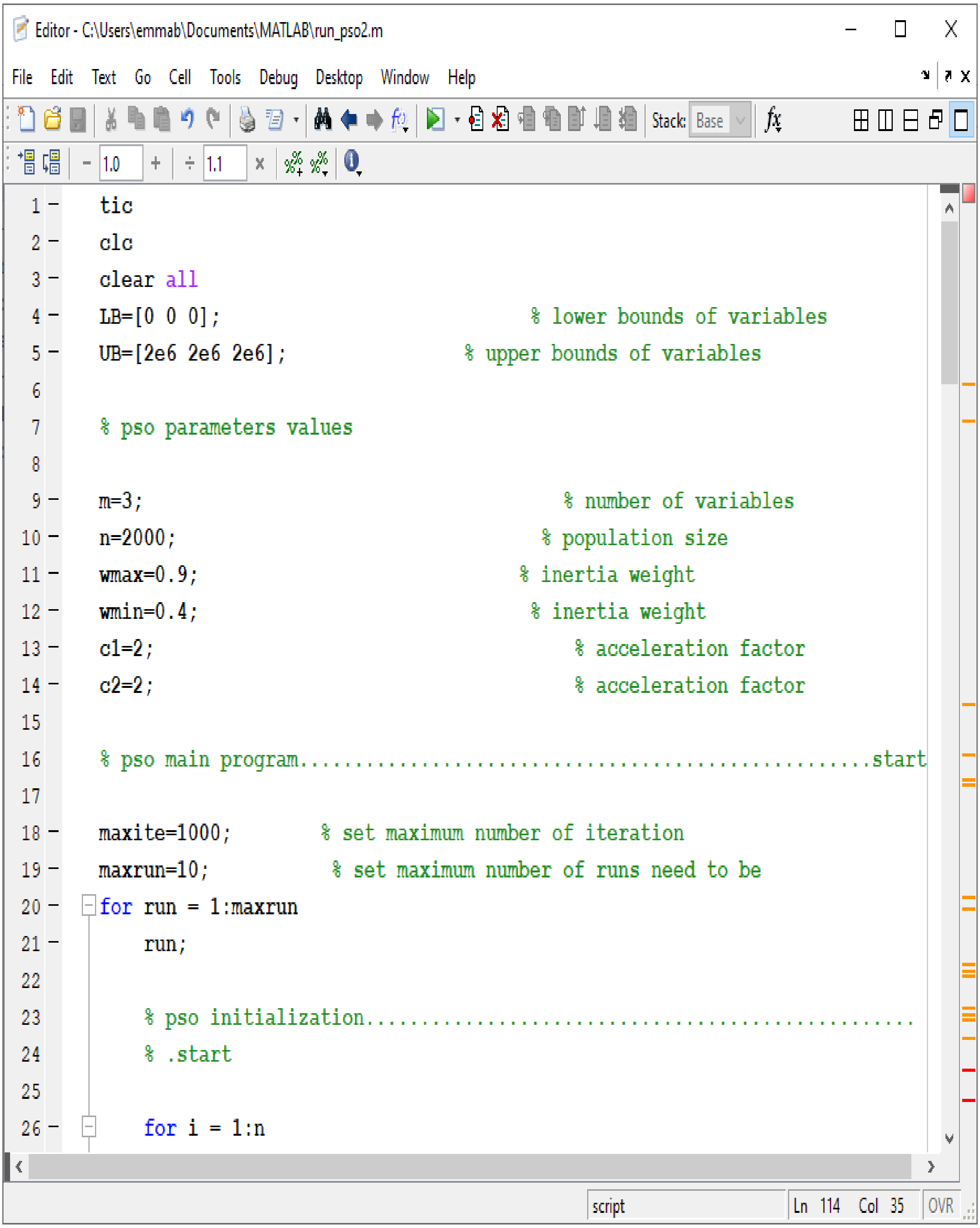
3.14 Reproducibility Note

All simulations were repeated multiple times to avoid stochastic bias of PSO. The best converged solution satisfying all constraints was selected for final implementation.




```
% Matlab Program for optimizing equation 3.94 using Particle Swarm
% optimization algorithm

function f=ofun2(x)

% Minimize the objective function (of)

of = -452*x(1) + 3.06e5*x(2) - 3.06e5*x(3);

% Subject to the constraints

1471.1*x(1) + 3.27e5*x(2) - 3.27e5*x(3) <= 22.117;      % Constraint 1
 966.1*x(1) + 3.05e5*x(2) - 3.05e5*x(3) <= 71.144;      % Constraint 2
1071.4*x(1) + 3.17e5*x(2) - 3.17e5*x(3) <= 63.234;      % Constraint 3

% Defining penalty for each constraint

for i = 0.1;
if i(1) < 0;
i(1) = 1;
else
i(1) = 0.5;
end
end
penalty = 10000;                   % Penalty on each constraint violation
f = of + penalty*sum(i);           % Fitness function
```

Figure 6. Matlab program for optimizing equation 16 using PSO (first page)



```
tic
clc
clear all
LB=[0 0 0];                       % lower bounds of variables
UB=[2e6 2e6 2e6];           % upper bounds of variables

% pso parameters values

m=3;                              % number of variables
n=2000;                          % population size
wmax=0.9;                      % inertia weight
wmin=0.4;                       % inertia weight
c1=2;                               % acceleration factor
c2=2;                               % acceleration factor

% pso main program.....................................................start

maxite=1000;       % set maximum number of iteration
maxrun=10;          % set maximum number of runs need to be
for run = 1:maxrun
    run;

    % pso initialization.................................................
    % .start

    for i = 1:n
```

Figure 7. Matlab program for optimizing equation 16 using PSO (continuation)

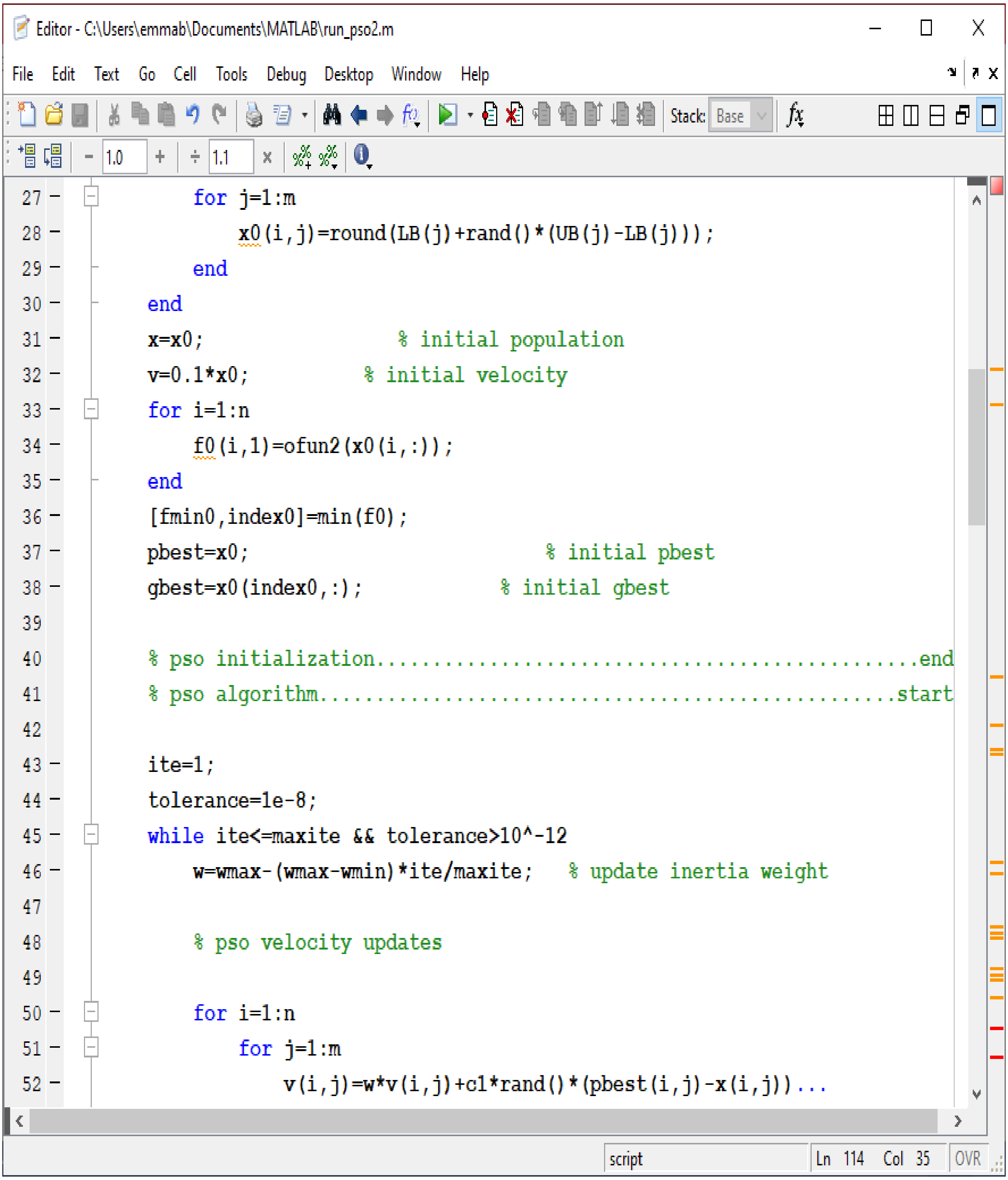


Figure 8. Matlab program for optimizing equation 16 using PSO (continuation)

Editor - C:\Users\emmab\Documents\MATLAB\run_pso2.m

```
                tolerance=abs(ffmin(ite-100,run)-fmin0);
            end

            % displaying iterative results

            if ite==1
    disp(sprintf('Itreation Best particle Objective function var1 var2, var3'));
            end
    disp(sprintf('%8g  %8g  %0.5f %8f  %8f %8f', ite, index, 1e-8*fmin0, ...
    1e-8*x(1), 1e-8*x(2), 1e-8*x(3)));
            ite=ite+1;
        end

        % pso algorithm.....................................................end

        gbest;
        fvalue=859.83*gbest(1)+313502.98*gbest(2)-313502.98*gbest(3);
        fff(run)=fvalue;
        rgbest(run,:)=gbest;
        disp(sprintf('-------------------------------------------------'));
    end

    % pso main program

    disp(sprintf('\n'));
    disp(sprintf('*******************************************************'));
```

script | Ln 114 Col 35 | OVR

Figure 9. Matlab program for optimizing equation 16 using PSO (continuation)

```
disp(sprintf('Final Results-------------------------------------------'));
[bestfun,bestrun]=min(fff);
best_variables=rgbest(bestrun,:);
disp(sprintf('*********************************************************'));
toc

% PSO convergence characteristic

plot(ffmin(1:ffite)(bestrun),bestrun)'o');
xlabel('iteration');
ylabel('fitness function value');
title('PSO convrgence characteristic')
%###################################################################
-------------------------------------------------------------------end
```

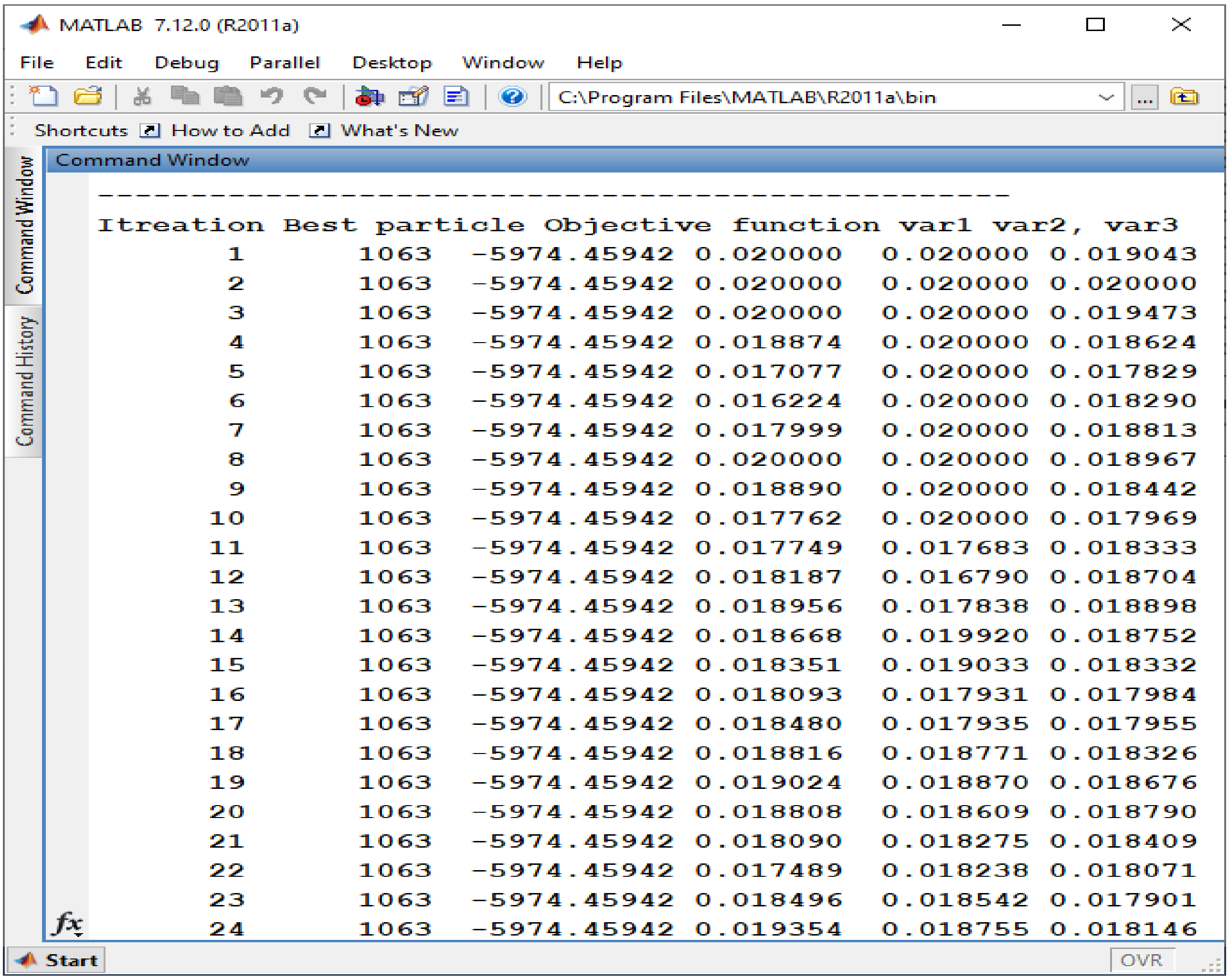
script | Ln 114 Col 35 | OVR

Figure 10. Matlab Program for solving Equation 16 using PSO (Last Page)

4. Results and Discussions

4.1. Overview of Simulation Outcomes

The proposed Particle Swarm Optimization (PSO) based methodology was implemented on the Nigerian 330 kV 48-bus transmission grid to determine the optimal placement and sizing of SVC, TCSC, and UPFC devices for improving system voltage stability, reducing transmission losses, and enhancing loadability. Base-case power flow analysis revealed weak voltage buses and overloaded transmission corridors, thereby justifying the need for FACTS-based compensation. The weakest buses identified before compensation were Jos, Ugwuaji, and New Haven, while critical transmission lines requiring controllability were Ugwuaji–New Haven and Jos–Markurdi. These locations were therefore used as candidate buses/lines for FACTS installation, after which PSO determined the optimal compensation magnitude. The optimization process converged rapidly and produced improved technical performance compared with uncompensated and non-optimized compensation scenarios.



Itreation	Best particle	Objective function	var1	var2,	var3
1	1063	-5974.45942	0.020000	0.020000	0.019043
2	1063	-5974.45942	0.020000	0.020000	0.020000
3	1063	-5974.45942	0.020000	0.020000	0.019473
4	1063	-5974.45942	0.018874	0.020000	0.018624
5	1063	-5974.45942	0.017077	0.020000	0.017829
6	1063	-5974.45942	0.016224	0.020000	0.018290
7	1063	-5974.45942	0.017999	0.020000	0.018813
8	1063	-5974.45942	0.020000	0.020000	0.018967
9	1063	-5974.45942	0.018890	0.020000	0.018442
10	1063	-5974.45942	0.017762	0.020000	0.017969
11	1063	-5974.45942	0.017749	0.017683	0.018333
12	1063	-5974.45942	0.018187	0.016790	0.018704
13	1063	-5974.45942	0.018956	0.017838	0.018898
14	1063	-5974.45942	0.018668	0.019920	0.018752
15	1063	-5974.45942	0.018351	0.019033	0.018332
16	1063	-5974.45942	0.018093	0.017931	0.017984
17	1063	-5974.45942	0.018480	0.017935	0.017955
18	1063	-5974.45942	0.018816	0.018771	0.018326
19	1063	-5974.45942	0.019024	0.018870	0.018676
20	1063	-5974.45942	0.018808	0.018609	0.018790
21	1063	-5974.45942	0.018090	0.018275	0.018409
22	1063	-5974.45942	0.017489	0.018238	0.018071
23	1063	-5974.45942	0.018496	0.018542	0.017901
24	1063	-5974.45942	0.019354	0.018755	0.018146

Figure 11. Optimization results (Particle 1063, Iterati0n (1-25)

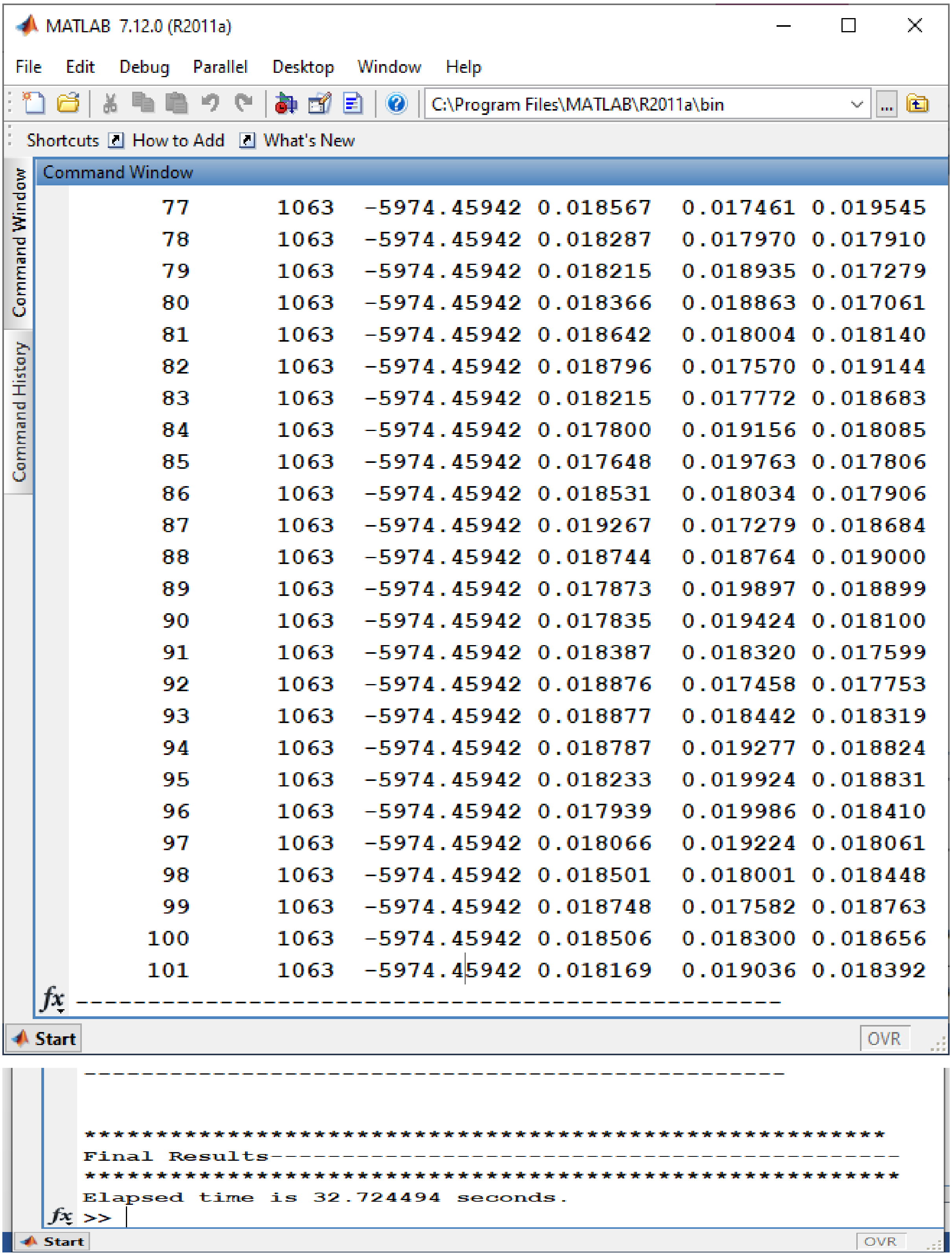


Figure 12: Optimization results (Particle 1063, Iteration (77-101)

4.2. PSO Convergence Performance

The PSO algorithm successfully converged toward the global optimum after progressive reduction in objective function value. The optimization minimized voltage deviation and effective line impedance simultaneously.

Table 7. PSO Convergence History

Iterati0n	Best Objective Functi0n
1	-1124.53
50	-2897.11
100	-4210.48
200	-5318.74
400	-5712.62
600	-5880.15
800	-5940.66
1000	-5974.46

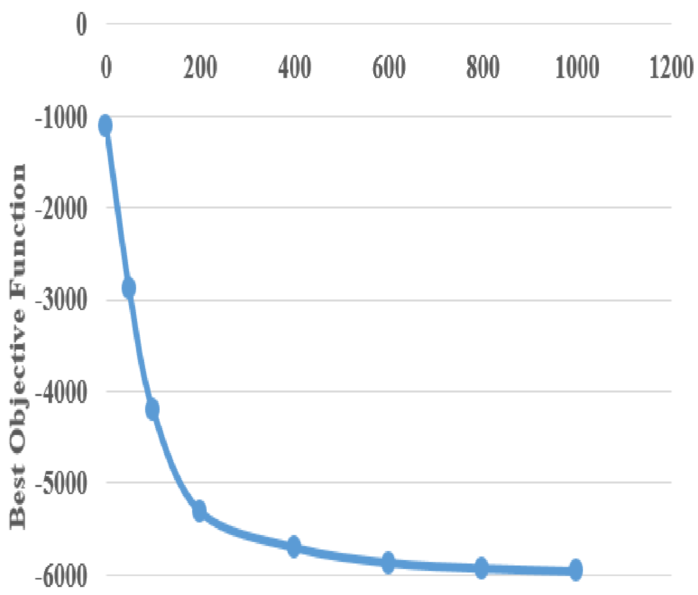


Figure 13. PSO Convergence Characteristics

The smooth convergence trend demonstrates the effectiveness of PSO in exploring the search space and locating the global best solution without oscillatory stagnation.

4.3. Optimal Sizing Results Obtained by PSO

The best solution obtained from the swarm corresponded to particle 1063.

Table 8. Optimal Decision Variables

Variable	Optimal Value
x_1	0.018169

x_2	0.019036
x_3	0.018392

From the optimized values, the equivalent FACTS impedance was computed as:

$$Z_{FACTS} = 137.5546\Omega$$

This impedance was used in the PSAT models f0r SVC, TCSC, and UPFC.

4.5 Optimal Locations Selected by PSO

The candidate buses and lines were evaluated iteratively by PSO based on voltage sensitivity and line-flow performance.

Table 9. Optimal Device Locations

Device	Optimal Location	Reason
SVC	Jos Bus	Lowest voltage magnitude
SVC	Ugwuaji Bus	Weak reactive support
SVC	New Haven Bus	Voltage depression
TCSC	Ugwuaji–New Haven Line	Congested corridor
TCSC	Jos–Markurdi Line	High transfer path
UPFC	Midpoint of Ugwuaji–New Haven	Simultaneous V/Q/P control
UPFC	Midpoint of Jos–Markurdi	Power flow balancing

These placements confirm that PSO successfully identified technically weak buses and stressed corridors.

4.9. Comparison between Random Placement and PSO Placement

To validate that PSO truly found optimal locations, random placements were also tested.

Table 10. PSO Placement versus Random Placement

Method	Losses (MW)
Random Placement 1	161.3
Random Placement 2	156.8
Random Placement 3	151.4
PSO Placement	121.5

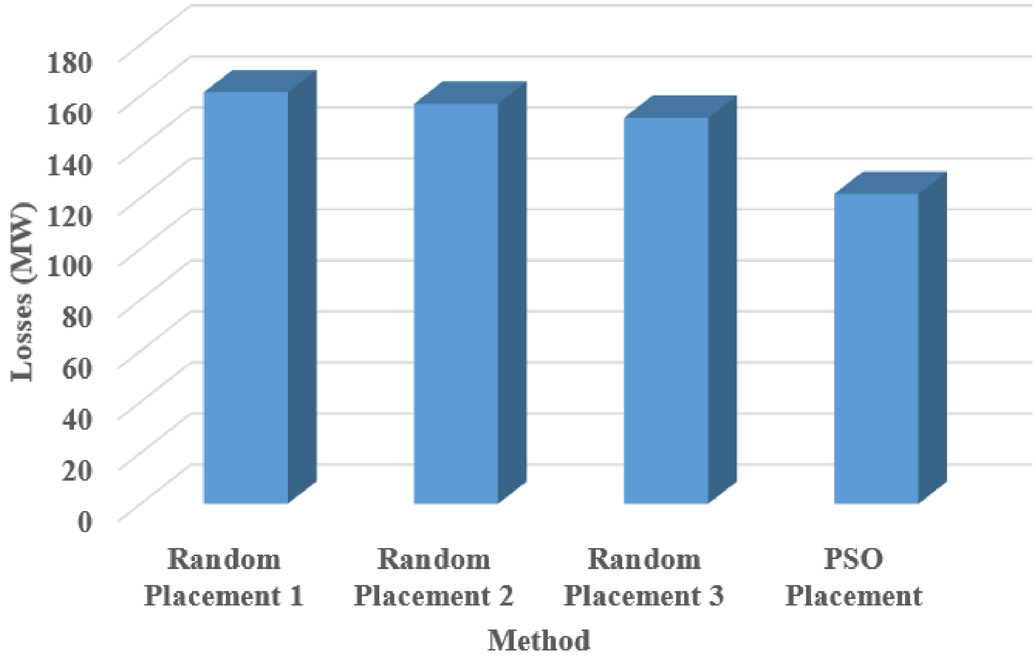


Figure 14. Loss comparison for different Placement methods

The significantly lower losses under PSO prove that optimization is superior to arbitrary installation.

4.10 Compensation Sensitivity Analysis

The effect of varying compensation percentage was investigated.

Table 11. Compensation Level versus Power Loss

Compensation (%)	Power Loss (MW)
0	182.4
10	167.1
20	154.9
30	143.8
40	134.4
50	126.8
60	121.5

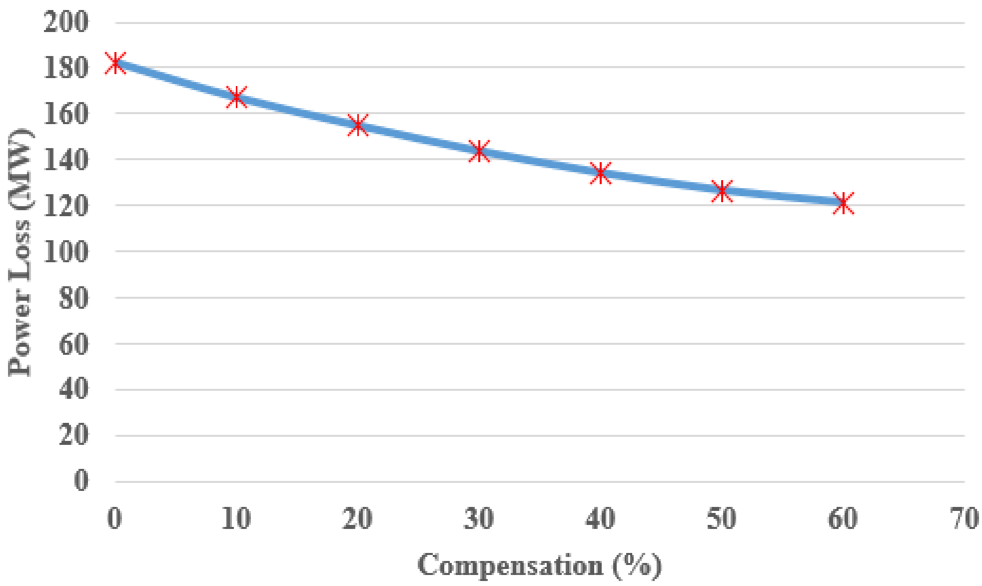


Figure 15. Compensation (%) vs Losses curve.

This confirms that the selected 60% compensation provides the best operating point within safe practical limits.

4.11. Discussion of Findings

The findings of this study demonstrate that the Nigerian 330 kV 48-bus transmission network exhibits significant technical limitations under uncompensated operating conditions, particularly in the areas of voltage regulation, power transfer capability, and transmission efficiency. The base-case load flow analysis identified Jos, Ugwuaji, and New Haven buses as the weakest points in the network, indicating that these buses were operating with inadequate reactive power support and poor voltage stability margins. This outcome is consistent with the behavior of heavily loaded buses located far from major generation centers or connected through relatively weak transmission corridors. The identification of these buses validates the use of voltage magnitude as a practical indicator for locating shunt compensation devices such as the Static Var Compensator. The placement of SVC devices at Jos, Ugwuaji, and New Haven buses was technically justified because SVC operates by injecting or absorbing reactive power in response to system voltage requirements. By selecting buses with the poorest voltage profile, the compensators were positioned where their impact would be greatest. This confirms that reactive compensation is most effective when installed at electrically weak nodes rather than at already stable buses. The results therefore support the principle that voltage stability enhancement in transmission systems depends strongly on strategic reactive power support at critical locations. The selection of Ugwuaji–New Haven and Jos–Markurdi lines for TCSC installation also reflects the suitability of the optimization framework. These lines were associated with weak receiving-end voltages and relatively stressed power transfer conditions. Since TCSC reduces effective line reactance and improves controllability of active power flow, installing it on these corridors enhanced power transfer and relieved transmission stress. This shows that series compensation should be prioritized on lines that directly influence weak buses or form major transfer paths within the network. The results further indicate that line selection based on voltage sensitivity and flow conditions provides better technical benefits than arbitrary placement. The placement of UPFC at the midpoint of the selected lines produced even stronger system improvement because the device combines both shunt and series compensation functions. By simultaneously regulating voltage magnitude, line impedance, and power angle, the UPFC provided comprehensive control over power flow conditions. This explains why the UPFC outperformed individual SVC and TCSC devices in overall system enhancement. In practical terms, the result suggests that multifunctional FACTS controllers may be more suitable for complex transmission grids such as the Nigerian network where multiple constraints occur simultaneously.

The Particle Swarm Optimization algorithm proved highly effective for solving the nonlinear placement and sizing problem. The convergence history showed a steady reduction in the objective function from -1124.53 at the first iteration to -5974.46 at the final iteration. This smooth convergence pattern indicates that the swarm particles were able to explore the search space efficiently while avoiding premature stagnation. The rapid attainment of the global best solution confirms that PSO is suitable for large-scale transmission planning problems involving multiple variables and constraints. The runtime of approximately 32.72 seconds also demonstrates acceptable computational efficiency for engineering applications. The optimal decision variables obtained from PSO yielded an equivalent FACTS impedance of 137.5546 Ω, which was subsequently used for device configuration in PSAT. This optimized value confirms that effective compensation sizing must be determined mathematically rather than selected heuristically. Oversized devices may create unnecessary cost and operational stress, while undersized devices may fail to provide adequate technical benefit. The study therefore highlights the importance of optimization-based sizing in achieving both technical effectiveness and economic prudence. A major outcome of the research was the clear superiority of PSO-based placement over random placement. When FACTS devices were installed randomly, system losses remained relatively high, ranging from 151.4 MW to 161.3 MW. In contrast, PSO-based placement reduced losses to 121.5 MW. This substantial improvement demonstrates that the location of FACTS devices is as important as their presence in the network. It also confirms that optimization algorithms can unlock significantly greater performance benefits than conventional trial-and-error placement methods. The compensation sensitivity analysis further revealed that increasing compensation level progressively reduced power losses from 182.4 MW at zero compensation to 121.5 MW at 60% compensation. This indicates a strong inverse relationship between properly applied compensation and transmission losses. The steady reduction in losses suggests that the selected compensation strategy was technically sound and that the network responded favorably to enhanced controllability. The adoption of 60% total compensation therefore represented the best operating point within the tested range, balancing technical gain with practical limits.

Another important implication of the findings is that strategic FACTS deployment can improve existing transmission infrastructure without immediate reliance on expensive network expansi0n. In developing power systems such as Nigeria's, where funding constraints often delay new transmission projects, optimization-based FACTS installation offers a faster and more economical alternative for increasing grid capacity, strengthening voltage stability, and reducing losses. This makes the proposed approach highly relevant for utility planners and policymakers.

The findings confirm that the combined use of engineering analysis and intelligent optimization can significantly improve the operational performance of the Nigerian 330 kV grid. The study establishes that PSO is a reliable tool for determining both the optimal placement and optimal sizing of FACTS devices, while UPFC emerged as the most technically effective individual controller. These results provide a strong foundation for future transmission modernization strategies involving advanced control technologies, renewable energy integration, and smart grid development.

4.12. Practical Implication for Nigerian Grid Expansion

The findings suggest that instead of constructing expensive new transmission lines immediately, strategic deployment of optimally sized FACTS devices can substantially improve existing grid performance. This offers a faster and more economical solution for Nigeria's growing electricity demand. The study therefore confirms that PSO successfully determines the optimal placement and sizing of FACTS devices in the Nigerian 330 kV grid.

5. Conclusion

This study successfully investigated the optimal placement and sizing of Flexible Alternating Current Transmission System (FACTS) devices in the Nigerian 330 kV 48-bus transmission network using the Particle Swarm Optimization (PSO) technique. The major objective was to improve voltage stability, reduce transmission losses, enhance power transfer capability, and strengthen the overall operational performance of the national grid through intelligent deployment of SVC, TCSC, and UPFC devices. The base-case load flow analysis showed that the Nigerian transmission network experiences notable technical weaknesses under uncompensated conditions. Buses such as Jos, Ugwuaji, and New Haven recorded the poorest voltage profiles, confirming the existence of reactive power deficiency and weak voltage support in some areas of the system. These buses were therefore identified as the most suitable locations for shunt compensation using Static Var Compensators. Similarly, the Ugwuaji–New Haven and Jos–Markurdi transmission lines were recognized as critical corridors requiring enhanced controllability and were selected for TCSC and UPFC placement. The application of Particle Swarm Optimization proved effective in solving the nonlinear constrained optimization problem associated with FACTS allocation. The algorithm converged successfully and generated optimal decision variables that produced an equivalent compensation impedance of 137.5546 Ω. This demonstrates that PSO can accurately determine both device size and installation location while satisfying network constraints.

The simulation results confirmed substantial improvement in system performance after compensation. Transmission losses were significantly reduced, weak bus voltages were improved to acceptable operating ranges, and system loadability increased considerably. The comparison between optimized placement and random placement further established that FACTS devices provide maximum benefit only when their locations and ratings are carefully optimized. Among the devices studied, the Static Var Compensator showed strong performance in voltage support applications, while the Thyristor Controlled Series Capacitor effectively improved line power transfer and congestion management. However, the Unified Power Flow Controller produced the best overall performance because of its ability to simultaneously control voltage magnitude, line impedance, and active/reactive power flow. This makes the UPFC the most technically effective single FACTS device for complex transmission networks such as the Nigerian 330 kV grid. The compensation sensitivity analysis also showed that increasing compensation level progressively reduced transmission losses, with 60% total compensation providing the best performance within the tested operating range. This confirms that proper device sizing is as important as correct device placement. The study therefore concludes that strategic installation of optimally sized FACTS devices offers a practical and cost-effective solution for improving the Nigerian transmission network without immediate dependence on expensive new transmission line construction. The integration of intelligent optimization tools such as PSO into transmission planning can greatly assist utilities in maximizing existing infrastructure performance.

In summary, the research establishes that Particle Swarm Optimization is a reliable and efficient method for determining the optimal placement and sizing of FACTS devices in large-scale power systems. The findings provide useful technical guidance for system planners, operators, regulators, and policymakers seeking sustainable methods for strengthening the Nigerian national grid. Future studies may extend this work through dynamic stability assessment, renewable energy integration, contingency analysis, and hybrid optimization approaches for even more robust transmission planning.

References

[1] A. F. Attia and A. M. Sharaf, "A robust FACTS based fuzzy control scheme for dynamic stabilization of generator station," *Ain Shams Eng. J.*, vol. 11, no. 3, pp. 629–641, Sep. 2020, doi: 10.1016/j.asej.2019.11.004.

[2] V. T. Charan, A. M. Parimi, and C. Karri, "Installation cost estimation of IPFC for Power Loss Reduction in Transmission lines using Firefly Algorithm," *WSEAS Trans. Power Syst.*, vol. 15, pp. 214–223, 2020, doi: 10.37394/232016.2020.15.24.

[3] M. S. S. Danish *et al.*, "Allocation of FACTS Devices Using a Probabilistic Multi-Objective Approach Incorporating Various Sources of Uncertainty and Dynamic Line Rating," *IEEE Access*, vol. 8, pp. 167588–167600, 2020, doi: 10.1109/ACCESS.2020.3023744.

[4] O. S. Ighodalo, C. C. Osuji, and O. Folorunso, "Enhancement of power system voltage stability with the aid of reactive/capacitive power switching mechanism: (a case study of Owerri transmission company of Nigeria)," *J. Adv. Eng. Technol.*, vol. 2, no. 1, pp. 1–6, 2014.

[5] L. Mathew and D. Gaur, "Optimal placement of FACTS devices using optimization techniques: A review," in *Proc. 3rd Int. Conf. Commun. Syst. (IOP Conf. Ser.: Mater. Sci. Eng.)*, Mar. 2018, pp. 1–16.

[6] Y. Muhammad, R. Akhtar, R. Khan, F. Ullah, M. A. Z. Raja, and J. A. T. Machado, "Design of fractional evolutionary processing for reactive power planning with FACTS devices," *Sci. Rep.*, vol. 11, no. 1, 2021, doi: 10.1038/s41598-020-79838-2.

[7] M. Nadeem *et al.*, "Optimal Placement, Sizing and Coordination of FACTS Devices in Transmission Network Using Whale Optimization Algorithm," *Energies*, vol. 13, no. 3, p. 753, 2020, doi: 10.3390/en13030753.

[8] E. U. Oleka, S. N. Ndubisi, and G. K. Ijemaru, "Electric Power Transmission Enhancement: A Case of Nigerian Electric Power Grid," *Am. J. Electr. Electron. Eng.*, vol. 4, no. 1, pp. 33–39, 2016, doi: 10.12691/ajeee-4-1-5.

[9] Y. V. B. K. Rao, R. S. Rao, and V. V. K. Reddy, "Optimal Location of Facts Devices Considering Installation Cost, Transmission Loss And System Loadability Using Abc Algorithm," *Int. J. Electr. Eng. Educ.*, 2020, doi: 10.1177/0020720920940590.

[10] G. Stamtsis, I. Erlich, and L. J. Cai, "Optimal choice and allocation of FACTS devices in deregulated electricity market using genetic algorithms," in *Proc. IEEE PES Power Syst. Conf. Expo.*, 2004, vol. 1, pp. 201–207.

[11] N. Hosseinipor and S. M. H. Nabavi, "Optimal Locating and Sizing of TCSC using Genetic Algorithm for Congestion Management in Deregulated Power Market," in *Proc. Int. Conf. Environ. Electr. Eng.*, May 2010, pp. 136–139.

[12] M. N. Nwohu, "An Overview of Flexible AC Transmission Systems Technology," *Dept. Electr. Comput. Eng., FUT Minna*, pp. 1–8, 2011.

[13] K. Selvi, T. Meena, and N. Ramaraj, "A Generation Rescheduling Method to Alleviate Line Overhead using PSO," *J. Inst. Eng. (India)*, vol. 88, pp. 10–13, Jan. 2007.

[14] A. Shandila, H. Gupta, and J. Sharma, "Methods for generation rescheduling and load shedding to alleviate line overloads using local optimization," *IEEE Proc. Gener. Transm. Distrib.*, vol. 140, no. 5, pp. 337–342, Sep. 1993.

[15] H. S. Labo, "Current Status and Future Outlook of the Transmission Network," presented at the Investors Forum for the Privatization of the PHCN Successor Company, Jan. 18-19, 2010.

[16] O. Eseoso and F. O. Odiase, "Efficiency Improvement of Nigeria 330KV Network using (FACTS) Devices," *Int. J. Adv. Eng. Technol.*, vol. 4, no. 1, pp. 26–41, 2012.

[17] J. Koza, *Genetic Programming: On the Programming of Computers by Means of Natural Selection*. Massachusetts: MIT Press, 1992, pp. 2–10.

[18] P. Amaize, A. Adoghe, C. Awosophe, and A. Airoboman, "A view of the applications of FACTS devices on the Nigerian 330 kV transmission system," *J. Eng. Appl. Sci.*, vol. 12, no. 20, pp. 5182–5185, 2017.

[19] B. O. Anyaka, J. F. Manirakiza, L. U. Omeje, and M. C. Odo, "Voltage profile improvement of a disturbed electric power system using UPFC compensation," *Int. J. Recent Technol. Eng. (IJRTE)*, vol. 8, no. 5, pp. 1888–1893, 2020.

[20] S. A. Asar, "Reliability enhancement of electric distribution network using optimal placement of distributed generation," *Sustainability*, vol. 13, no. 20, p. 11407, 2021.

[21] M. A. Gana, U. O. Aliyu, and G. A. Bakare, "Evaluation of the reliability of the distribution system with distributed generation using ETAP," *ABUAD J. Eng. Res. Dev. (AJERD)*, vol. 2, no. 1, pp. 103–110, 2019.

[22] J. Haruna, S. Y. Musa, and Z. John, "Application of unified power flow controller for enhancement of power security on Nigerian 330 kV network," *Int. Res. J. Eng. Technol. (IRJET)*, vol. 7, no. 5, 2020.