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# Improving the Nigerian 330kV Power System Steady State Voltage Stability Using Static VAr Compensation and Genetic Algorithm Optimization

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## ABSTRACT

The Nigeria 330kV network has been presented in this research work. The network just like many power systems in the world suffer from voltage instability caused by the variation in the reactive power requirement of the systems' components. This has a resulting effect on consumers' loads designed to operate within a specific voltage range. The system voltage goes high when there is excessive injection of reactive power and goes low when there is excessive absorption of reactive power. Ten (10) generating station buses and twenty-two (22) transmission line buses totalling thirty-two (32) buses were considered. Load flow solution was performed on the buses using Newton-Raphson method. This was programmed in matlab and the voltage magnitudes of all the buses were determined. The steady state voltage stability was investigated and the problem buses were identified. These were bus 16 (Yola), bus 23 (Alaoji), bus 26 (Gombe) and bus 30 (Ugwuaji). The voltage magnitude of bus 16 (Yola), bus 26 (Gombe) and bus 30 (Ugwuaji) are higher than what is specified in the Operating Procedure of the National Control Centre while that of bus 23 (Alaoji) is lower than the statutory limit specified. The Static VAr Compensation scheme deployed did not allow a noticeable voltage drop or voltage increase beyond the statutory limit. The scheme was used in this research to supply reactive power to boost the power system voltage magnitude on any of the problem buses and absorb reactive power to reduce the voltage on any of the buses. The compensation scheme reduced the voltage magnitudes of bus 16 (Yola), bus 26 (Gombe) and bus 30 (Ugwuaji) from 1.137pu to 0.975pu, 1.131 to 0.986pu and 1.055pu to 0.987pu respectively. The reactive power compensation scheme was also applied to bus 23 (Alaoji) to increase its voltage magnitude from 0.832pu to 0.954pu. Other buses that were affected positively are bus 10 (Kaduna) from 1.049 pu to 1.000 pu, bus 13 (Kano) from 1.042 pu to 0.992 pu, bus 14 ( Jos) from 1.052 pu to 0.993 pu, bus 15 (Makurdi) 1.051pu to 0.992pu, bus 18 (Benin) from 1.026pu to 1.027pu, bus 19 (Onitsha) from 0.978 to 0.984, bus 22 (New Haven) from 0.975pu to 0.981pu. The transmission line active power losses in the network were also determined before and after the compensation were applied. These two values were compared to get the increase in transmission efficiency due to the compensation. The compensation brought about a 17.48 percent increase in efficiency. The Static VAr Compensation scheme in this research has been shown to be an efficient tool in maintaining short and long term voltage stability so as to reduce overall transmission losses in the Power System Network. In order to ensure a cost effective optimal load flow, Genetic Algorithm was employed to reduce the cost of electricity generation by the generating power stations. These allotted the generating stations with appropriate capacity to meet the load demand while reducing the cost. This further improved the voltage stability of the network.

## INTRODUCTION

The stability of a power system network is its ability to return to its normal operating condition after small or large disturbances. For convenience of analysis, stability problems are generally divided into two major categories; steady-state stability and transient stability. Steady state stability refers to the ability of the power system to regain synchronism after small and slow disturbances, such as gradual power changes. An extension of the steady state stability is the dynamic stability. The dynamic stability is concerned with small disturbances lasting for a long time with the inclusion of automatic control devices. It is often convenient that the disturbances causing the changes disappear. (Saadat, H. 1999).

In 1968 the first 330 kV network in Nigeria emerged with the construction of the Kainji hydro station which supplied power through a 330 kV transmission line. This was constructed alongside the 132 kV lines to wheel out power to the Northern and Southern parts of the country. Some of the transmission lines are so fragile and radial in nature, which is prone to frequent system collapse. Some causes of instability are poor network configuration in some regional load centres, controlling the transmission line parameters, large numbers of overloaded transformers in the grid system, frequent vandalism of 330 kV transmission lines in various parts of the country and using the transmission lines beyond their limit.

Before the unbundling of the Power Holding Company of Nigeria (PHCN), the Nigeria existing 330 kV network consists of nine generating stations, twenty eight buses and thirty two transmission lines. It is recommended that, the generators require reactive compensation while the transmission lines require both real and reactive power compensation using Flexible Alternating Current Transmission Systems (FACTS) devices for effective utilization. (Ogbuefi U. C and Madueme T. C 2015).

This paper presents a means of improving the steady state voltage stability of Nigeria 330kV transmission network using Static Var Compensation scheme while optimizing generation cost. The incessant power supply failure in Nigeria has reached an unprecedented level that the public are losing their trust in the present government of the day. Several efforts made to rescue the power short fall has not yielded the expected outcome. The huge amount expended and the man-hours deployed have not met the yearnings of the people.

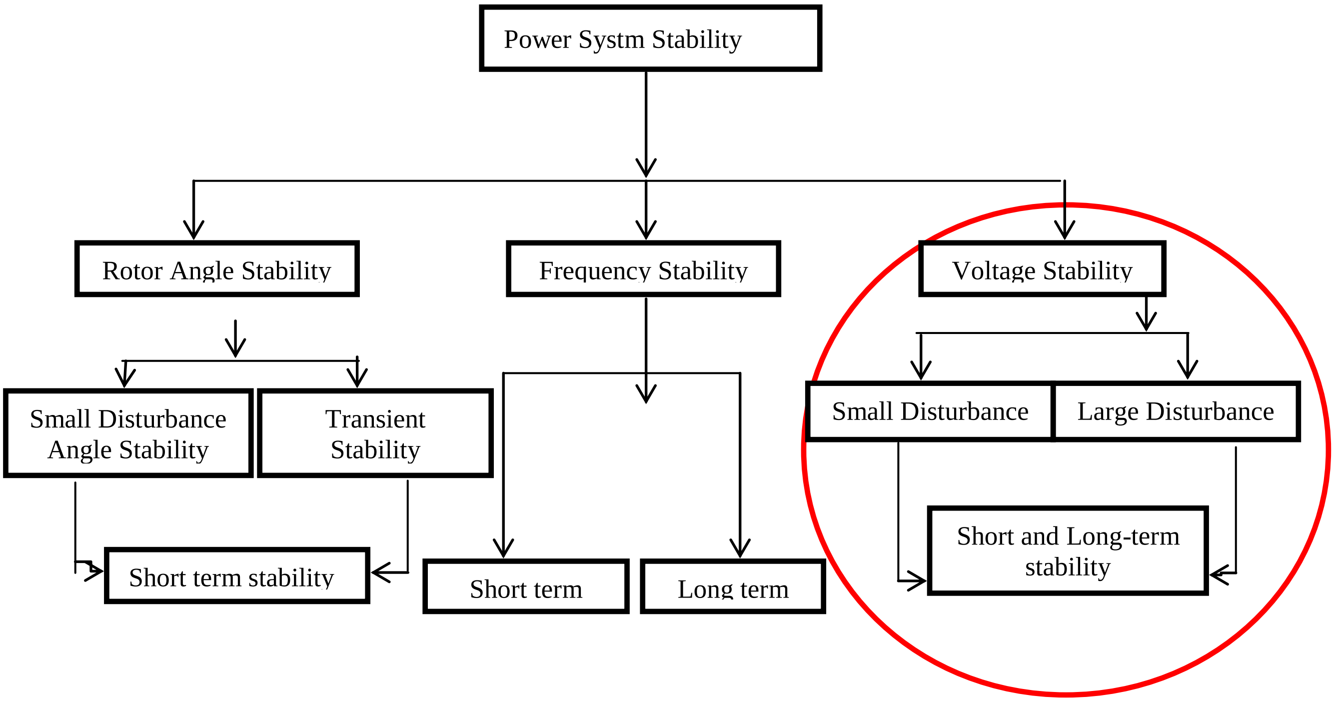

**Fig. 1.1:** Electric Power system stability chart showing steady state stability
**Source:** (P. Kundur *et al*; 2004).

**Table 1.1: System collapse records for the period of year 2000-2009**

| **Year** | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
|---|---|---|---|---|---|---|---|---|---|---|
| **System collapse** | 11 | 19 | 41 | 53 | 52 | 36 | 30 | 27 | 42 | 39 |

**Source**: (Isaac, S. *et al*; 2014)

System collapse is on the increase resulting in insecurity and unreliability of the entire Power System Network (PSN). This shows an average of 35 collapses in a year. The inconvenience and economic cost it inflicts on both domestic and industrial customers is high and unbearable. The resultant power outages cost the nation an estimated $1billion per year (2.5% of GDP). (Amoda O. 2007)
Reactive power balance is pertinent to the operation of a power system network because it serves as the problem as well as the solution to the loss of voltage on the buses. The Power system components installed in power stations have a certain maximum and minimum operating voltage range in which a smooth operation is maintained.

Beyond these, the operating characteristics may be seriously affected in terms of speed, output torque, energy losses and the continuity of the network may be lost. In Nigeria, as the population of electricity consumers increases, power demand increases steadily while the expansion of power generation and transmission has been limited due to financial, economic and environmental factors. This gives cause for concern as it contributes to the constant power failure in the power system, since greater demands have been placed on the generation and transmission network by the continuous addition of load.

Flexible AC Transmission System (FACTS) provide compensation in a veritable way to reduce the excess voltage to avoid damage to the much expensive substation components as well as consumer gadgets; they also serve to increase the voltage profiles to the statutory values when they have been reduced. Examples of FACTS that play a very important role in compensation are Static VAr Compensators (SVC), Static Synchronous Compensators (STACOM) and Synchronous condensers.

Shunt and series reactive compensation using capacitors have been widely recognized as powerful tools to combat the problems of voltage drops, power losses, and voltage flickers in power distribution networks. The importance of these schemes has increased in recent years due to the increased awareness of energy conservation and quality of supply on the part of the Power Utility as well as power consumers. Though shunt compensation are expensive but they control voltage directly and also control temporary over voltage rapidly.

## The Nigerian Network

Nigeria is a vast country with a total of 356, 667 sq. miles (923,768 km2), of which 351,649 sq. miles (910,771 sq km or 98.6% of total area) is land. The nation is made up of six geo-political zones subdivided into 36 states and the Federal Capital Territory (F.C.T.). Furthermore, the vegetation cover, physical features and land terrain in the nation vary from flat open savannah in the North to thick rain forests in the south, with numerous rivers, lakes and mountains scattered all over the country with an estimated population of over 170 million.(Ariyo and Omoigui, 2012).

The Operational Procedure of the NCC have it in Section 5.1 that the allocation of MX to dynamic plant and the allocation of MX reserve shall enable the voltage at Power Stations, Grid Substations, and bulk supply points to be held within the following limits stated in Operational Procedure 1 for both the pre-fault and post-fault conditions.

**Table 2.1: Acceptable voltage limits of the Nigeria Power System Network**

| S/N | Voltage (kV) | Percentage limit | Value limit (kV) |
|---|---|---|---|
| 1 | 330kV | +5% /-15% | 346.5kV/ 280.5kV |
| 2 | 132kV | +10% /-15% | 145.2kV / 112.2kV |
| 3 | 33kV | +6% /-6% | 34.98kV/ 31.02kV |

**Source:** (Operational Procedure of TCN, 2013)

Nigeria electric power system is undergoing changes as a result of constant power demand increase, thus stretching it beyond their stability and thermal limit. This drastically affects the power quality delivered. Transmission systems should be flexible to respond to generation and load patterns. Solving the problem of increasing power demand is either by building more generating and transmission facilities which is not very economical or environmentally friendly or the use of Flexible Alternating Current Transmission System (FACTS) Devices (Omorogiuwa et al, 2012)

Nigeria power system is faced with series of technical challenges due to long, radial, weak and aging transmission network (Ogunjuyigbe and Ayodele, 2015). Different studies have been carried out on Nigerian 330 kV transmission network by various indigenous researchers with each researcher focusing on different aspect of performance assessment with a view to improving the network. Technical losses on the 330 kV Nigerian transmission lines have been studied by Anumaka (Anumaka, 2012).

The concept of the STATCOM was proposed by Gyugyi (Gyugyi, 1976). According to IEEE a STATCOM can be defined as a static synchronous generator operated as a shunt-connected Static VAr Compensator with capacitive or inductive output current can be controlled independent of the AC system voltage. A STATCOM is a static compensator that is connected to the grid in parallel for the compensation of reactive power. It is able to inject or absorb reactive power in a controlled way regardless of the grid voltage.

Flexible AC transmission systems (FACTS) controllers have been mainly used for solving various power system steady state control problems. However, recent studies reveal that FACTS controllers could be employed to enhance power system stability in addition to their main function of power flow control. The literature shows an increasing interest in this subject for the last two decades, where the enhancement of system stability using FACTS controllers has been extensively investigated. This paper presents a comprehensive review on the research and developments in the power system stability enhancement using FACTS damping controllers. Several technical issues related to FACTS installations have been highlighted and performance comparison of different FACTS controllers has been discussed. (Abido, 2009)

The main difference between a STATCOM and an SVC is the way they operate; a STATCOM works as a controllable voltage source while an SVC works as a dynamically controllable reactance connected in parallel. Compared with an SVC, a STATCOM offers the possibility of feeding the grid with the maximum available reactive current even at low voltage levels; this is possible because in every equilibrium condition the injected reactive power varies linearly with the voltage at the Point of Common Coupling (PCC).

SVC is the most popular FACTs device in the recent years. It typically consists of a TCR in parallel with a capacitor bank. From the operational viewpoint, the SVC acts as a shunt connected variable reactance. Compared to the TCR that can only generate reactive power, SVC cannot only generate but also absorb reactive power. SVC is also a shunt connected device, and is always modelled into three phase form.

## Data Collection

In recent years technological advances in power electronics have facilitated the development of electronic equipment that offer the ability to handle large amounts of power; consequently, the use and application of this technology into electrical power systems have increased significantly.

In Nigeria, the National Control Centre (NCC), Osogbo is responsible for all operations of Transmission Company of Nigeria (TCN), Grid operations, Monitoring and Control within the Transmission network. It is equipped with the state of the art Supervisory Control and Data Acquisition (SCADA) Energy Management System, Tele-control Interfaces, Human Machine Interfaces, Communication Equipment, Planning tools etc. Data needed for the analysis were collected from NCC and were sorted out and arranged in the format to be used for the analysis.

## Flow Chart of Method

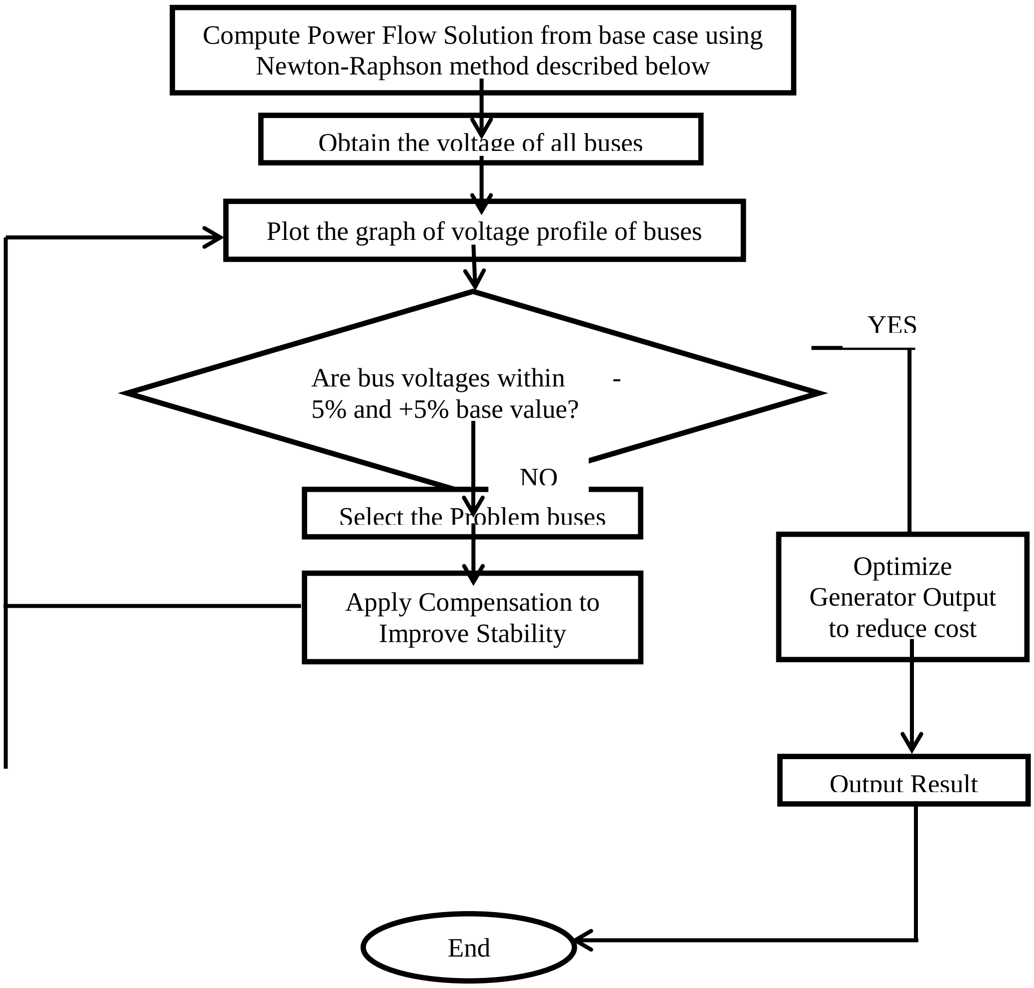

Fig. 1.2: Flow chart for improving the Power System Voltage stability

## Input Data

## Table 1.2: Bus data before Compensation

| Bus No | Bus Name | Generation | | Load | | V | Angle | Remarks |
|---|---|---|---|---|---|---|---|---|
| | | P(MW) | Q(MVAr) | P(MW) | Q(MVAr) | (p.u volts) | (degree) | Bus Type |
| 1 | Shiroro | - | - | 0.00 | 0.00 | 1.000 | 0.000 | Swing |
| 2 | Delta | 318.00 | - | - | - | 1.027 | 0.000 | PV |
| 3 | Sapele | 170.80 | - | - | - | 1.021 | 0.000 | PV |
| 4 | Jebba G.S | 349.00 | - | - | - | 1.021 | 0.000 | PV |
| 5 | Kainji | 294.00 | - | - | - | 1.012 | 0.000 | PV |
| 6 | Egbin | 409.00 | - | - | - | 1.006 | 0.000 | PV |
| 7 | Omotosho | 181.60 | - | - | - | 1.042 | 0.000 | PV |
| 8 | Olorunshogo | 63.40 | - | - | - | 0.964 | 0.000 | PV |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 9 | Osogbo | - | - | 119.90 | 74.34 | 1.000 | 0.000 | PQ |
| 10 | Kaduna | - | - | 92.00 | 57.04 | 1.000 | 0.000 | PQ |
| 11 | Ganmo | - | - | 44.00 | 27.28 | 1.000 | 0.000 | PQ |
| 12 | Katampe | - | - | 135.50 | 84.01 | 1.000 | 0.000 | PQ |
| 13 | Kano | - | - | 210.00 | 130.2 | 1.000 | 0.000 | PQ |
| 14 | Jos | - | - | 53.00 | 32.83 | 1.000 | 0.000 | PQ |
| 15 | Makurdi | - | - | 66.00 | 40.92 | 1.000 | 0.000 | PQ |
| 16 | Yola | - | - | 13.00 | 8.06 | 1.000 | 0.000 | PQ |
| 17 | Ajaokuta | - | - | 124.00 | 76.88 | 1.000 | 0.000 | PQ |
| 18 | Benin | - | - | 154.90 | 96.04 | 1.000 | 0.000 | PQ |
| 19 | Onitsha | - | - | 107.00 | 66.34 | 1.000 | 0.000 | PQ |
| 20 | Birnin-Kebbi | - | - | 108.00 | 66.96 | 1.000 | 0.000 | PQ |
| 21 | Jebba T.S | - | - | 12.00 | 7.44 | 1.000 | 0.000 | PQ |
| 22 | New-Haven | - | - | 78.00 | 48.36 | 1.000 | 0.000 | PQ |
| 23 | Alaoji | - | - | 303.60 | 187.86 | 1.000 | 0.000 | PQ |
| 24 | Ikeja West | - | - | 779.00 | 482.98 | 1.000 | 0.000 | PQ |
| 25 | Ayede | - | - | 158.00 | 97.96 | 1.000 | 0.000 | PQ |
| 26 | Gombe | - | - | 50.00 | 30.67 | 1.000 | 0.000 | PQ |
| 27 | Sakete | - | - | 121.00 | 75.02 | 1.000 | 0.000 | PQ |
| 28 | Akangba | - | - | 0.00 | 0.00 | 1.000 | 0.000 | PQ |
| 29 | Aja | - | - | 0.00 | 0.00 | 1.000 | 0.000 | PQ |
| 30 | Ugwuaji | - | - | 0.00 | 0.00 | 1.000 | 0.000 | PQ |
| 31 | Geregu | 124.00 | - | - | - | 1.000 | 0.000 | PV |
| 32 | Okpai | 424.00 | - | - | - | 1.000 | 0.000 | PV |

**Source:** Daily load flow of TCN (27/07/16)

**Table 1.3: Line Parameters of Buses**

| S/N | Bus Name | | Bus Number | | Length | Resistance | Inductive Reactance | Shunt B/2 |
|---|---|---|---|---|---|---|---|---|
| | From | To | From | To | (km) | (pu) | (pu) | |
| 1 | Shiroro | Kaduna T.S | 1 | 10 | 95 | 0.0034 | 0.0290 | 0.182 |
| 2 | Delta | Benin | 2 | 18 | 107 | 0.0023 | 0.0190 | 0.120 |
| 3 | Delta | Sapele | 2 | 3 | 93 | 0.0023 | 0.0190 | 0.120 |
| 4 | Sapele | Benin | 3 | 18 | 50 | 0.0018 | 0.0140 | 0.104 |
| 5 | Jebba G.S | Jebba T.S | 4 | 21 | 8 | 0.0003 | 0.0020 | 0.033 |
| 6 | Kainji | Jebba T.S | 5 | 21 | 81 | 0.0029 | 0.0250 | 0.154 |
| 7 | Egbin | Benin | 6 | 18 | 218 | 0.0160 | 0.0190 | 0.183 |
| 8 | Egbin | Ikeja-West | 6 | 24 | 62 | 0.0022 | 0.0170 | 0.129 |
| 9 | Omotosho | Ikeja-West | 7 | 25 | 160 | 0.0249 | 0.0290 | 0.183 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 10 | Omotosho | Benin | 7 | 18 | 120 | 0.0160 | 0.0190 | 0.183 |
| 11 | Olorunshogo | Ayede T.S | 8 | 25 | 60 | 0.0291 | 0.0350 | 0.219 |
| 12 | Olorunshogo | Ikeja West | 8 | 24 | 30 | 0.0398 | 0.0480 | 0.298 |
| 13 | Oshogbo | Jebba T.S | 9 | 21 | 157 | 0.0056 | 0.0480 | 0.298 |
| 14 | Oshogbo | Ayede T.S | 9 | 25 | 119 | 0.0041 | 0.0350 | 0.219 |
| 15 | Ganmo | Jebba T.S | 11 | 21 | 70 | 0.0341 | 0.0420 | 0.120 |
| 16 | Ganmo | Oshogbo | 11 | 9 | 87 | 0.0160 | 0.0190 | 0.120 |
| 17 | Katampe | Shiroro | 12 | 1 | 144 | 0.0215 | 0.0250 | 0.154 |
| 18 | Kano | Kaduna T.S | 13 | 10 | 230 | 0.0082 | 0.0700 | 0.874 |
| 19 | Jos | Kaduna T.S | 14 | 10 | 197 | 0.0070 | 0.0290 | 0.374 |
| 20 | Makurdi | Jos | 15 | 14 | 285 | 0.0020 | 0.0022 | 0.154 |
| 21 | Yola | Gombe | 16 | 26 | 240 | 0.0245 | 0.0292 | 0.505 |
| 22 | Ajaokuta | Benin | 17 | 18 | 195 | 0.0070 | 0.0560 | 0.372 |
| 23 | Benin | Onitsha | 18 | 19 | 137 | 0.0049 | 0.0420 | 0.261 |
| 24 | Birnin-Kebbi | Kainji | 20 | 5 | 310 | 0.0111 | 0.0940 | 0.589 |
| 25 | Jebba T.S | Shiroro | 21 | 1 | 244 | 0.0067 | 0.0700 | 0.464 |
| 26 | New-Haven | Onitsha | 22 | 19 | 96 | 0.0030 | 0.0290 | 0.182 |
| 27 | Alaoji | Onitsha | 23 | 19 | 138 | 0.0490 | 0.0420 | 0.262 |
| 28 | Ikeja-West | Oshogbo | 24 | 9 | 235 | 0.0049 | 0.0420 | 0.261 |
| 29 | Gombe | Jos | 26 | 14 | 265 | 0.0095 | 0.0810 | 0.505 |
| 30 | Sakete | Ikeja-West | 27 | 24 | 70 | 0.0398 | 0.0480 | 0.261 |
| 31 | Akangba | Ikeja-West | 28 | 24 | 18 | 0.0022 | 0.0170 | 0.129 |
| 32 | Aja | Egbin | 29 | 6 | 14 | 0.0022 | 0.0170 | 0.129 |
| 33 | Ugwuaji | Makurdi | 30 | 15 | 50 | 0.2050 | 0.0250 | 0.154 |
| 34 | Geregu | Ajaokuta | 31 | 17 | 5 | 0.0155 | 0.0170 | 0.129 |
| 35 | Okpai | Onitsha | 32 | 19 | 56 | 0.0090 | 0.0070 | 0.052 |

**Source:** (NIPP in house data from NCC)

## Power flow Analysis

Load flow solution by Newton-Raphson method in mat lab environment may be divided basically into three steps. The first step involves specifying the variables that will be used within the program.

These variables are the power system base MVA, power mismatch accuracy, acceleration factor and maximum number of iterations. These were set to the following values; base MVA = 200, accuracy = 0.001; accel = 1.6 and maxiter = 60.

The next step is the filling of data in the Bus data file. This involves but not limited to the sequential numbering of each bus with a code assigned depending on the classification of the bus; slack bus is assigned the number1, load buses are assigned **0** and voltage controlled buses are assigned **2**. The information required in this stage prepared in matrix form must contain the bus number, bus code, voltage magnitude in per unit, phase angles in degrees, load active and reactive powers, minimum and maximum values of generator reactive powers in MVAr as well as injected values of reactive powers of shunt capacitors or reactors in the grid.

The next step in the matlab programming of load flow solution using Newton-Raphson method involves the preparation of the line data. The line data in matrix form identifies lines by the node-pair method. These contain the line bus numbers, line resistance, reactance and one-half of the total line charging susceptance in per unit on the specified MVA base.

## Operation of the SVC

The Thyristor Controlled Reactor- Fixed Capacitor scheme of the SVC has a reactor and thyristor valve incorporated in each single phase branch with a fixed capacitor. It can be used to keep the voltage at a bus constant by injecting or absorbing reactive power into and from the bus respectively. The amount of reactive power injected is a function of the susceptance. Therefore voltage control may be achieved by varying the equivalent susceptance. They are often characterized by having a compact design, continuous control, no transients, elimination of harmonics by tuning the FCs as filter as depicted in Figure 3.2 below.

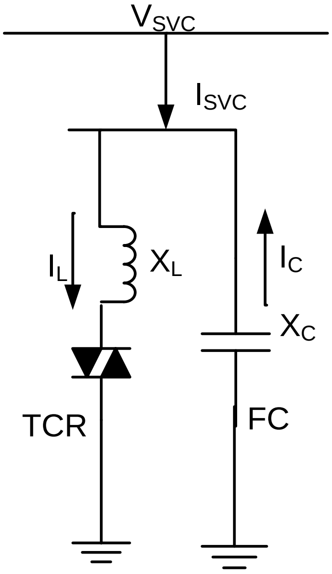

Fig. 1.3: An SVC Model Showing Currents

One of the SVC branch is purely capacitive while the other is inductive. As a result, the SVC consumes no active power. However, it has the capability to either consume reactive power through the inductive branch (TCR) so as to reduce the system's voltage or injects reactive power into the system through the capacitive branch (FC) in order to increase the voltage. The reactor current $I_L$ is positive, while the capacitor current $I_C$ is negative. Thus, SVC current ($I_{SVC}$) value at maximum VAr is expressed as follows:

$$I_{SVC} = I_L - I_C \qquad (1)$$

where $I_C = \frac{V_{SVC}}{X_C}$, $I_L = \frac{V_{SVC}}{X_L}$ and $V_{svc}$is the bus voltage magnitude.

Since no active power is taken by the SVC, the reactive power consumed can be expressed as:

$$Q_{SVC} = I_{SVC} \times V_{SVC} \qquad (2)$$

Where $V_{SVC}$ is the bus voltage,

Substituting (1) into (2) yields the following:

$$Q_{SVC} = (\mathrm{I}_L - \mathrm{I}_C) \times \mathrm{V}_{SVC} \qquad (3)$$

$$Q_{SVC} = (\frac{V_{SVC}}{X_L} - \frac{V_{SVC}}{X_C}) \times \mathrm{V}_{SVC} \qquad (4)$$

$$Q_{SVC} = (\frac{1}{X_L} - \frac{1}{X_C}) \times \mathrm{V}^2{}_{SVC} \qquad (5)$$

$$Q_{SVC} = (\frac{X_C - X_L}{X_L X_C})\mathrm{V}^2{}_{SVC} \qquad (6)$$

The SVC is designed such that the TCR is switched off when the bus voltage falls below the reference voltage and turns on when it is above it. Therefore, the maximum reactive power consumed by the fixed capacitor (FC) and the thyristor controlled reactor (TCR) is given as:

$$Q_{SVC}^{\max} = (\frac{X_C - X_L}{X_L X_C})\mathrm{V}^2{}_{SVC} \qquad (7)$$

While the minimum VAr consumption is obtained as:

$$Q_{SVC}^{\min} = -\frac{1}{X_C}\mathrm{V}^2{}_{SVC} \qquad (8)$$

## Genetic Algorithm

Optimal power flow (OPF) is the way by which loads are allocated to generators for minimum costs while meeting the network constraints. It is an optimization problem which may be used to minimize total fuel cost while meeting the network constraints.

The most commonly used objective in the OPF problem formulation is the minimisation of the total cost of real power generation. The individual costs of each generating unit are assumed to be function, only, of active power generation and are represented by quadratic curves of second order. The objective function for the entire power system can then be written as the sum of the quadratic cost model at each generator.

$$F(x) = \sum_{i=1}^{ng}(a_i + b_i Pg_i + c_i Pg_i^2) \qquad (9)$$

Where $ng$ is the number of generation including the slack bus

$Pgi$ is the generated active power at bus $i$.

$a_i$, $b_i$ and $c_i$ are the unit costs curve co-efficients for $i^{th}$ generator.

$a$ was modelled for each generator as the average cost of electricity generated by each generator in N/kW-hr

$b$ was modelled for each generator as the farthest distance in length to a load bus connected to each of the generators in percent

$c$ is the capacity utilization co-efficient of the generators

The power output of any generator must not exceed its rating nor drop below a given value for stable operation. In minimizing cost of generating electrical power without compromising system reliability and market security, inequality constraints of each of the ten generators supplying the grid must also be defined

$$P_i^{min} \leq P_{Gi} \leq P_i^{max} \qquad (10)$$

$P_i^{min}$ and $P_i^{max}$ are directly related to the lower and upper boundaries of the generators.

$P_{Gi}$ is the best generator output to reduce cost.

## RESULTS

The data were input in the matlab editor window and the program was run, the solution converged after five iterations and the maximum power mismatch was $3.82306e^{-11}$. Total generation was 2683.827MW with a total reactive power of -409.371MVAr while the total load was 2535MW and the total load reactive power was 1570MVAr.

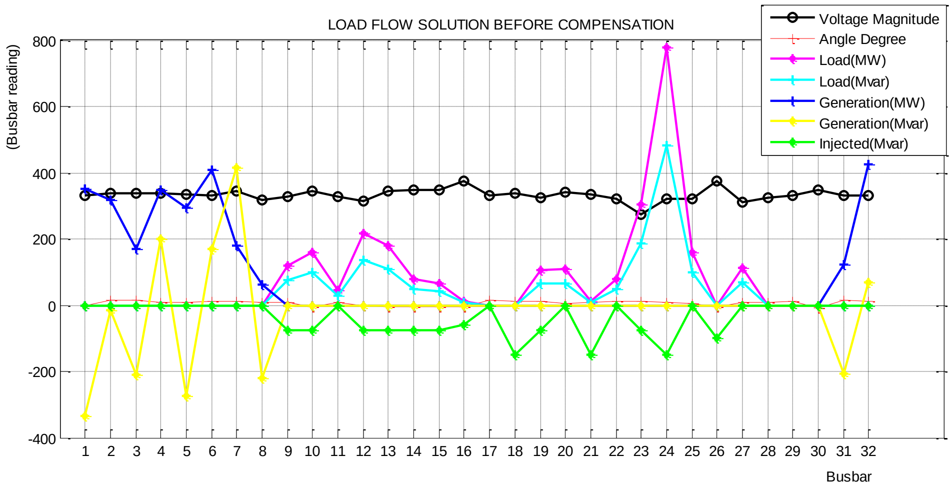

Fig. 1.4: Load flow solution plot before compensation

The figure above shows a plot of the bus parameters against the buses. This shows the bus voltage magnitude (V), angle (degree), load (MW), load reactive power (MVAr), generator active power (MW), generator reactive power (MVAr) and the injected reactive power (MVAr). The voltage magnitude was extracted from the plot above and shown on the bar chart below in (pu).

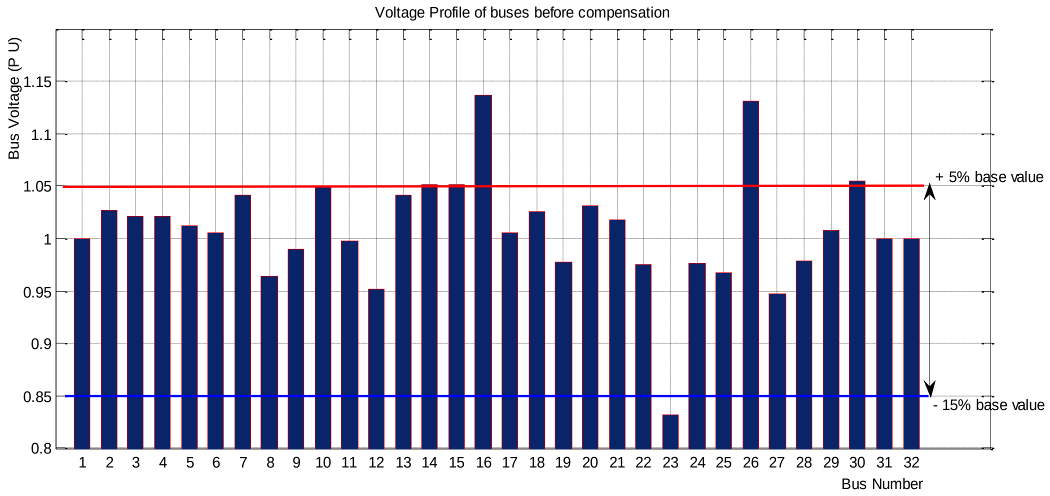

**Fig.1.5: Plot of Voltage Profile of buses before compensation**

Fig. 1.5 above shows that bus 16 (Yola), 26 (Gombe) and 30 (Ugwuaji) have voltage magnitudes of 1.137pu, 1.131pu and 1.055pu which are very much beyond the +5% statutory limit. Bus 14(Jos) and bus 15 (Makurdi) also have a voltage magnitude of 1.052pu and 1.051pu which are very close to the 1.05pu statutory limit. Meanwhile only bus 23(Alaoji) has a voltage magnitude of 0.832pu which is below the -15% statutory limit specified in the operational procedure of the NCC. These buses will be compensated for and the load flow solution will be re-performed.

The major buses that require compensation with the absorption of reactive power are bus 16 (Yola), 26 (Gombe) and 30 (Ugwuaji). 90MVAr, 50MVAr and 60MVAr were absorbed from the buses with a modelled Static VAr compensator. From equation (3.23), the total reactance of the Thyristor-controlled reactor, required by the SVC is calculated thus:

$$Q_{SVC}^{\max} = (\frac{X_C - X_L}{X_L X_C}) \mathrm{V}^2{}_{SVC}$$

For bus 16 (Yola), the inductive reactance required to absorb 90MVAr will be

$$V_{svc} = 330kV , Q_{SVC}^{min} = 90MVAr , \frac{X_L X_C}{X_C - X_L} = 1.210k\Omega$$

For bus 26 (Gombe), the inductive reactance required to absorb 50MVAr will be

$$V_{svc} = 330kV\,, Q_{SVC}^{min} = 50MVAr\,, \frac{X_L X_C}{X_C - X_L} = 2.178k\Omega$$

For bus 30 (Ugwuaji), the inductive reactance required to absorb 60MVAr will be

$$V_{svc} = 330kV\,, Q_{SVC}^{min} = 60MVAr\,, \frac{X_L X_C}{X_C - X_L} = 1.815k\Omega$$

For bus 23 (Alaoji), the capacitive reactance required to supply 350MVAr will be

$$V_{svc} = 330kV\,, Q_{SVC}^{max} = 350MVAr X_C = \quad 311.14\Omega.$$

This was done by introducing a tap change of 1.08 to the bus.

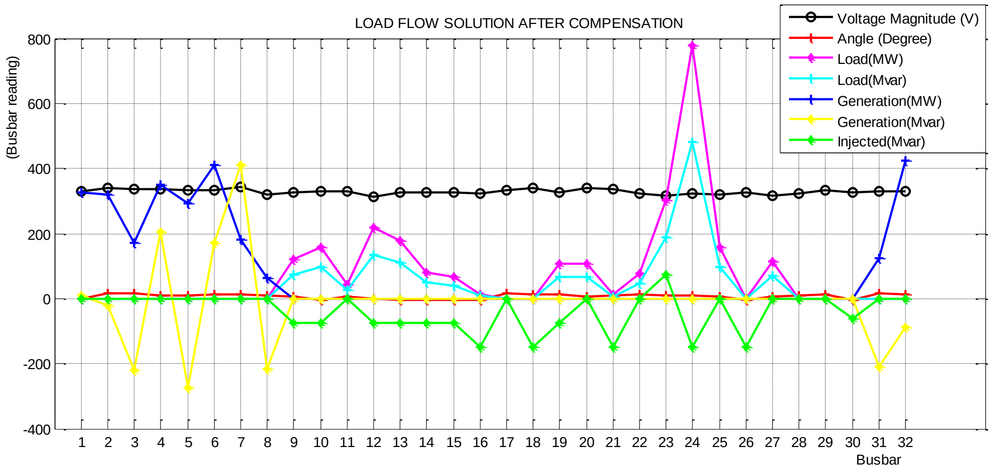

Fig. 1.6: Load flow solution plot after compensation

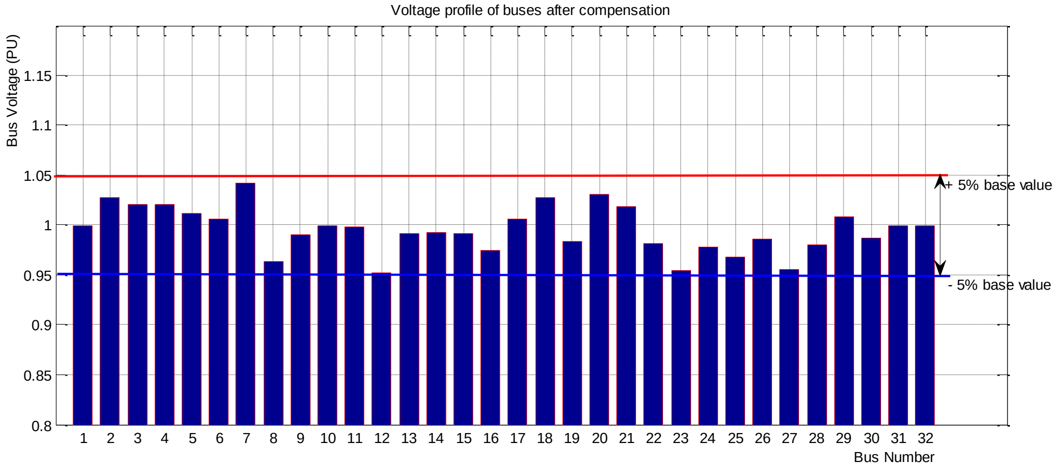

**Fig.1.7: Plot of Voltage Profile of buses after compensation**

The Static VAr Compensation scheme has reduced the per unit values of the voltage of bus 16 (Yola), bus 26 (Gombe) and bus 30 (Ugwuaji) from 1.137pu to 0.975pu, 1.131 to 0.986pu and 1.055pu to 0.987pu respectively. It has also brought up the voltage of bus 23(Alaoji) from 0.832pu to 0.954pu.

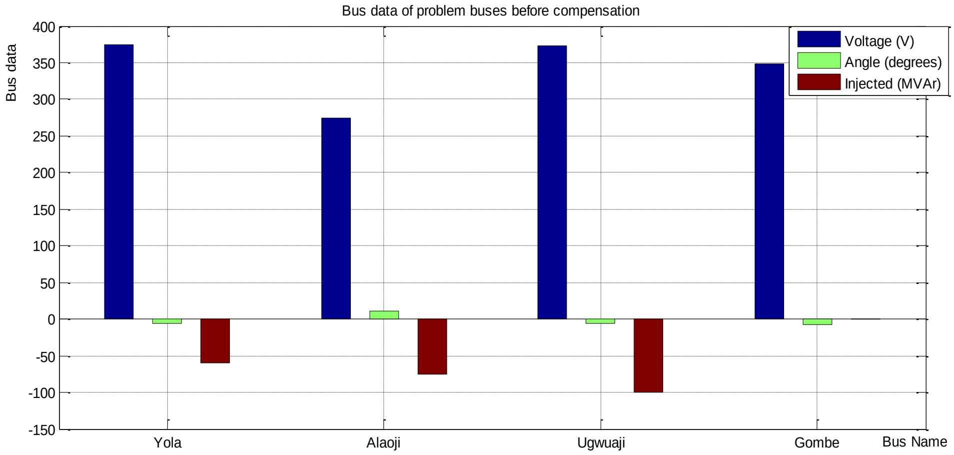

**Fig 4.5: Plot of bus data of problem buses before compensation**

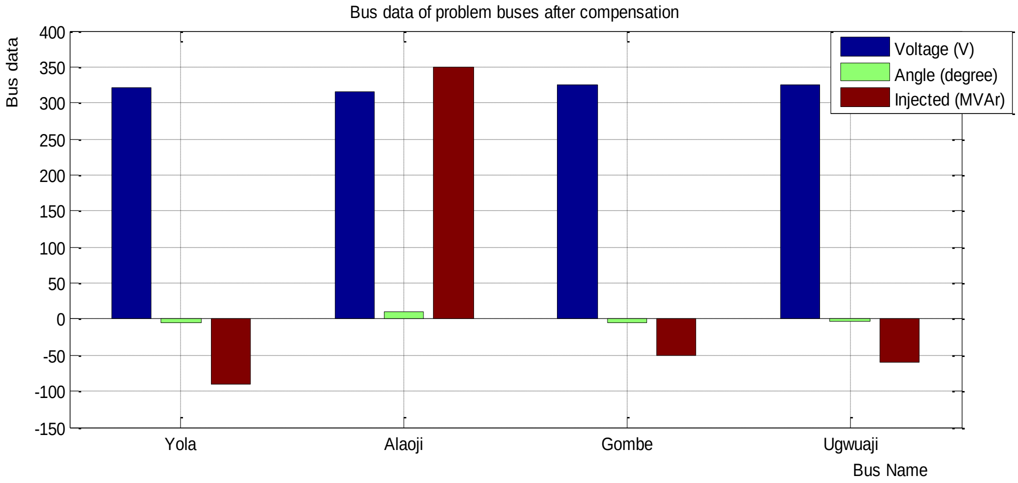

Fig. 1.8: Plot of bus data of problem buses after compensation

Since the problem buses are linked to other buses in the grid, the application of compensation at one end of the problem buses, through the link will have effect on the other connected buses. Other buses that were affected positively are bus 10 (Kaduna) from 1.049 pu to 1.000 pu, bus 13 (Kano) from 1.042 pu to 0.992 pu, bus 14 ( Jos) from 1.052 pu to 0.993 pu, bus 15 (Makurdi) 1.051pu to 0.992pu, bus 18(Benin) from 1.026pu to 1.027pu, bus 19 (Onitsha) from 0.978 to 0.984, bus 22 (New Haven) from 0.975pu to 0.981pu.

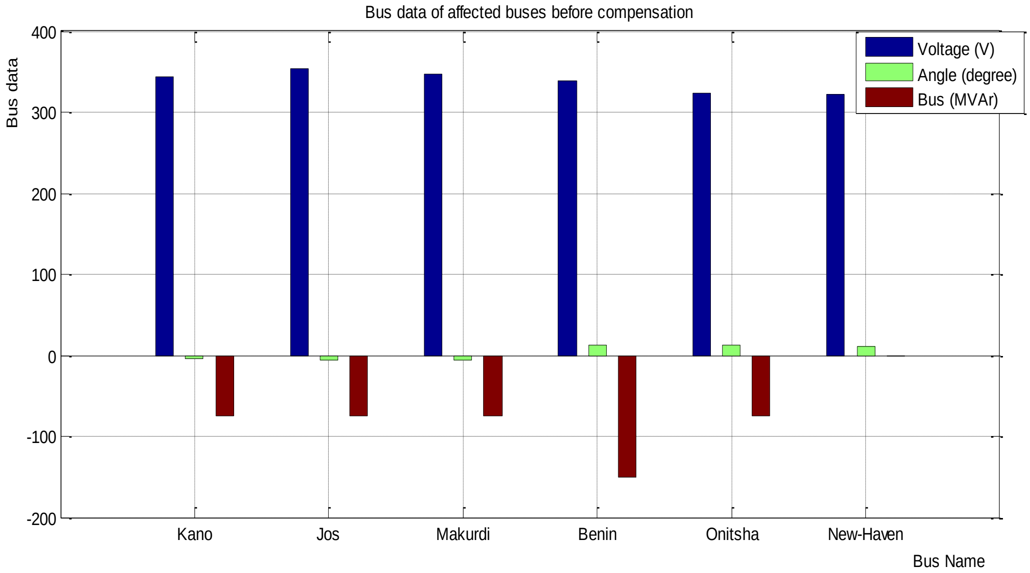

Fig. 1.9: Plot of bus data of affected buses before compensation

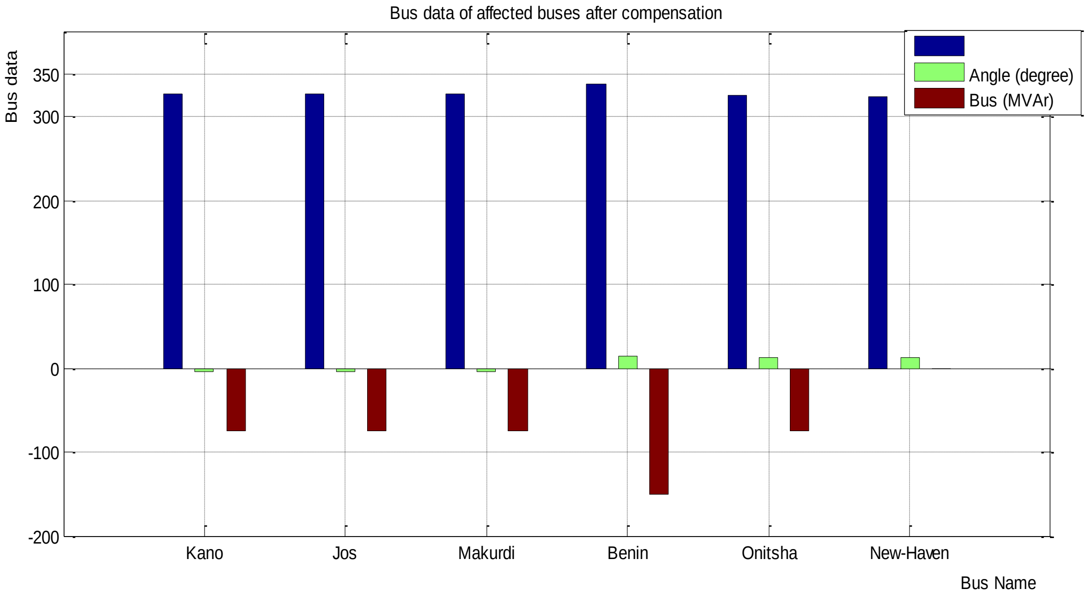

Fig. 1.10: Plot of bus data of affected buses after compensation

## Table 1.4: Losses on the Network

| S/N | | Before Compensation | After Compensation |
|---|---|---|---|
| 1 | Problem buses losses (MW) | 54.399 | 32.199 |
| 2 | Affected buses losses (MW) | 89.625 | 65.363 |

After the load flow solution was performed, a total of 144.024 (MW) losses were found on the problem buses and the affected buses before compensation. These constitute 96.8 per cent of the total loss in the grid. After the compensation was applied, the total loss in the grid reduced to 122.810 MW and the problem and affected buses constituted 79.44 per cent of the grid loss after compensation. The overall grid efficiency with the compensation applied has increased by 17.48 per cent as the overall grid loss reduced from 148.827 (MW) to 122.810 (MW). The chart in figure 4.9 below shows the contribution of the problem and affected buses to the grid loss.

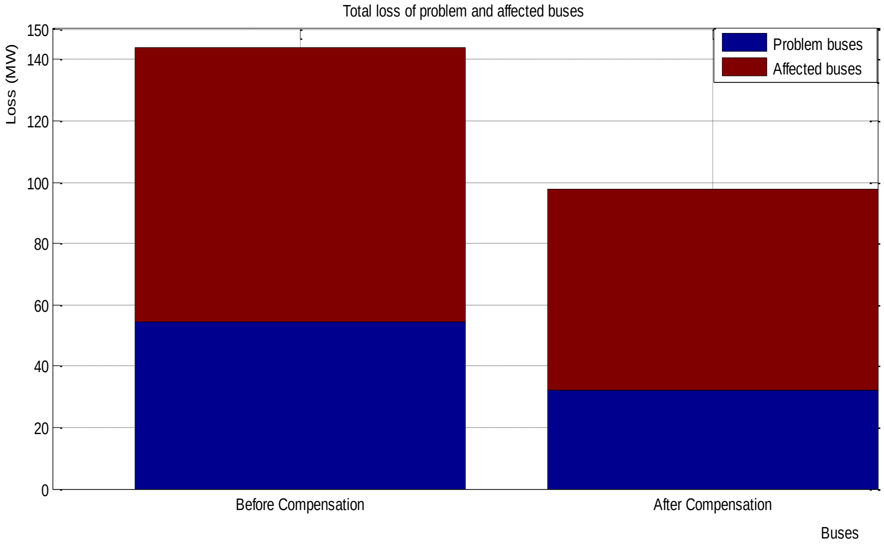

Fig. 4.9: Plot of losses due to the problem and affected buses

## Genetic Algorithm Optimization Results

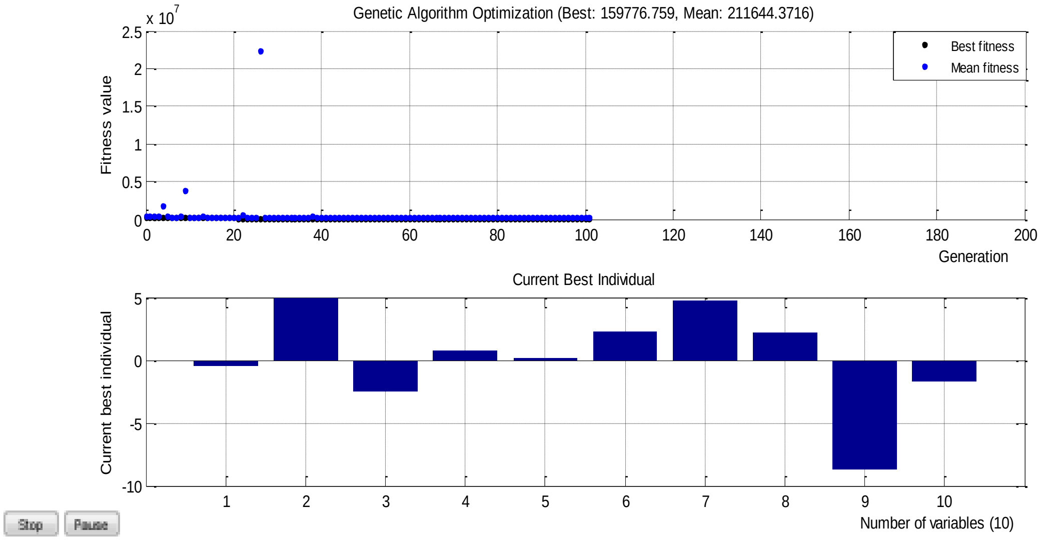

Fig. 1.11: Initial Fitness plot before Optimization

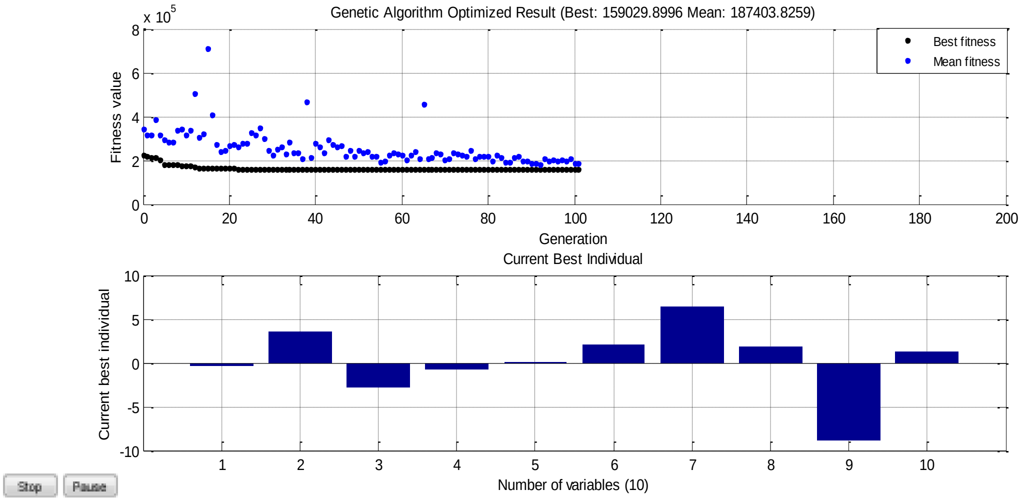

Fig. 1.12: Genetic Algorithm Optimized Fitness plot

After the Optimization was performed, from the fig 4.11 above, judging from the fitness displayed, we can deduce that the algorithm used for the optimization performs better than the current best algorithm on the average in all generations. Best fitness here refers to the fitness of the best individual in the current population which is synonymous to the best cost while the mean fitness is simply the average of the fitness values across the entire population which is also synonymous to the average cost. At each generation, the population changes and we get a new average population. The difference between the average fitness and the best fitness kept on decreasing as shown until the algorithm completely converged. The mean generation cost stood at $2.1164e^5$ before GA allotted power individually to the generating stations.

The power allotted to the ten generating stations for optimal power flow from the Genetic Algorithm solution are Shiroro (266.85MW), Delta (250.37MW), Sapele (287.00MW), Jebba (296.51MW), Kainji (294.00MW), Egbin, (266.74MW), Omotosho (304MW), Olorunshogo (266MW),Geregu (435MW), Okpai (184.92MW). This changed the mean fitness value to $1.87403e^5$. This shows that the average generation cost has been reduced.

The effect on the voltage profile of all other buses was also checked and is as shown in the voltage profile below. It kept still the Problem buses and affected buses within statutory limits.

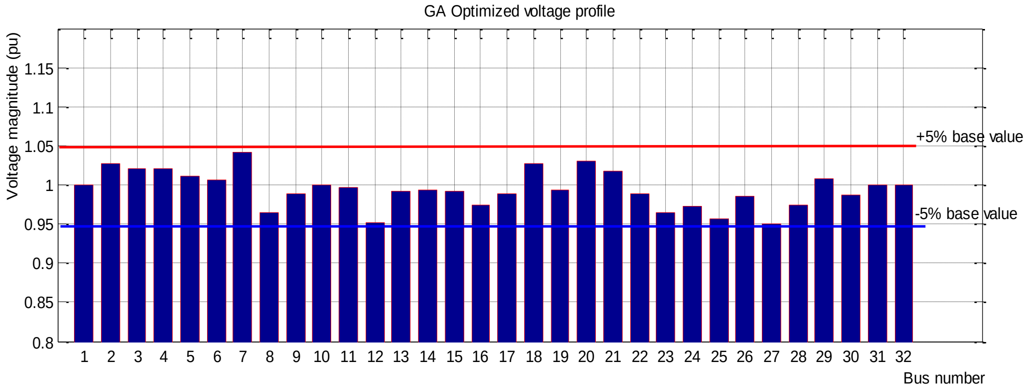

**Fig. 1.13: GA Optimized voltage profile**

## CONCLUSON

The Aim of this research which was to improve the voltage stability of the Nigerian 330kV network using Static VAr Compensators was achieved. The network was modelled to contain 32 buses and a load flow solution using Newton-Raphson method was performed to know the voltage magnitude of each of the buses. The Nigerian 330kV network is one in which needs to be researched on from time to time. It consists of over 56 buses with lines spanning across the 923,768 square-kilometre area of the country. These buses sometimes have no readings as some generating stations supplying them are shut down due to inadequate gas or frequency control. Environmental factors, ageing and increase in load demand from the power stations are causes of frequent loss of voltage on buses, shutdown of generators and subsequently a partial or total system collapse.

A proper reactive power management scheme in place does not allow a noticeable voltage drop or voltage increase beyond the statutory limit. The Static VAr Compensation scheme deployed in this research has been shown to be a veritable tool in supplying reactive power to boost the power system voltage on any of the affected buses or absorbing reactive power to reduce the voltage on any of the problem buses.

This was demonstrated with the injection of reactive power at bus 16 (Yola), bus 26 (Gombe) and bus 30 (Ugwuaji) respectively. This reduced their voltage magnitudes from 1.137pu to 0.975pu, 1.131 to 0.986pu and 1.055pu to 0.987pu respectively. The reactive power compensation scheme was also applied to bus 23 (Alaoji) to increase its voltage magnitude from 0.832pu to 0.954pu.

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