



APPLICATION OF GENETIC ALGORITHM BASED OPTIMAL PLACEMENT OF STATIC VAR COMPENSATOR FOR THE NIGERIAN 330 KV ELECTRICITY GRID PERFORMANCE ENHANCEMENT

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ABSTRACT

Power supply-demand imbalance is one of the critical challenges bedeviling the electricity grid operation of a third world nation such as Nigeria. This has consequently led to the system's poor voltage profile with its associated high-power losses. Many potent solutions have been proposed to address these problems; however, technological advancements favour the adoption and widespread use of a class of economic and fast acting solid-state controllers called flexible alternating current transmission systems (FACTS). This study, therefore, assessed the potential of an optimally placed static var compensator (SVC) via genetic algorithm (GA) in enhancing the performance of the Nigerian 330 kV, 28-bus electricity grid. The static power flow model of the system with and without SVC was analyzed using Newton-Raphson method and simulated in MATLAB R2020a environment. The system performance with SVC placed optimally using GA was compared with the first principle approach. The simulation results revealed that before compensation, the test grid had five buses namely Ayede, New-Haven, Gombe, Kano and Makurdi with voltage magnitudes of 0.926, 1.058, 0.906, 0.859 and 0.944 p.u., respectively, violating the acceptable voltage tolerance limit of $0.95 \leq V_i \leq 1.05$ p.u. The first principle-based compensation improved the voltage magnitudes of the critical buses on the test grid to 1.015, 1.008, 0.958, 0.995 and 0.975 p.u., respectively, while compensation via GA enhanced the voltage magnitudes to 1.05, 0.985, 1.038, 1.016 and 0.996 p.u. respectively. The grid's total active and reactive line losses reduced from 181.479 to 149.786 MW and 145.323 to 125.161 MVar, respectively with compensation from the first principle approach, whereas the values were minimized to 115.675 MW and 109.336 MVar, respectively with the GA based compensation. The GA based optimal placement of SVC exhibited better enhancement characteristics on the considered Nigerian electricity grid than the first principle method.

1.0 Introduction

Electrical energy is one of the available and most widely used forms of energy. It is a key ingredient in measuring the development of a nation. In a third world country such as Nigeria, increasing population and technological advancements have placed enormous demand on electrical power usage without sufficient energy generation to address it. Hence, creating electricity supply-demand imbalance (Dahunsi *et al.*, 2022; Akpojedje and Ogujor, 2021; Hussaini *et al.*, 2021; Ayamolowo *et al.*, 2019; Ogonnaya *et al.*, 2019; Yakuba, 2019; Emodi and

Yusuf, 2015). The imbalance between electricity supply and demand along with poor allocation of loads and overloading of transmission lines has affected the performance of the Nigerian power system negatively resulting into problems such as poor voltage profile, increased power losses, unreliable and poor-quality power supply among others (Ahmad and Sirjan, 2020; Idoniboyeobu *et al.*, 2018).

Over the years, many efforts have been put forward generally to solve the key operational problems hampering power systems from attaining full potential without the desired goal achieved. Conventional methods including construction of new generating stations, upgrading of existing transmission lines, expansion of distribution networks, the use of mechanical switches and capacitor banks have all been proposed in the past for improving the power system networks to enhance service delivery, however, some major limitations such as high investment cost, possible wear and tear of the mechanical components and time delay overshadowed the merits offered by these techniques (Ahmad and Sirjan, 2020; Muhammad *et al.*, 2020; Adebayo and Sun, 2017). This has, therefore, led to the emergence and adoption of FACTS for compensating power network performance.

FACTS are solid state devices with capacity to improve power system performance in a prompt manner, increase voltage profile, reduce power losses, increase system reliability, prevent cascading outages through emergency control and damp oscillations that can threaten system security (Shehata *et al.*, 2020; Rana *et al.*, 2019; Adebisi *et al.*, 2018; Simeon *et al.*, 2018; Adebisi *et al.*, 2017). Members of this family include but not limited to unified power flow controller, static synchronous compensator, interline power flow controller, static synchronous series compensator, static var compensator and thyristor-controlled series capacitor (Bharambe, 2021; Shelke and Bhole, 2021; Kaur and Gupta, 2021; Muhammad *et al.*, 2020; Siddique *et al.*, 2019; Movahedi *et al.*, 2019; Adebisi *et al.*, 2018). Usually, FACTS are incorporated into power system networks for performance improvement either through the use of first principle or optimization approach. While first principle involves manual installation of FACTS devices in some defective buses where voltage tolerance limit has been violated, optimization approach involves the integration of FACTS controllers at the best node or branch where its impact can generally be felt by the entire system using versatile techniques such as artificial intelligence (AI). Placement of FACTS devices via first principle which is inherently characterised by slow response is unsuitable for today's large-scale power system operation considering the complexity of different networks and the data structure. This, therefore, paves way for optimal placement of FACTS controllers using efficient optimization techniques such as AI based methods that can handle the complexity involved in the analysis of power system networks with spontaneous response.

Artificial intelligence, in a simple term, is a field of study concerned with the creation of human-like thought processes such as reasoning, perceiving, learning, interaction and self-correction to facilitate robust problem solving (Ergen, 2019; Grewal, 2014). Widespread adoption of AI based applications in recent times in various aspects of human endeavours including power system engineering has been attributed to massive data, advancements in algorithms as well as growing economical computational power and storage (Ergen, 2019). Different AI techniques have been deployed for optimal placement of FACTS for enhancing power system network performance. Among the commonly used techniques are artificial neural network (ANN), fuzzy logic (FL), differential evolution algorithm, ant colony optimization, genetic algorithm (GA),

particle swarm optimization (PSO) and harmony search algorithm (Singh and Swami, 2020; Gaur and Mathew, 2018; Nabavi et al., 2011). Each of these techniques offers varying degree of dynamisms which adapts them suitably to the problems being addressed.

Therefore, in this work, an optimally placed SVC via GA was employed to enhance the performance of the Nigerian 330 kV electricity grid. SVC possesses an excellent capability to compensate reactive power and regulate voltages at various buses in power system networks (Ćalasan et al., 2020; Biswas and Das, 2011). Due to these reasons, several investigations have been conducted on potential application of SVC for varieties of performance improvement related issues in power system; voltage stability control (Muthukumar et al., 2023; Al-Saidi et al., 2023), power loss minimization (Osman et al., 2023; Lakshmi, 2021), transient stability improvement (Ikonwa et al., 2023; Sahare and Bonde, 2020) and dynamic stability enhancement (Essien et al., 2023; Himaja et al., 2022). The choice of GA for optimal placement of SVC to improve the performance of a power system network in the present work was due to its high flexibility, efficiency, positive outcomes and user-friendliness (Kothai and Jayapal, 2021; AdebANJI et al., 2020).

1.1 Static Var Compensator

An SVC is a shunt compensator capable of generating or drawing var for power system voltage stabilization. SVC will consume reactive power from the power network if such system is characterized by a capacitive or leading reactive load and hence, reduces the system voltage. It will, however, increase the system voltage through reactive power injection if the network is characterized by an inductive or lagging condition (Kumar and Dash, 2016).

Basically, SVC is composed of air core reactors in series with thyristor which is connected in parallel to filter banks as shown in Figure 1. With proper adjustment of the thyristor firing angle, the current of air-core reactors can be controlled to produce voltage within acceptable limit at the bus. Generally, SVC is an efficient FACTS device that can regulate bus voltage magnitude, improve power flow along transmission lines, reduce power losses, increase system load ability among other (Anand, 2017; Kumar and Dash, 2016).

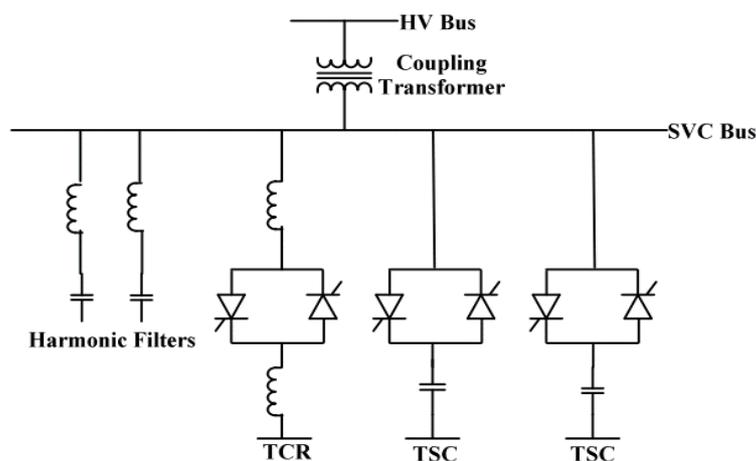


Figure 1: An SVC configuration (Adebisi et al., 2018)

2 Materials and Methods

2.1 Power Flow Analysis

Power flow is an essential mathematical tool for obtaining insightful information about power system performance under steady state operating conditions (Gupta, 2011; Hadi, 2008; Kothari and Nagrath, 2008). For this work, a typical power system bus arrangement depicted in Figure 2 was considered for the theoretical analysis of power flow. The resultant current with KCL applied to the n-bus arrangement in Figure 2 and the complex apparent power delivered at bus i are respectively expressed by equations (1) and (2):

$$I_i = \sum_{j=1}^n Y_{ij} V_j ; i, j = 1, 2, \dots, n \quad (1)$$

$$S_i = P_i + jQ_i = V_i I_i^* \quad (2)$$

where: V_i , I_i , P_i , Q_i and S_i respectively denote voltage (V), current (A), active power (W), reactive power (VAR) and apparent power (VA) associated with bus i ; I_i^* , V_j and Y_{ij} denote complex conjugate of bus i current (A), bus j voltage (V) and transfer admittance of bus i relative to bus j respectively (U).

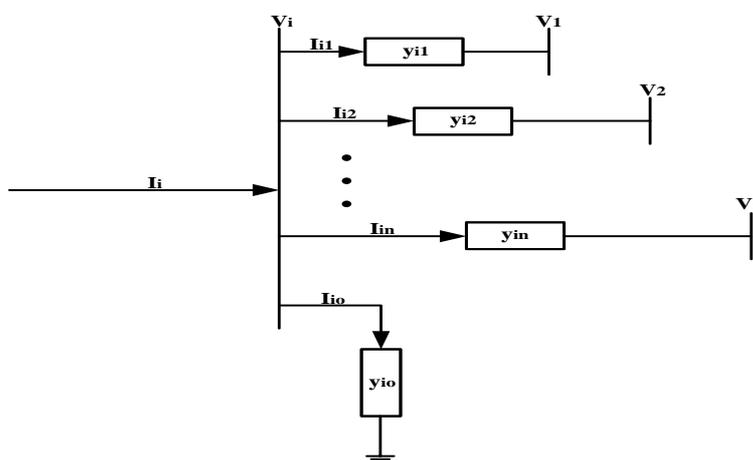


Figure 2: A typical power system n-bus arrangement (Gupta, 2011; Kothari and Nagrath, 2008; Hadi, 2008)

The use of equation (1) in equation (2) yields equation (3) which was decoupled into real and imaginary parts expressed by equations (4) and (5) respectively:

$$S_i^* = P_i - jQ_i = V_i^* \sum_{j=1}^n Y_{ij} V_j ; i = 1, 2, \dots, n \quad (3)$$

$$P_i = \text{Re}\{V_i^* \sum_{j=1}^n Y_{ij} V_j\} \quad (4)$$

$$Q_i = -\text{Im}\{V_i^* \sum_{j=1}^n Y_{ij} V_j\} \quad (5)$$

The use of polar coordinates form of V_i , V_i^* , V_j , and Y_{ij} given by equation (6) in equations (4) and (5) results in equations (7) and (8) respectively:

$$\left. \begin{aligned} V_i &= |V_i|e^{jd_i} \\ V_i^* &= |V_i|e^{-jd_i} \\ V_j &= |V_j|e^{jd_j} \\ Y_{ij} &= |Y_{ij}|e^{j\theta_{ij}} \\ e^{jf} &= \cos f + j \sin f \end{aligned} \right\} \quad (6)$$

where: d_i and θ_{ij} respectively denotes bus i voltage angle ($^\circ$) and line admittance angle ($^\circ$).

$$P_i = \sum_{j=1}^n Y_{ij} V_i V_j \cos(\theta_{ij} + d_j - d_i) \quad (7)$$

$$Q_i = - \sum_{j=1}^n Y_{ij} V_i V_j \sin(\theta_{ij} + d_j - d_i) \quad (8)$$

The expressions of equations (7) and (8) together constitute the static power flow equations. They are non-linear equations whose solutions are obtained through numerical iterative method (Gupta, 2011; Hadi, 2008; Kothari and Nagrath, 2008). Newton-Raphson iterative technique was employed in this work to linearize equations (7) and (8) because of its faster convergence, accuracy, reduced iteration number and reliability.

$$\begin{bmatrix} P_2 \\ P_3 \\ \vdots \\ P_n \\ Q_2 \\ Q_3 \\ \vdots \\ Q_n \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2}{\partial d_2} & \frac{\partial P_2}{\partial d_3} & \dots & \frac{\partial P_2}{\partial d_n} & | & \frac{\partial P_2}{\partial V_2} & \frac{\partial P_2}{\partial V_3} & \dots & \frac{\partial P_2}{\partial V_n} \\ \frac{\partial P_3}{\partial d_2} & \frac{\partial P_3}{\partial d_3} & \dots & \frac{\partial P_3}{\partial d_n} & | & \frac{\partial P_3}{\partial V_2} & \frac{\partial P_3}{\partial V_3} & \dots & \frac{\partial P_3}{\partial V_n} \\ \vdots & \vdots & \vdots & \vdots & | & \vdots & \vdots & \vdots & \vdots \\ \frac{\partial P_n}{\partial d_2} & \frac{\partial P_n}{\partial d_3} & \dots & \frac{\partial P_n}{\partial d_n} & | & \frac{\partial P_n}{\partial V_2} & \frac{\partial P_n}{\partial V_3} & \dots & \frac{\partial P_n}{\partial V_n} \\ \frac{\partial Q_2}{\partial d_2} & \frac{\partial Q_2}{\partial d_3} & \dots & \frac{\partial Q_2}{\partial d_n} & | & \frac{\partial Q_2}{\partial V_2} & \frac{\partial Q_2}{\partial V_3} & \dots & \frac{\partial Q_2}{\partial V_n} \\ \frac{\partial Q_3}{\partial d_2} & \frac{\partial Q_3}{\partial d_3} & \dots & \frac{\partial Q_3}{\partial d_n} & | & \frac{\partial Q_3}{\partial V_2} & \frac{\partial Q_3}{\partial V_3} & \dots & \frac{\partial Q_3}{\partial V_n} \\ \vdots & \vdots & \vdots & \vdots & | & \vdots & \vdots & \vdots & \vdots \\ \frac{\partial Q_n}{\partial d_2} & \frac{\partial Q_n}{\partial d_3} & \dots & \frac{\partial Q_n}{\partial d_n} & | & \frac{\partial Q_n}{\partial V_2} & \frac{\partial Q_n}{\partial V_3} & \dots & \frac{\partial Q_n}{\partial V_n} \end{bmatrix} \begin{bmatrix} d_2 \\ d_3 \\ \vdots \\ d_n \\ V_2 \\ V_3 \\ \vdots \\ V_n \end{bmatrix} \quad (9)$$

The linearized set of Newton-Raphson power flow equations is given by equation (9) with modified variant in equation (10).

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} d \\ V \end{bmatrix} \quad (10)$$

where: P , Q , d and V respectively denotes mismatch in active power (W), reactive power (VAr), phase angle ($^\circ$) and voltage (V) and J_1, J_2, J_3 and J_4 are the Jacobian matrix elements obtained as partial derivatives of equations (7) and (8) with d and V as independent variables.

At each level of iteration, the mismatch in active and reactive power with updated bus voltage phase angle and magnitude are given equations (11) to (14):

$$P_i^k = P_i^{spec} - P_i^k \quad (11)$$

$$Q_i^k = Q_i^{spec} - Q_i^k \quad (12)$$

$$d_i^{k+1} = d_i^k + \Delta d_i^k \quad (13)$$

$$V_i^{k+1} = V_i^k + \Delta V_i^k \quad (14)$$

where: k is the iteration count, P_i^k , Q_i^k , d_i^k and V_i^k respectively denotes mismatch in bus i active power (W), reactive power (VAr), voltage angle ($^\circ$) and voltage magnitude (V) at

iteration k , P_i^{spec} and Q_i^{spec} denote bus i specified active power (W) and reactive power (VAr) respectively, P_i^k , Q_i^k , d_i^k and V_i^k respectively denotes bus i calculated active power (W), reactive power (VAr), voltage angle ($^\circ$) and voltage magnitude (V) at iteration k and d_i^{k+1} and V_i^{k+1} denote updated bus i voltage angle ($^\circ$) and voltage magnitude (V) at iteration $k + 1$ respectively.

The voltage and reactive power constraints imposed at bus i are expressed by equations (15) and (16) respectively:

$$V_{imin} = V_i = V_{imax} \quad (15)$$

$$Q_{imin} = Q_i = Q_{imax} \quad (16)$$

where: V_{imin} , V_{imax} , Q_{imin} and Q_{imax} respectively denotes minimum voltage magnitude (V), maximum voltage magnitude (V), minimum reactive power supply (VAr) and maximum reactive power supply (VAr) at bus i .

2.2 Power Flow Modeling of an SVC

Referring to Figure 2, an SVC placed at bus i acted or served as reactive power Q_{SVCi} generator or absorber. Hence, the effective var at bus i is obtained by equation (17) (Auchariyamet and Sirisumrannukul, 2010):

$$Q_i = Q_{gi} - Q_{SVCi} = Q_{li} \quad (17)$$

where: Q_{gi} , Q_{li} and Q_{SVCi} respectively represents reactive power generation (VAr), reactive power demand (VAr) and SVC reactive power (VAr) at bus i .

Considering the SVC representation in Figure 3, the controller was modelled as a variable susceptance with the right constraint imposed on the susceptance or the firing angle.

The current taken by the SVC and the equivalent reactive power absorbed are respectively expressed by equations (18) and (19) (Adebisi et al., 2018; Adebisi et al., 2017):

$$I_{SVC} = B_{SVC}V_i \quad (18)$$

$$Q_{SVC} = Q_i = -V_i^2 B_{SVC} \quad (19)$$

where: I_{SVC} , B_{SVC} and Q_{SVC} represents SVC current (A), susceptance (U) and reactive power (VAr) respectively.

Equation (19) gives an expression for the reactive power supplied when an SVC is installed at bus i . The linearized set of equations modeling the SVC at bus i where B_{SVC} is considered as a state variable are expressed by equation (20) (Adebisi et al., 2018; Adebisi et al., 2017):

$$\begin{bmatrix} P_i \\ Q_i \end{bmatrix}^{(k)} = \begin{bmatrix} 0 & 0 \\ 0 & Q_i \end{bmatrix}^{(k)} \begin{bmatrix} d_i \\ B_{SVC}/B_{SVC} \end{bmatrix}^{(k)} \quad (20)$$

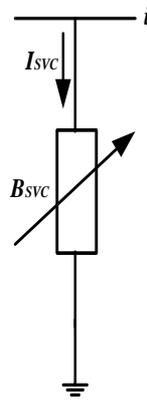


Figure 3: A variable shunt susceptance model of an SVC

At the end of iteration k , the updated B_{SVC} is expressed as equation (21):

$$B_{SVC}^{(k)} = B_{SVC}^{(k-1)} + \left(\frac{\Delta B_{SVC}}{B_{SVC}}\right)^{(k)} B_{SVC}^{(k-1)} \quad (21)$$

The susceptance of the SVC, B_{SVC} , is related to its firing angle a_{SVC} by equation (22):

$$B_{SVC} = \frac{-1}{X_C X_L} \left\{ X_L - \frac{X_C}{p} [2(p - a_{SVC}) + \sin(2a_{SVC})] \right\} \quad (22)$$

where: X_C and X_L are respectively the SVC capacitive and inductive reactances in Ω .

The Newton-Raphson power flow equations with firing angle a in degrees ($^\circ$) as the new state variable is expressed as equation (23) (Adebisi et al., 2018; Adebisi et al., 2017):

$$\begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix}^{(k)} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{dQ_i}{da} \end{bmatrix}^{(k)} \begin{bmatrix} \Delta a_{SVC} \\ \Delta i \end{bmatrix}^{(k)} \quad (23)$$

Where:

$$\frac{dQ_i}{da} = \frac{2V_i^2}{pX_L} [\cos(2a_{SVC}) - 1] \quad (24)$$

The updated a_{SVC} after iteration k is given by equation (25):

$$a_{SVC}^{(k)} = a_{SVC}^{(k-1)} + \Delta a_{SVC}^{(k)} \quad (25)$$

2.3 Genetic Algorithm Based Optimal Placement of SVC

With the inherent shortcomings of the conventional methods, FACTS devices today play crucial roles in enhancing the power system performance so that the wide margin between supply and demand for electrical energy could be minimized. The deployment of FACTS controllers for power system performance improvement usually involves a huge initial capital investment. Therefore, to ensure these devices operate at maximum efficiency and produce satisfactory effect, their placement and sizing in power networks needs to be optimised. Various approaches are available for optimizing the location or placement of FACTS devices. However, for this study, an artificial intelligence-based technique called genetic algorithm was adopted for optimizing the location of SVC.

Genetic algorithm is a heuristic optimization approach inspired by the principle of genetics and natural selection. It is commonly employed tool for solving constrained and unconstrained problems arising in many fields of study. It is fast, efficient and has a good parallel capability in addition to its ability to produce multiple of good solutions. The flowchart of the implementation process of the genetic algorithm based optimal placement of SVC in this work is shown in Figure 4.

Typically, GA architecture is segmented into three distinct phases which are initial population generation, objective function evaluation and genetic operations. Initial population generation phase involves random generation of possible solutions of the problem. This is followed by the computation of the objective function on every individual of the population to evaluate their fitness. New population sets are then generated via genetic operation involving reproduction, crossover and mutation until the maximum number of iterations is reached with each iteration equating to a generation. The cycle represented by these three phases of GA architecture is repeated severally until final improved solution is achieved. For the GA optimization in this work, the SVC was configured based on two control parameters which are location and size setting of the device. To take these two parameters into account in the optimization process, each individual was represented with two strings during implementation.

The first string corresponds to the location of the SVC which comprises the number of buses where the device is to be installed while the second string corresponds to the size setting of the controller. The strings have discrete values between 0 and 1, with 0 representing the minimum value that the controller can take and 1, the maximum value. The creation of an individual was done by randomly generating all the possible buses or lines of the power network that could be a suitable location for the SVC within the range of the number of bus data under consideration.

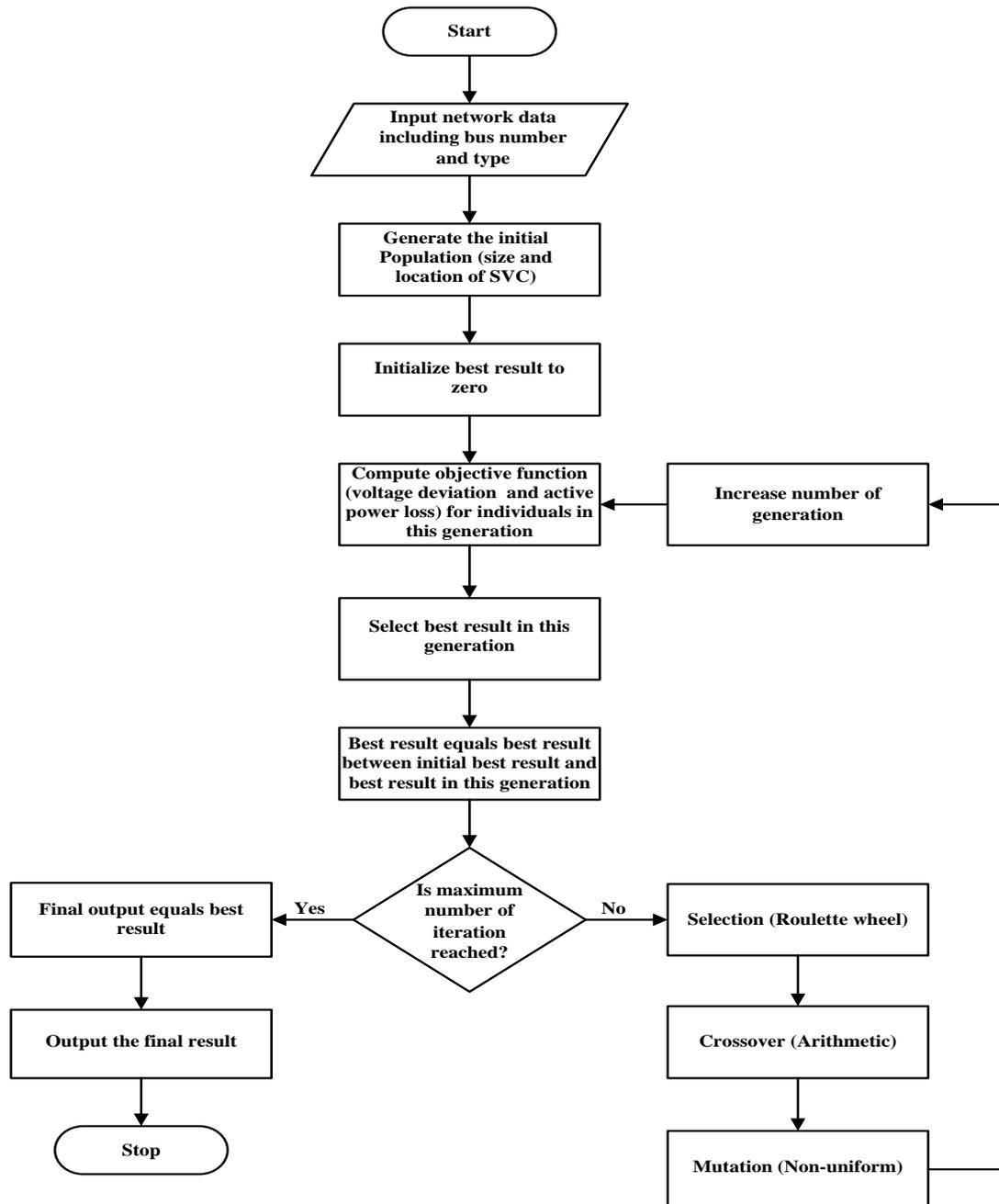


Figure 4: GA flowchart for the implementation of optimal placement of SVC

This was then followed by the characterization of the controller. Finally, the size of the device was randomly chosen among the possible values and the objective functions which are voltage deviation minimization and active power loss reduction were determined for every individual of the population sets and subjected to further optimization procedures involving reproduction, crossover and mutation to produce new and improved population sets which are the final solutions. The two components of the objective function in the flowchart of Figure 4, that is, voltage deviation and active power loss are respectively defined by equations (32) and (33):

$$V_D = \sum_{j=1}^n |V_j - V_j^{ref}| \quad (32)$$

$$P_L = \sum_{j=1}^n (g_j (V_i^2 + V_j^2 - 2V_i V_j \cos(d_i - d_j))) \quad (33)$$

where: V_D is the voltage deviation (V), V_j^{ref} is the reference of the bus j voltage (V), P_L is the real power loss (W) and g_j is the conductance of the connecting line between buses i and j (Ω).

For power system analysis, unless specified, it is usual to maintain the bus voltages within $\pm 5\%$ of the nominal value (Ezeruigbo *et al.*, 2021). Hence, the voltage tolerance of $0.95 = V_i = 1.05 p.u.$ was adopted in this work.

2.4 Test Network

The test network considered in this work to assess the performance enhancement capability of SVC was the Nigerian 28-bus power grid. The grid whose one-line diagram is presented in Figure 5 comprised of twenty-eight buses, fifty-two transmission lines and nine generating stations. The network and generator data of the system are respectively presented in Tables 1 to 3.

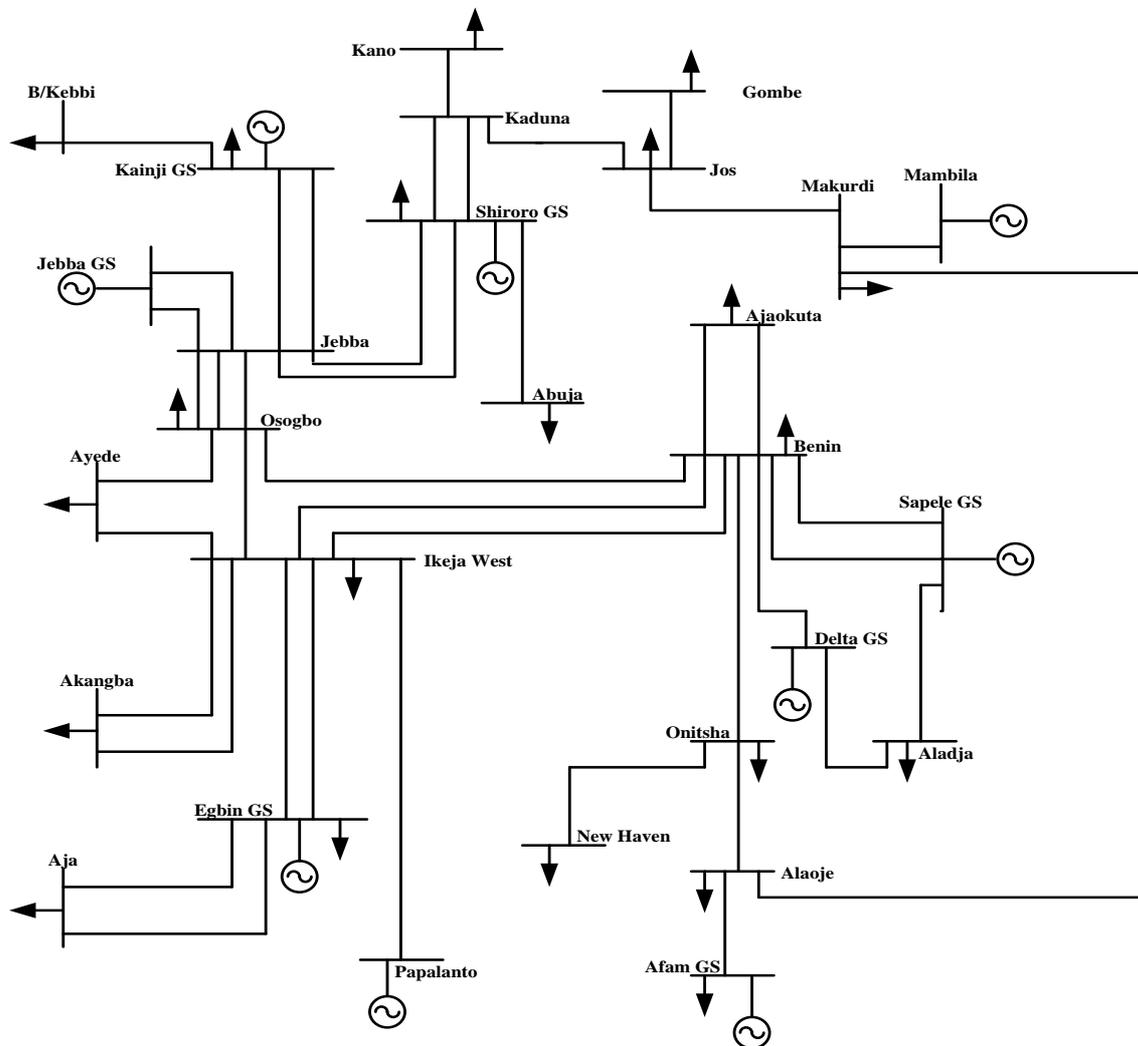


Figure 5: The Nigerian 28-bus power network (NCC, 2012)

Table 1: Bus data of the Nigerian 28-bus power network

Bus Identification		Bus Loads	
Name	No	MW	MVA _r
Egbin	1	68.90	51.70
Delta	2	0.00	0.00
Aja	3	274.40	205.80
Akangba	4	244.70	258.50
Ikeja-West	5	633.20	474.90
Ajaokuta	6	13.80	10.30
Aladja	7	96.50	72.40
Benin	8	383.30	287.50
Ayede	9	275.80	206.8
Osogbo	10	201.20	150.90
Afam	11	52.50	39.40
Alaoji	12	427.00	320.20
New-Heaven	13	177.90	133.40
Onitsha	14	184.60	138.40
B/Kebbi	15	114.50	85.90
Gombe	16	130.60	97.90
Jebba	17	11.00	8.20
Jebba G	18	0.00	0.00
Jos	19	70.30	52.70
Kaduna	20	193.00	144.70
Kanji	21	7.00	5.20
Kano	22	220.60	142.90
Shiroro	23	70.30	36.10
Sapele	24	20.60	15.40
Abuja	25	110.00	89.00
Makurdi	26	290.10	145.00
Mambila	27	0.00	0.00
Papalanto	28	0.00	0.00

Table 2: Transmission Line of the Nigerian 28-Bus Power System

Transmission Lines Data			
Bus		Resistance R(pu)	Reactance X(pu)
From	To		
1	3	0.0006	0.0044
4	5	0.0007	0.0050
1	5	0.0023	0.0176
5	8	0.0110	0.0828
5	9	0.0054	0.0405
5	10	0.0099	0.0745
6	8	0.0077	0.0576
2	8	0.0043	0.0317
2	7	0.0012	0.0089
7	24	0.0025	0.0186
8	14	0.0054	0.0405
8	10	0.0098	0.0742
8	24	0.0020	0.0148
9	10	0.0045	0.0340

15	21	0.0122	0.0916
10	17	0.0061	0.0461
11	12	0.0010	0.0074
12	14	0.0060	0.0455
13	14	0.0036	0.0272
16	19	0.0118	0.0887
17	18	0.0002	0.0020
17	23	0.0096	0.0271
17	21	0.0032	0.0239
19	20	0.0081	0.0609
20	22	0.0090	0.0680
20	23	0.0038	0.0284
23	25	0.0038	0.0284
12	26	0.0071	0.0532
19	26	0.0059	0.0443
26	27	0.0079	0.0591
5	28	0.0016	0.0118

Table 3: Generator Data of the Nigerian 28-Bus Power System

Bus Identification		Voltage	Generator		Reactive Limits	
Name	No	Magnitude	MW	MVAR	Q_{min}	Q_{max}
Egbin	1	1.05	0.00	0.00	-1006	1006
Delta	2	1.05	670.00	0.00	-1030	1000
Afam	11	1.05	431.00	0.00	-1000	1000
Jebba G	18	1.05	495.00	0.00	-1050	1050
Kanji	21	1.05	624.70	0.00	-1010	1010
Shiroro	23	1.05	388.90	0.00	-1010	1010
Sapele	24	1.05	190.30	0.00	-1010	1010
Mambila	27	1.05	750.00	0.00	-1010	1010

2.5 Simulation Software

In power system analyses, computer programs or software play a very vital role. They allow the performance of complicated system to be simulated or verified within a short period of time so that insightful information about the real time behaviour of the system can be obtained. In this work, the GA steps in the flowchart of Figure 4 were implemented on the network of Figure 5 through codes written using a MATLAB programming language, R2020a version. MATLAB was adopted because it provides an interactive environment for design and manipulation of algorithms in addition to data visualization, data analysis and numerical computation capabilities (Nasiruzzaman, 2010).

3 Results and Discussion

The voltage profile and power losses of the test power grid before and after optimally placed SVC with the bus, branch and generator data in Tables 1 to 3 as the input variables during simulation to fully characterize the network are shown in Figures 6 and 7. The results in Figure 6 showed that GA based optimal placement of SVC on the Nigerian 28-bus power grid improved the voltage profile of the overall network much better than the first principle procedure. When no compensation was applied on the grid, the voltage magnitudes of Ayede, New-Haven, Gombe, Kano and Makurdi (buses 9, 13, 16, 22 and 26) which were 0.926, 1.058,

0.906, 0.859 and 0.944 p.u. respectively fell out of the voltage tolerance limit of $0.95 \leq V_i \leq 1.05$ p.u. Optimal placement of the SVC via first principle on Makurdi where the size of the compensator was 10.35 MVar improved the voltage magnitude of the node itself and Ayede, New Haven and Gombe to 1.015, 1.008, 0.958 and 0.995 p.u. respectively, which are now within the voltage tolerance limit. However, this process produced a voltage magnitude of 1.065 p.u. at Kano which was still outside the statutory limit. This drawback was overcome by GA based optimization technique.

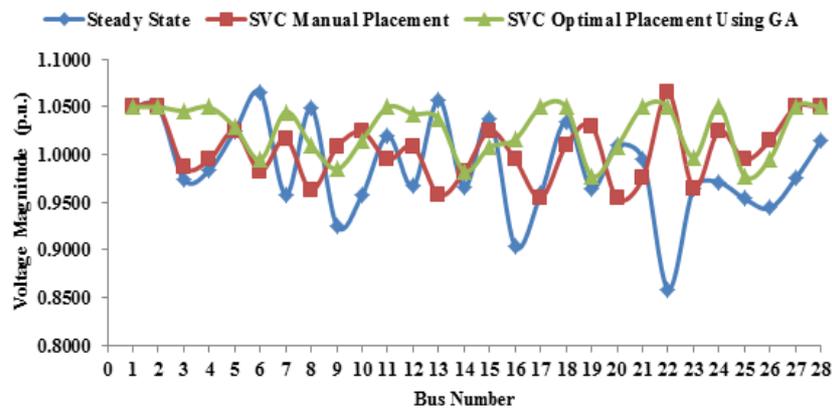


Figure 6. Voltage profile of the Nigerian 28-bus power grid with and without compensation

A 9.65 MVar rated SVC optimally placed on Kano via genetic algorithm improved the voltage magnitude of the node and Ayede, New-Haven, Gombe and Makurdi to 1.05, 0.985, 1.038, 1.016 and 0.996 p.u. respectively; the values which are all within the statutory limit. This result revealed that with the GA based optimization approach, the compensator performed better with a reduced size unlike the first principle approach where the size was a bit higher. The enhancement of the Nigerian 28-bus power grid voltage profile through optimal location of SVC impacted positively on power losses of the network as presented in Figure 7.

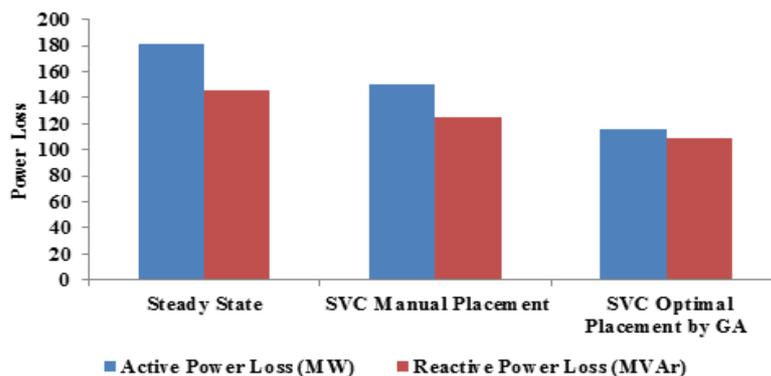


Figure 7. Total active and reactive power losses on the Nigerian 28-bus power grid with and without compensation

While the grid's total active and reactive line losses respectively reduced by 17.46 and 13.87 % from 181.479 to 149.786 MW and 145.323 to 125.161 MVar respectively through first principle, GA based placement of the SVC minimized the grid's total active and reactive line losses from 181.479 to 115.675 MW and 145.323 to 109.336 MVar, producing a percentage reduction of 36.26 and 24.76 % in the respective total active and reactive line losses of the grid. These results indicated the suitability of SVC placed by appropriate optimization techniques such as genetic algorithm for enhancing the performance of power system network.

The results obtained are in agreement with the outcomes of the work of Aryal and Gynawali (2020), Nassar *et al.* (2019), Mulyadi *et al.* (2018) and Duraisamy and Ponnusamy (2017), who all conducted investigations on the GA based placement of SVC considering different types of power networks. Aryal and Gynawali (2020) noted that GA based optimal placement of SVC was a better approach for enhancing power system voltage profile and line loss, although stressing that the performance of the compensator could be improved further when used in combination with other FACTS controller. While Nassar *et al.* (2019) observed that GA based optimal location of SVC offered the best results in terms improved voltage profile and well minimized power losses of the four scenarios examined for power system voltage performance enhancement, Mulyadi *et al.* (2018) showed that optimal placement of SVC via GA on 150 kV electricity transmission grid enhanced the system's overall performance such that voltage magnitude of each bus was raised to standard tolerance limit and line losses were significantly reduced. Duraisamy and Ponnusamy (2017) reported that voltage profile and total lines losses of the considered network after SVC was optimally placed SVC using GA improved appreciably. Hence, all these previous works are suggestions that optimal placement of SVC via artificial intelligence technique such as genetic algorithm is a potential candidate for enhancing the quality of electric power transmitted through grid system which was equally confirmed by the present study.

4 Conclusion

One of the key solutions presently gaining widespread attentions of power system engineers and researchers globally is the use of artificial intelligence based techniques for optimal FACTS placement for performance improvement of electricity grids. Hence, this work employed an SVC optimally placed by genetic algorithm for improving line losses and voltage profile on the Nigerian 28-bus power grid. Findings from the work revealed that optimal placement of static var compensator via GA in addition to exhibiting superior positive effects on the system's voltage profile produced a much more reduced total active and reactive power losses compared to the manual process and the initial load flow analysis. This, therefore, suggests that adoption of this approach for the Nigerian power system grid will not only go a long way towards facilitating the transmission of a better quality electric power but also will increase transfer capability of the grid, thereby, making more electrical energy that can serve the end-users available. As a means to validating the results obtained in this study, further work is ongoing to comparatively evaluate the performance of GA based siting of the SVC on the Nigerian electricity with other optimization methods including FL, ANN and PSO to provide useful insights on the appropriate approach to locate the device since this is decisive in enhancing its effectiveness and efficiency for the performance improvement of power system networks where it is deployed.

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