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# APPLICATION OF UPFC FOR OPTIMIZATION OF THE NIGERIA ELECTRIC POWER SYSTEM

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## ABSTRACT

*In this work, the optimization of power flow of Nigerian 330kv network was conducted. The optimization was achieved by the simulation of a Flexible Alternating Current Transmission System device (FACTS) called the Unified Power Flow Controller (UPFC) on the 330kv Nigerian network. A load flow analysis was first carried out on twenty-six buses, eight generators and twenty-nine transmission lines of the 330kv network of Nigerian power system. The load flow analysis was done using three techniques which included Newton-Raphson, Gauss-Seidel and Fast decoupled load flow (FDLF) in a Matlab 7.5 based program. FDLF was confirmed to be the fastest with a convergence time of 0.02 second after twenty eight iterations and hence recommended for this work. Gauss-Seidel technique failed to converge even after 1000 iterations. The bus voltages as well as line losses were obtained from the analysis. System Line Overload Index (SLOI) analysis was also carried out to determine overloaded lines. The branches identified for the simulation of UPFC in order to optimize the 330kv network include; Kainji-Jebba TS-Oshogbo, Oshogbo-Ikeja West, Oshogbo-Aiyede, Egbin-Delta GS, Shiroro-Afam, Jos-Gombe and Benin-Onitsha. The simulation of UPFC increased the maximum power transferred to the lines considered. Kainji-Jebba increased by 0.688%, Jebba TS-Oshogbo had an increase of 7.552%. Egbin-Delta GS had an increase of 38.12% which is the highest. The simulation of UPFC also increased the voltage magnitude of the buses at the receiving end of the transmission lines. The technical benefit derivable from the simulation of UPFC in Nigeria power system has been demonstrated in this work. The simulation of UPFC resulted in an optimization of Nigerian power system.*

**Keyword:** *Flexible Alternating Current Transmission System, Unified Power Flow Controller, System Line Overload Index, Load Flow, Gauss-Seidel, Fast Decoupled load Flow.*

## INTRODUCTION

The UPFC is a versatile Voltage source FACTS device that is capable of controlling any or all of the transmission system parameters (Voltage, Impedance and angle) [1-4].According to [5-7], the UPFC is a combination of the STATCOM and SSSC in a single device with a common control system.

Fig 1.0 shows the UPFC System.

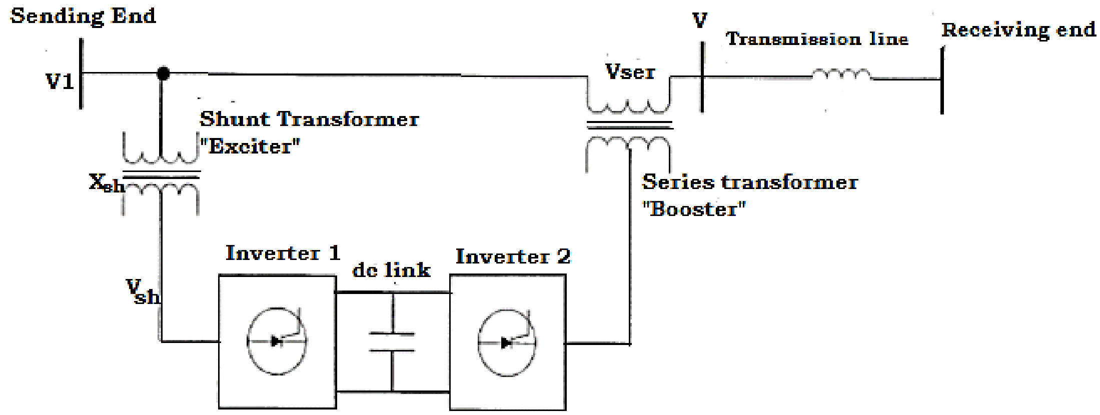



Figure 1.0 Schematic diagram of a UPFC system.

Table 1.0 shows a list of UPFCs installed.

Table 1.0 Complete list of UPFC Installations

| S/N | YEAR INSTALLED | COUNTRY | CAPACITY MVA | VOLTAGE LEVEL(KV) | PURPOSE | PLACE |
|---|---|---|---|---|---|---|
| 1 | 1998 | USA | ±320 | 138 | DYNAMIC VOLTAGE SUPPORT AND ADDED REAL POWER SUPPLY FACILITY | AEP INEZ SUBSTATION |
| 2 | 2003 | SOUTH KOREA | 80 | 154 | DYNAMIC VOLTAGE SUPPORT AND ADDED REAL POWER SUPPLY FACILITY | GANGJIN SUBSTATION |

Source: [5]

The UPFC is a SSSC and an ASVC operated from a d.c link. The SSSC cannot independently control the reactive power flow in the line and thus the reactive power remains proportional to the real power. Unlike the SSSC, the magnitude and phase angle of the compensating voltage of the UPFC are independent of the line current and the transmission angle. Therefore, the maximum change in power flow achievable by the UPFC is independent of the transmission angle and is determined only by the maximum inserted voltage. The ASVC part is responsible for supplying the real power demand of the SSSC. Hence, the UPFC allows for precise control of both real and reactive power flow. In addition, the ASVC part can operate independently within the VA rating to support the bus voltage or compensate for the load and /or line reactive power. The coordination between the UPFC two parts is much depending on the kind of the bus at which the UPFC is connected. It could be a PQ or a PV bus. The total VA exchanged between the UPFC and the a.c system is not supplied or absorbed by the a.c system.

## Steady State Modelling of UPFC

In steady state power flow analysis, UPFC can be modelled and its function in the power system can be studied.

The circuit diagram for the FACTS model is shown in fig 2.0

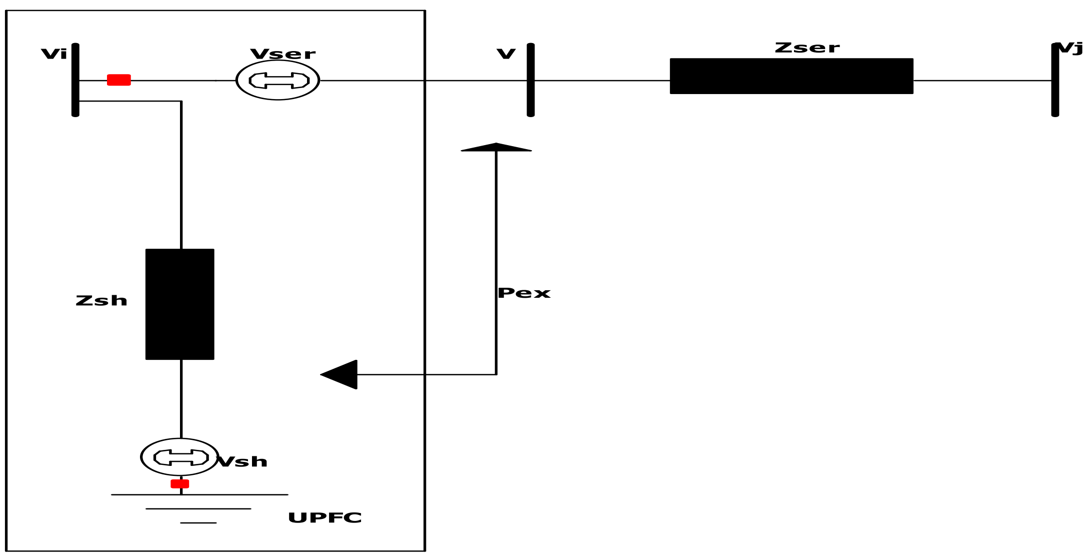



**Figure 2.0 Circuit diagram for the UPFC Model**

*Vi* and *Vj* are voltages at buses *i, j,* respectively. *V* is the voltage of bus of the receiving-end of the transmission line .The active and reactive power flows in the shunt converter is $P_{sh}$ and $Q_{sh}$. respectively. The power flow direction of $P_{sh}$ and $Q_{sh}$ is leaving bus *i*. $P_{ij}$ and $Q_{ij}$ are the UPFC series active and reactive power flows, respectively, leaving bus *i*. *Pji* and *Qji* are the UPFC series branch active and reactive power flows, respectively, leaving bus *j*. $P_{sh}$ is the real power exchange of the shunt converter with the DC link. $P_{se}$ is the real power exchange of the series converter with the DC link.

## Power Flow Constraints of UPFC

For the equivalent circuit of the UPFC shown in Fig. 3.1, suppose *Vsh* = *Vsh*∠θ *sh*, *Vse* = *Vse*∠θ *se*, *Vi* = *Vi*∠θ *i*, *Vj* = *Vj*∠θ *j*; then the power flow constraints of the UPFC shunt and series branches are [8]:

$$P_{sh} = V_i^2 g_{sh} - V_i V_{sh}(g_{sh}\cos(\theta_i - \theta_{sh}) + b_{sh}\sin(\theta_i - \theta_{sh})) \quad 1.0$$

$$Q_{sh} = -V_i b_{sh} - V_i V_{sh}(g_{sh}\sin(\theta_i - \theta_{sh}) - b_{sh}\cos(\theta_i - \theta_{sh})) \quad 2.0$$

$$P_{ij} = V_i^2 g_{ij} - V_i V_j (g_{ij}\cos\theta_{ij} + b_{ij}\sin\theta_{ij}) - V_i V_{se}(g_{ij}\cos(\theta_i - \theta_{se}) + b_{ij}\sin(\theta_i - \theta_{se})) \quad 3.0$$

$$Q_{ij} = -V_i^2 b_{ij} - V_i V_j (g_{ij}\sin\theta_{ij} - b_{ij}\cos\theta_{ij}) - V_i V_{se}(g_{ij}\sin(\theta_i - \theta_{se}) - b_{ij}\cos(\theta_i - \theta_{se})) \quad 4.0$$

$$P_{ji} = V_j^2 g_{ij} - V_i V_j (g_{ij}\cos\theta_{ji} + b_{ij}\sin\theta_{ji}) + V_j V_{se}(g_{ij}\cos(\theta_j - \theta_{se}) + b_{ij}\sin(\theta_j - \theta_{se})) \quad 5.0$$

$$Q_{ji} = -V_j^2 b_{ij} - V_i V_j (g_{ij}\sin\theta_{ji} - b_{ij}\cos\theta_{ji}) + V_j V_{se}(g_{ij}\sin(\theta_j - \theta_{se}) - b_{ij}\cos(\theta_j - \theta_{se})) \quad 6.0$$

Where

$$g_{sh} + jb_{sh} = \frac{1}{Z_{sh}}, g_{ij} + jb_{ij} = \frac{1}{Z_{se}}, \theta_{ij} = \theta_i - \theta_j, \theta_{ji} = \theta_j - \theta_i$$

## Active Power Balance Constraint of UPFC

The operating constraint of the UPFC (active power exchange between two inverters via the DC link) is:

$\Delta P_{\Sigma} = PE_{sh} - PE_{se} = 0$

where

$PE_{sh} = \mathrm{Re}(V_{sh} I^*_{sh})$ and $PE_{se} = \mathrm{Re}(V_{se} I^*_{ji})$ are active power exchange of the shunt converter and the series converter with the DC link, respectively. The symbol * represents conjugate.

UPFC can control the active power flow in a network. Equation 7.0 shows the active power control mode for UPFC.

$$P_{ji} - P_{ji}^{spec} = 0 \quad 7.0$$

$P_{ji}^{spec}$ is a specified active power flow control reference in the UPFC.

To control the bus voltage at bus j (receiving bus), a reference voltage $V_j^{spec}$ is injected into the line.

$$V_j - V_j^{Spec} = 0 \quad 8.0$$

## METHODOLOGY

This project begins with the collation of bus data and transmission line parameters of the 330KV line. Based on the data collected for the 330KV line, a load flow study of the system using the Load flow techniques is done to obtain the voltage profile at the respective buses as well as real power flow in the network. The result obtained from the load flow study is further analyzed to obtain buses whose voltage magnitude is lower or greater than a limit of ±5% together with the overall real power loss of the system. Also the System Line Overload Index (SLOI) is computed. The buses with unacceptable voltage magnitude as well as transmission lines with unacceptable losses are identified from the network. That is, the buses voltages, line losses and SLOI for the network are analysed for the 330KV network of Nigerian power system. Any of the transmission lines having any two of the violations (bus voltage<5%, SLOI <1.0 and losses >5%) are considered for the simulation of UPFC. The FACTS device (Unified Power Flow Controller) is introduced to such affected lines and hence the behavior of such buses and lines after the introduction of the FACTS device is observed. An attempt is also made to determine the capacity of the FACTS device suitable for such lines.

A Flow chart of the methodology is displayed in Fig 3.0

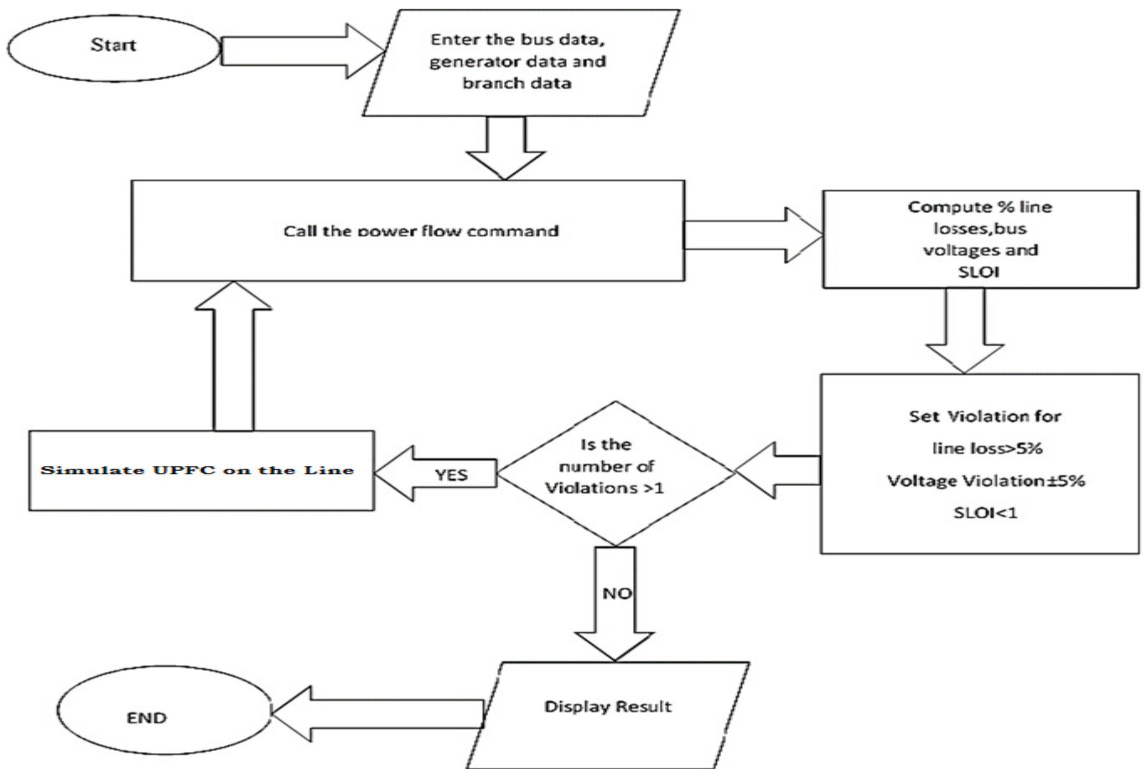



Figure 3.0 Flow Chart of the Methodology

The bus numbers are represented in the table below.

**Table 2.0 Generator Data**

| S/NO. | BUS NAME | PG(MW) | VOLTAGE (PU) |
|---|---|---|---|
| 1 | KAINJI GS | 756 | 1 |
| 2 | SHIRORO | 413 | 1 |
| 3 | JEBBA GS | 339 | 1 |
| 4 | SAPELE | 70 | 1 |
| 5 | EGBIN | 967 | 1 |
| 6 | AFAM | 316 | 1 |
| 7 | DELTA GS | 498 | 1 |
| 8 | AES | 235 | 1 |
| 9 | CALABAR | 0 | 1 |

Source: [9]

**Table 3.0 Load Data**

| S/NO. | BUS NAME | ACTIVE POWER(MW) | REACTIVE POWER(MVAR) |
|---|---|---|---|
| 10 | BIRIN-KEBBI | 89 | 55 |
| 11 | KANO | 226 | 140 |
| 12 | JOS | 114 | 90 |
| 13 | GOMBE | 130 | 80 |
| 14 | KADUNA | 260 | 161 |
| 15 | JEBBA TS | 7.44 | 3.79 |
| 16 | KATAMPE | 236 | 146 |
| 17 | OSHOGBO | 194 | 120 |
| 18 | AJAOKUTA | 72 | 45 |

| S/NO. | BUS NAME | ACTIVE POWER(MW) | REACTIVE POWER(MVAR) |
|---|---|---|---|
| 19 | NEW HAVEN | 182 | 112 |
| 20 | AIYEDE | 210 | 130 |
| 21 | IKEJA-WEST | 484 | 300 |
| 22 | BENIN | 136 | 84 |
| 23 | ONITSHA | 146 | 77 |
| 24 | ALAOJI | 248 | 153 |
| 25 | AKANGBA | 389 | 241 |
| 26 | AJA | 200 | 124 |
| 27 | ALADJA | 47.997 | 24.589 |

Source: [9]

FDLF was used to carry out the load flow studies. Convergence was reached after 0.02 second with twenty eight iterations. The voltage profile obtained from the FDLF technique applied on the 330KV power network of Nigerian power system is represented with the bar chart below.

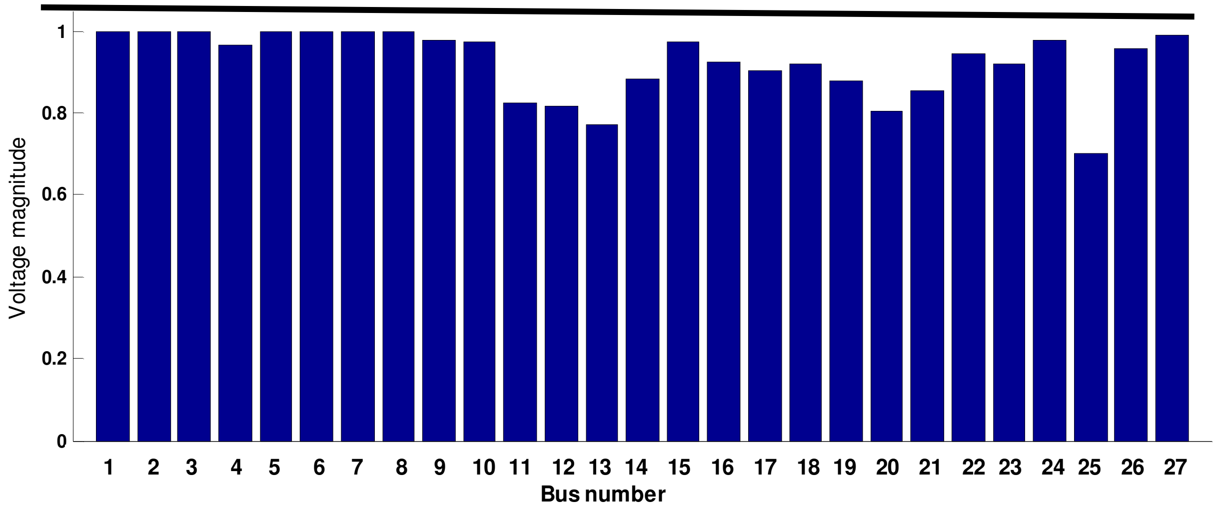


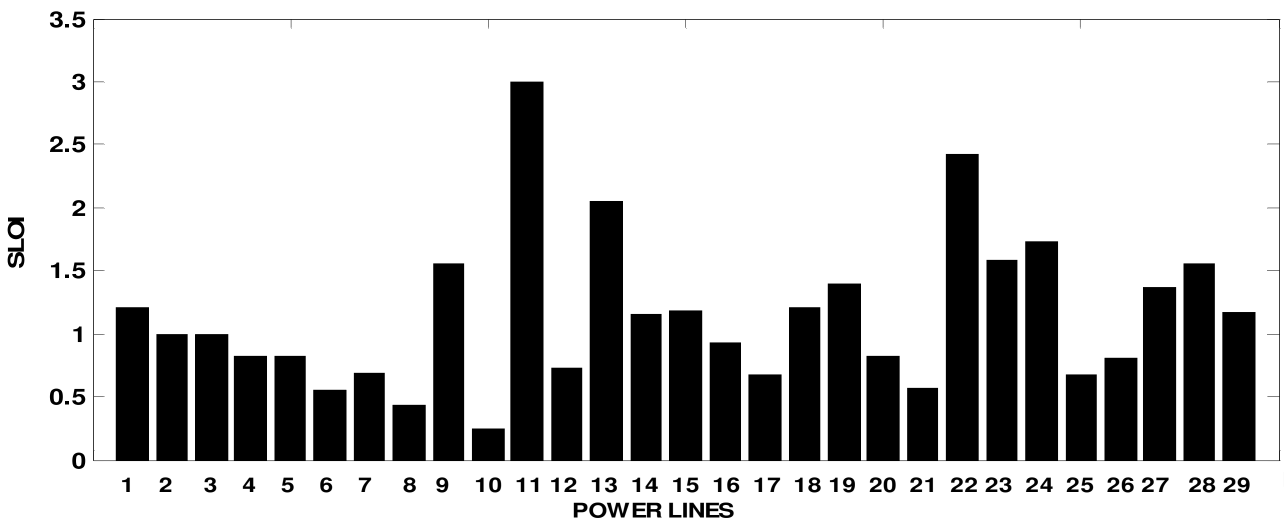

Figure 4.0 A Bar Chart showing Voltage magnitude of the various Buses in the 330kv Network

It can be seen that buses 11,12,13,14,16,17,18,19,20,21,22,23,25, representing Kano, Jos, Gombe, Kaduna, Katampe, Oshogbo, Ajaokuta, New Haven, Aiyede, Ikeja West, Benin, Onitsha and Akamgba respectively, have a voltage magnitude that is less than 0.95pu while buses 1,2,3,4,5,6,7,8,9,10,15,24,26,27 all have voltage magnitude above the 0.95pu mark.

Hence, UPFC will be simulated on the buses whose voltage magnitude is less than the 0.95pu level.

**Figure 5.0 A bar chart of the SLOI for the different lines**

Branches having SLOI less than one were considered critical lines.line 10 was considered the most critical.Others include lines 4,5,6,7,8,12,16,17,20,21,25,26.



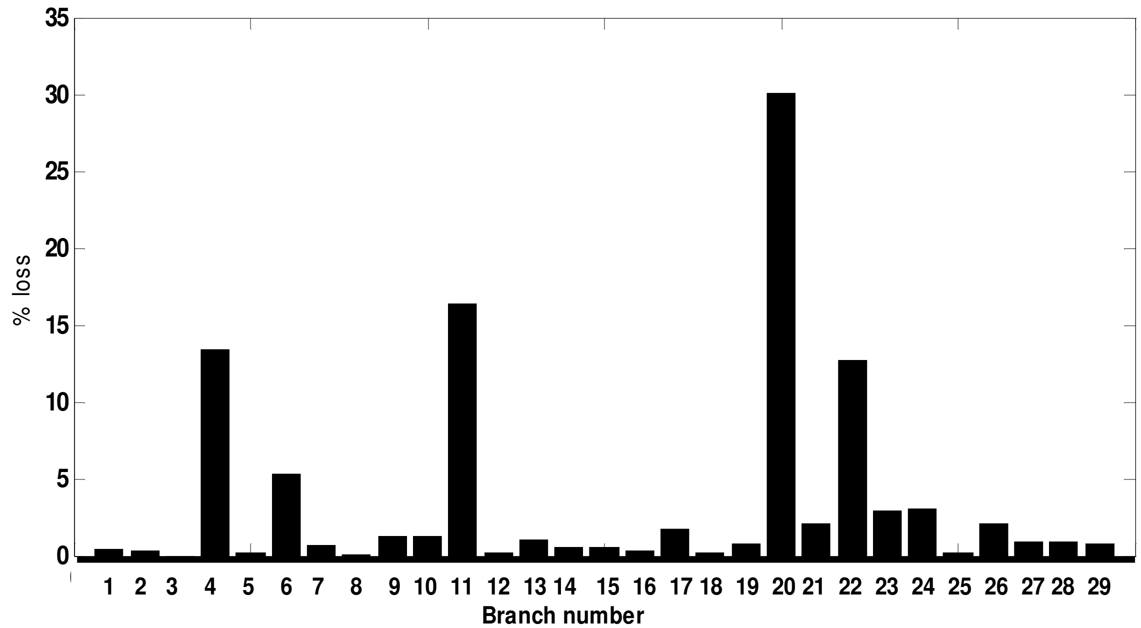



**Figure6.0 A Chart showing the percentage losses in the transmission line**

It can be seen that branch number 20 (Shiroro to Jebba TS) has the highest percentage loss followed by branch 11 (Egbin to Ikeja-west),branch 4(Kainji GS to Jebba TS),branch 22(Shiroro to Kaduna) and branch 6(Jebba TS to Oshogbo).Branch 3 recorded no loss (power was not tranfered through that branch).

**Table 4.0 Summary Table of the Analysis of branches to be considered**

| S/NO. | BRANCHES | | LINE WITH BUS VOLTAGE <0.95 | LOSSES >5% | SLOI<1.0 | COMMENT |
|---|---|---|---|---|---|---|
| | FROM | TO | | | | |
| **4** | 1 | 15 | NONE | YES | YES | CONSIDERED |
| **6** | 15 | 17 | BUS 17 | YES | YES | CONSIDERED |
| **7** | 17 | 21 | BOTH | NO | YES | CONSIDERED |
| **8** | 17 | 20 | BOTH | NO | YES | CONSIDERED |
| **10** | 21 | 25 | BOTH | NO | YES | CONSIDERED |
| **17** | 7 | 22 | BUS 22 | NO | YES | CONSIDERED |
| **20** | 2 | 15 | NONE | YES | YES | CONSIDERED |
| **21** | 2 | 16 | BUS 16 | NO | YES | CONSIDERED |
| **25** | 12 | 13 | BOTH | NO | YES | CONSIDERED |
| **26** | 22 | 23 | BOTH | NO | YES | CONSIDERED |

**Simulation of UPFC along Branch 4 (Kainji to Jebba Ts)**

Although the voltage profile on both buses is within the accepted limit nevertheless UPFC is simulated for possible voltage improvement and increase in power transfer along the line. The reference active power in the UPFC is set at 900MW as its final value and 870.06MW as its initial value.

**Fig7.0** shows the wave form from the simulation of real power flow from Kainji to Jebba TS using UPFC.

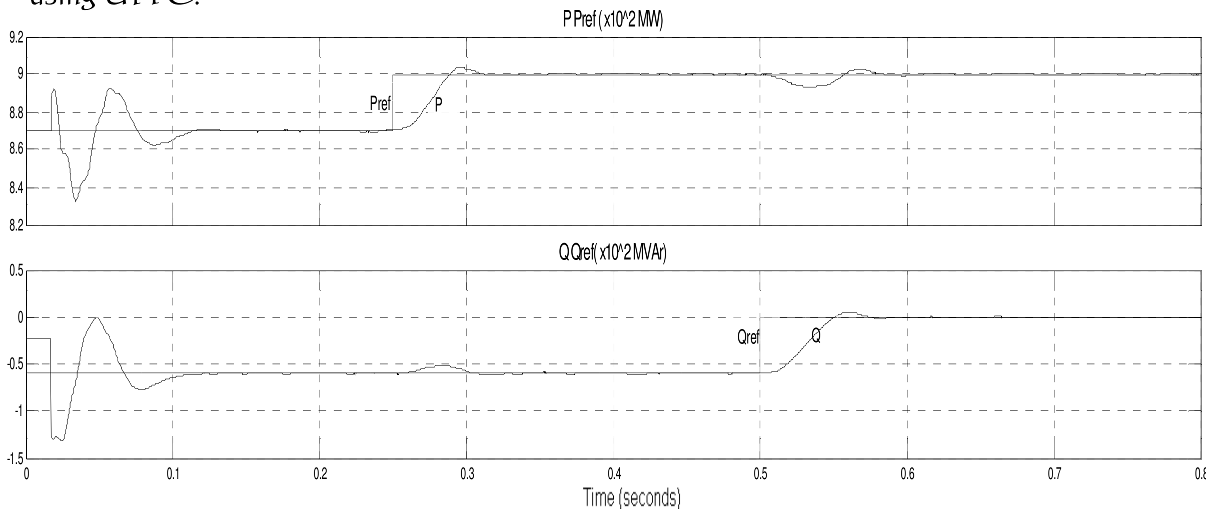



**Figure 7.0 Wave form of the Real and Reactive Power Flow from Kainji to Jebba TS**

From the wave form in **Fig 7.0**, it can be seen that after a transient period lasting for approximately 0.15sec, the steady state is reached at P=870.06MW and Q=60MVAr.At approximately 0.3sec, real power (P)is ramped to a new level of 900MW. It continued at that state for 0.2sec.At 0.5sec there was a noticeable drop in real power. This occurred just as the reactive power increased to a new ramped value of 0MVAR. Both P and Q continued at their ramped value till the end of the simulation. All other simulations follow similar pattern.

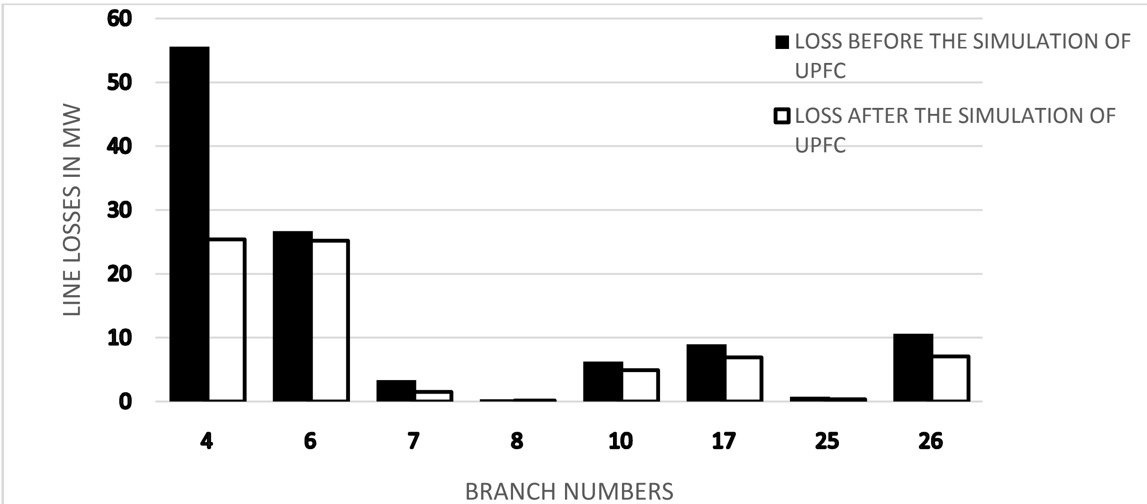



Figure 8.0 A Chart Representing the Line Losses before and after the Implementation of UPFC

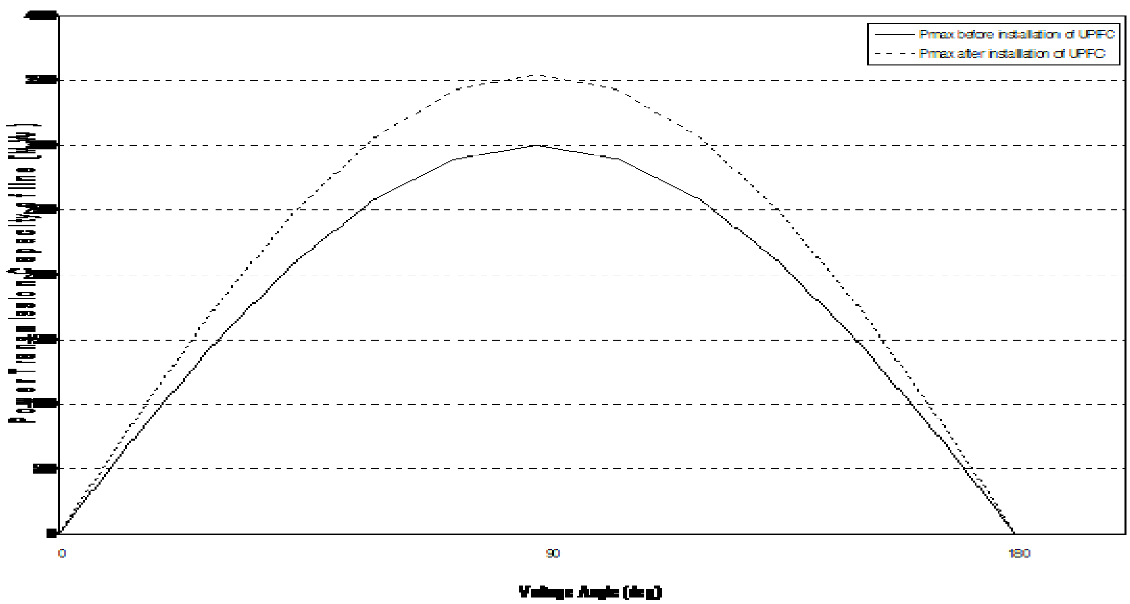



**Figure 9.0 . A graph of the Maximum Power Capacity of Branch 8 before and after UPFC Installation.**

The graph of branch 4, 6, 7,10,17,25 and 26 show similar resemblances with figure 9.0 hence, they are not represented. From the graph in figure 9.0, as the angle between the sending end voltage and receiving end voltage becomes 90°(Vr quadrature to Vs), the capacity of power that can be transmitted without loss in stability, becomes maximum. It can be seen from fig9.0 that the maximum power capacity of the transmission line without a loss in stability is increased with the installation of UPFC. UPFC installation has a positive effect on the stability of the transmission line.

The improvement in voltage magnitude at the receiving end is shown in Fig 10.0

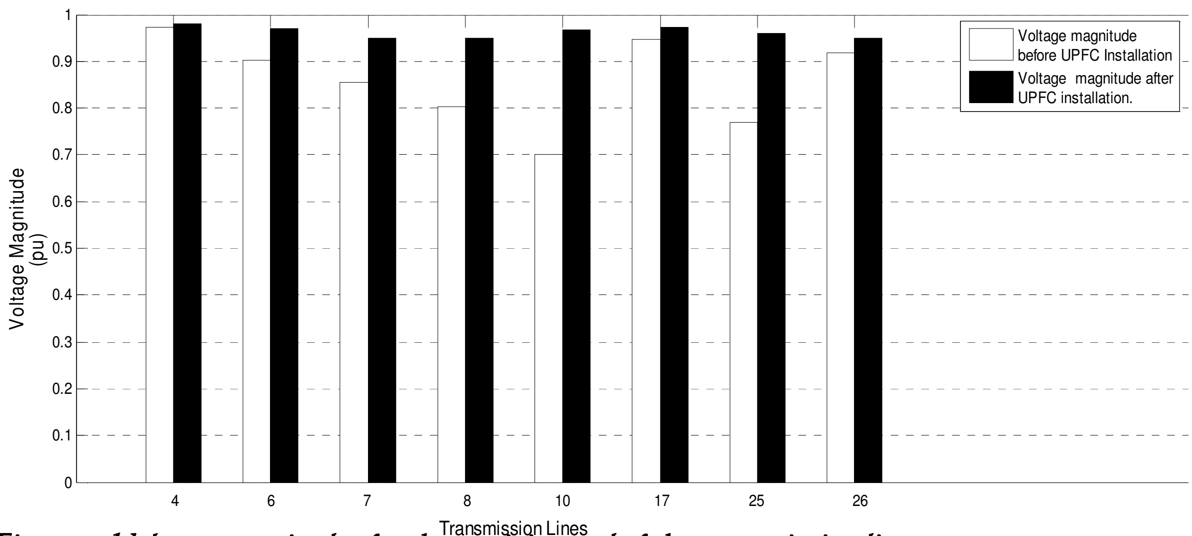



**Figure 10 Voltage magnitudes for the receiving end of the transmission lines.**

From **Fig 10**, it can be seen that the voltage magnitude of the receiving end of the transmission line improved after the installation of UPFC.

## CONCLUSION

The simulation of the Unified Power flow Controller (UPFC) which is a voltage sourced converter (VSC) based Flexible Alternating Current Transmission System (FACTS) controller was presented in this thesis. Power flow analysis of the 330KV line of Nigerian power system was carried out. This was done to identify possible locations for the simulation of the FACTS model (UPFC).The FDLF technique used had a convergence time of 0.02 seconds after 28 iteration.

The voltage profile of the buses in the 330KV line were obtained using three LF techniques (NR, GS and FDLF). GS did not converge even after 1000 iterations. NR and FDLF converged but FDLF technique converged faster in 0.02second. The voltage profile increase is at follows after the simulation of UPFC on the considered lines; Jebba TS at branch 4 increased by 0.72.Oshogbo at branch 6 increased by 7.54%.Ikeja west at branch 7 increased by 11.20%.Aiyede at branch 8 increased by 18.50%.Akangba at branch 10 increased by 38.14%.Benin at branch 17 increased by 2.75%.Gombe at branch 25 increased by 24.84%.With the introduction of UPFC on the simulated line, the voltage magnitude of the lines were increased. The simulation of UPFC also caused an increase in the voltage magnitude of the buses at receiving end. Hence, the technical benefit derivable from the use of the FACTS model UPFC in Nigerian power system has been simulated in this work. The simulation of the UPFC on the 330KV Nigerian network led to the optimization of the voltage profile as well as power transmitted along the transmission lines of the Nigerian power system.

## RECOMMENDATIONS

The technical information provided in this thesis forms a veritable database for future work towards improved Nigeria power system operation.

The following are recommended to ensure efficient operation of the Nigeria grid system:

a) UPFC with an appropriate size should be installed at the branches considered for implementation in the work
b) The implementation of UPFC should be implemented preferably at the receiving end of the transmission line. This is to take care of the drop in voltage as well as losses during transmission
c) Power flow studies should be carried out at least twice a year. This is to ensure that a change in power demanded is taken into account.
d) The staff in the control room should be adequately trained on the configuration of the device (UPFC) to ensure an optimum operation of the device.
e) Finally, routine maintenance of the device should be done so that the device can remain at its optimum condition.

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