Voltage Profile Improvement of a Disturbed Electric Power System using UPFC Compensation

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Abstract— The major objective of using flexible alternating current transmission systems (FACTS) devices in an interconnected electric power transmission network is to improve the parameters of the transmission line. This study presents the voltage profile improvement and power loss reduction of the Nigeria 330 kV transmission network using the unified power flow controller (UPFC) as an optimal FACTS device. The study utilized the power systems analysis toolbox (PSAT) 2.1.10 that is embedded in MATLAB 2017a to model the Nigeria 330 kV transmission network that consists of 9 generating stations, 31 buses and 42 transmission lines. The Newton Raphson load flow algorithm was used to carry out the load flow study using data obtained from the transmission company of Nigeria. Voltages less than 0.95pu (313.5kV) were assumed to be low voltage while those greater than 1.05pu (346.5kV) were assumed to be high voltage. A base case load flow study was carried out without the use of UPFC to determine weak buses. The outcome of the base case simulation without the use of the UPFC showed that seven buses were operating outside the lower operating limit. After compensation using the UPFC, the operating voltages at each of the buses were found to be within the stated limit. Findings from the study show that the weak buses occurred as a result of the long distances between the transmission lines and the generating stations. The transmission line losses were found to have been reduced from 71.66MW to 32.95MW and from 76.7MVAR to 41.89MVAR respectively.

Keywords—Newton-Raphson, Reactive/ Real power, Transmission network, UPFC

I. INTRODUCTION

With the increase in power demand, the performance of transmission network has come under increasing threats due to widespread failures [1]. This is because, as power system network are being operated close to their boundary conditions due to line congestions, their performance is decreased. While the expansion of transmission network would have been the best solution to increase the performance of transmission systems, their expansion is restricted due to environmental, health and budgetary challenges [2], [3]. Therefore, to improve the performance of alternating current power system, we need power electronic devices to control both active and reactive powers and to enhance the usable capacity of the present transmission system [4].

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One major way of tackling the poor performance of transmission network is the use of a fast-responding electrical system known as the Flexible Alternating Current Transmission Systems (FACTS) [5]. FACTS devices have been defined by the IEEE as an “alternating current transmission system that incorporates power electronic-based and other static controllers to enhance controllability and increase power transfer capability” [6], [7]. Among the FACTS devices, the unified power flow controller (UPFC) is the most versatile and effective [8], [9]. The UPFC belongs to the family of series shunt FACTS controllers that combines series and shunt controllers controlled in a coordinated manner [10]. It has the ability to adjust the three control parameters, i.e. the bus voltage, transmission line reactance, and phase angle between two bus voltages, either simultaneously or independently. A UPFC performs this through the control of the in-phase voltage, quadrature voltage and shunt compensation. Several trials have been reported in the literature to model the UPFC for steady – state and transient studies [11, [12]. In the area of power flow analysis, models of the UPFC have been published [13], [15] – [19] which treat the UPFC either as one series voltage source and one shunt current source or both the series and the shunt are represented by voltage sources. [13] surveyed the possibility of installing a UPFC on a 500kV transmission system exploring the application of the UPFC for control of active and reactive power flow. The result showed that the attainable response of the control is very fast, almost instantaneous, and thus the UPFC is effective in handling dynamic system response. Reference [15], presented the performance of the UPFC power flow controller in controlling the flow of power over the transmission line using a voltage source model to study the behaviour of the UPFC in regulating the active, reactive power and voltage profile. Findings from the study showed that the UPFC is capable of regulating the voltage of the bus as well as regulating the active and reactive power flow and the lines within specified limits. In [19], the authors’ studied the important implications of complex variable Newton-Raphson load flow analysis. The study developed a Newton-Raphson load flow analysis formulation which included a UPFC. The model was simulated using the IEEE 30 bus system using M-power software. The study reported a reduction in the active and reactive power loses. Relating to the optimality of UPFC in relation to other FACTS devices [20], carried out an enhancement of power profiles by various FACTS devices in power system using MATLAB/SIMULINK on an 11kV transmission line. Findings of the study showed that the UPFC improved more real and reactive power compared to SSSC and performed better in every respect as compared to other FACTS devices in load flow stability and voltage quality.
In all of the literatures surveyed however, none of the authors used PSAT to model a transmission network and to the best of the knowledge of the authors, the switching states of the thyristors as used in the UPFC have not been discussed in any literature. In this study, the UPFC is used in PSAT that is embedded in MATLAB to improve the voltage profile and reduce power loss of the Nigeria 330 kV transmission network with a step by step analysis of the thyristor operating states of the UPFC converters.

II. UPFC OPERATING PRINCIPLE

The UPFC is an electrical device that is used to provide fast active and reactive power compensation on high-voltage electricity transmission network. The UPFC uses a pair of three-phase controllable bridges to produce current that is injected into a transmission line using a series transformer. The UPFC is used to control active and reactive power in a transmission line. The converters are connected to the AC system by a shunt and a series transformer. A UPFC consists of two converters, two transformers and a DC link as shown in Figure.1.

The inner circuitry of the UPFC is also shown in Figure.1. It consists of two gate-turn-off (GTO) based converters, one connected in the shunt and the other in series with the transmission line and the DC sides are connected back to back. The UPFC is connected to the transmission line through coupling transformers. The thyristor as used in the UPFC functions as a controlled diode in which case it is used as a power switch. The thyristor is a four-layer, three terminals, three junction PNPN device with high reliability and low loss enabling them to be used for all high-power applications. The three terminals are anode, cathode and the gate; the four layers are ‘P’, ‘N’, ‘P’ ‘N’. The state of the switches depends on whether we want the transmission line to inject or absorb reactive power in series with the line in which case it can serve as an inverter or a rectifier.

III. UPFC SWITCHING STATES

A. Switching States for the Inverting Process

In using the UPFC, the firing angle is the reference to the voltage at which the thyristor is turned ON. The thyristors are switched ON when the gate pulses are received. The state of the pulses determines if they are inverting or rectifying. The switching state for the inverting process of the six-state thyristor power switches is shown in Fig. 2.

![Figure 1. UPFC principle of operation](image)

![Figure 2. Switching ON and OFF of each thyristor for various inverting stage](image)

Six switches (gate-turn-off thyristors) are used in either side of the two converters of the UPFC with each switch switched ON at an interval of 60°. S1 is switched on at 0°, S2 is switched on at 60°, S3 is switched on at 120°, S4 is switched on at 180°, S5 is switched on at 240° and S6 is switched on at 300° for both converters.

Also, the phase difference between the upper and the lower thyristors for the series converter is 180°. Thus, for the upper and lower thyristor on the same line, they have the same polarity at each point in time. That is, switch S1 and S4, S2 and S5 and S3 and S6 have a phase difference of 180°. Further, for consecutive even or odd thyristor switching states, the phase difference is 120°. Thus, S1 and S3 have a phase difference of 120°. The same phase angle difference exists between S2 and S5, S4 and S3 and S6.

At a single phase, 3 switches are switched ON. Not more than two switches are switched ON in either the upper or lower region of the thyristor. If the DC link is charged which indicates the excess of real power, the series part of the converter acts as an inverter. During the first pulse, that is, at a firing angle of 0°, switches S1, S3 and S5 of the series converter are turned ON while switches S2, S4 and S6 are turned OFF. At this first firing angle of 0°, the shunt converter acts as a rectifier, converting ac to dc and injecting the excess real power into the transmission line. At such a time, switches S2, S4 and S6 of the shunt converter are turned ON while switches S1, S3 and S5 are turned OFF.

Further, at this same charged state of the DC link and at the second firing angle of 60°, switches S1, S3 and S5 of the series converter are turned ON while switches S2, S4 and S6 are turned OFF. At this first firing angle of 60°, the shunt converter acts as a rectifier, converting ac to dc and injecting the real power into the transmission line. At such a time, switches S2, S4 and S6 of the shunt converter are turned ON while switches S1, S3 and S5 are turned OFF. In the same vein, if the DC link is not charged indicating a shortage of real power, the series converter acts as a rectifier while the shunt part acts as an inverter following the same sequence of the switching ON and OFF of the thyristors.
This circle of the switch turning ON and OFF for each state of the firing angle for the 6 pulses, continues until such a time that the system is balanced. The letters ‘1’ and ‘0’ are respectively used to represent the ‘ON’ and ‘OFF’ state of the thyristors as shown in Table 1.

### TABLE 1. SWITCHING STATES OF THE SIX THYRISTOR SWITCHES FOR THE INVERTING MODE

| Firing Angle (°) | Switching States of the 6 Thyristors for the inverting stage |
|-----------------|-------------------------------------------------------------|
| 0               | S₁ 0 0 0 1 1                                               |
| 60              | 1 0 0 1 0 1                                              |
| 120             | 1 1 1 0 0 0                                             |
| 180             | 0 1 1 0 1 0                                             |
| 240             | 0 0 1 1 0 1                                             |
| 300             | 0 0 0 0 1 1                                           |

B. Switching States for the Rectifying Process

Here, the 120° conduction mode is used to explain the state of the switches.

![Switching States for the Rectifying Process](image)

That is, at a single phase, only two switches are in the ON state, one in the upper part and the other in the lower part of the converter. Consider the plot of the 6 thyristor switches shown in Fig.3.where only two switches are in the ON state at the same time. At a firing angle of 0°, only switches S₁ and S₆ are in the ON state while switches S₂, S₃, S₄, and S₅ are switched OFF. Also, at a firing angle of 60°, switches S₂ and S₅ are switched ON while switches S₁, S₃, S₄, and S₆ are switched OFF. This switching ON and OFF process continues until such a time that the real power becomes equal to the reactive power.

### TABLE 2. SWITCHING STATES OF THE 6 THYRISTOR SWITCHES FOR THE RECTIFYING MODE

| Firing Angle (°) | Switching States of the 6 Thyristors for the rectifying stage |
|-----------------|-------------------------------------------------------------|
| 0               | S₁ 0 0 0 0 1                                               |
| 60              | 1 1 0 0 1 0                                              |
| 120             | 0 1 1 0 0 0                                             |
| 180             | 0 0 1 0 1 0                                             |
| 240             | 0 0 0 1 1 0                                             |
| 300             | 0 0 0 0 1 1                                           |

IV. SIMULATION OF UPFC

The Nigeria transmission network is managed by Independent power project, private participating partners and the Generation Company (GENCO). The Nigeria national grid is an interconnection of 9,454km length of 330 kV transmission lines made up of nine generating stations [21]. The system under study interconnects these generating stations through a network of thirty-one (31) buses and forty-two (42) transmission lines of either dual or single circuit lines with four control centres. Of the four control centres, the control centre at Osogbo is the national control centre while the other three control centres are at Benin, Shiroro and Egbin [22] – [24]. Of the nine generating stations, three are hydro power stations while the remaining six are thermal power stations. The single line diagram of the Nigeria 330 kV 31 bus transmission grid network used as the case study is redrawn for load flow studies as shown in Figure.4. The Egbin station was chosen as the slack bus among other generating stations because it is the generator with the largest power in the network.

![Single Line Diagram of the Nigeria 330 kV 31 Bus Network before compensation](image)
Table 3: Per Unit Voltage Profile of the Nigeria 330 kV before Compensation

| B/N | Bus Name  | Uncompensated Voltage Profile (per unit) | Bus angle (degree) |
|-----|-----------|------------------------------------------|-------------------|
| 1   | Abuja     | 0.915214                                 | 12.6533           |
| 2   | Alain GS  | 1.0000                                  | 12.3541           |
| 3   | Aja       | 0.971100                                 | -0.86970          |
| 4   | Ajaoakuta | 0.997653                                 | 8.89540           |
| 5   | Akangbe   | 0.965989                                 | 2.45990           |
| 6   | Aladja    | 1.012346                                 | -15.8765          |
| 7   | Alaoji    | 0.9358265                                | -6.91050          |
| 8   | Ayele     | 0.987423                                 | -16.6543          |
| 9   | Brinin Kebbi | 1.054332                                 | 2.87640           |
| 10  | Benin     | 0.996754                                 | -8.9812           |
| 11  | Delta PS  | 1.0000                                  | 11.1400           |
| 12  | Egbin GS  | 1.0000                                  | 0.0000            |
| 13  | Egbin TS  | 0.987834                                 | 3.18040           |
| 14  | Geregu    | 1.0000                                  | 0.98000           |
| 15  | Gombe     | 0.885320                                 | -7.8732           |
| 16  | Ikeja West| 0.999563                                 | -4.0993           |
| 17  | Jebba GS  | 1.0000                                  | 4.8000            |
| 18  | Jebba TS  | 0.992319                                 | 1.3075            |
| 19  | Jos       | 0.892145                                 | -13.6289          |
| 20  | Kaduna    | 0.925412                                 | -14.5418          |
| 21  | Kainji GS | 1.0000                                  | 8.5143            |
| 22  | Kano      | 0.814312                                 | -13.8765          |
| 23  | Maiduguri | 0.800231                                 | -15.8675          |
| 24  | Makurdi   | 0.892312                                 | -13.9843          |
| 25  | New Heaven| 0.963412                                 | 11.8643           |
| 26  | Okpai GS  | 1.0000                                  | 3.2100            |
| 27  | Onisha    | 0.974523                                 | 9.54345           |
| 28  | Oshogbo   | 1.049921                                 | 1.8755            |
| 29  | Sapele PS | 1.0000                                  | 10.1190           |
| 30  | Shiroro GS| 1.0000                                  | -6.2540           |
| 31  | Shiroro TS| 0.985634                                 | -3.2340           |

In Table 3, the buses outside the lower operating range of 0.95pu are seven (7) namely: Abuja (0.915214), Gombe (0.885320), Jos (0.892145), Kaduna (0.925412), Kano (0.814312), Maiduguri (0.800231) and Makurdi (0.892319). The values of these buses in actual kV are Abuja (295.32kV), Gombe (292.15 kV), Kaduna (305.38kV), Kano (268.72kV), Maiduguri (264.08kV) and Makurdi (294.46kV).

Figure 5. A bar chart showing voltage profile before compensation

Figure 5 shows a bar chart that represents the voltage profile of the Nigerian 330 kV transmission network before compensation with UPFC.

Table 4: Per Unit Voltage Profile of the Nigeria 330 kV after Compensation

| B/N | Bus Name  | Compensated Voltage Profile (per unit) | Bus angle (degree) |
|-----|-----------|----------------------------------------|-------------------|
| 1   | Abuja     | 0.97120                                 | 15.9999           |
| 2   | Alain GS  | 1.00000                                 | 14.5644           |
| 3   | Aja       | 0.98832                                 | -9.2659           |
| 4   | Ajaoakuta | 0.99128                                 | 9.2987            |
| 5   | Akangbe   | 0.98295                                 | 3.3456            |
| 6   | Aladja    | 1.00000                                 | -10.6967          |
| 7   | Alaoji    | 0.98912                                 | 7.0351            |
| 8   | Ayele     | 0.97454                                 | -15.0456          |
| 9   | Brinin Kebbi | 0.98345                                 | 3.4509            |
| 10  | Benin     | 0.99345                                 | 8.3435            |
| 11  | Delta PS  | 0.99942                                 | 11.3406           |
| 12  | Egbin GS  | 1.00000                                 | 0.0000            |
| 13  | Egbin TS  | 0.99743                                 | 3.3673            |
| 14  | Geregu    | 1.00000                                 | 1.8249            |
| 15  | Gombe     | 0.96439                                 | -16.3298          |
| 16  | Ikeja West| 0.98342                                 | -3.4330           |
| 17  | Jebba GS  | 0.98543                                 | 4.9675            |
| 18  | Jebba TS  | 0.99431                                 | 1.4583            |
| 19  | Jos       | 0.96763                                 | -3.5445           |
| 20  | Kaduna    | 0.95604                                 | -17.3495          |
| 21  | Kainji GS | 1.00000                                 | 8.5853            |
| 22  | Kano      | 0.95843                                 | -12.444           |
| 23  | Maiduguri | 0.95604                                 | -14.3291          |
| 24  | Makurdi   | 0.97349                                 | -12.6671          |
| 25  | New Heaven| 0.98548                                 | 12.4358           |
| 26  | Okpai GS  | 1.00000                                 | 4.1100            |
| 27  | Onisha    | 0.97563                                 | 10.9490           |
| 28  | Oshogbo   | 0.99854                                 | 2.3202            |
| 29  | Sapele PS | 1.00000                                 | 10.2772           |
Table. 4 shows the per unit voltages and the bus angle of each buses of the Nigeria 330 kV transmission network after compensation. The highlighted buses indicate those buses that were hitherto operating below the lower operating range of 0.95pu, (313.5kV). After these buses were compensated using the UPFC, their operating voltages improved considerably and fell within the operating range as shown in Table 4.

**TABLE 5. LINE LOSSES OF THE NIGERIA 330 kV NETWORK BEFORE AND AFTER COMPENSATION**

| B/Sequence | From | To     | Line losses before compensation (p.u.) | Line losses after compensation (p.u.) |
|------------|------|--------|---------------------------------------|--------------------------------------|
|            |      |        | Real | Imaginary | Real | Imaginary |
| B. Kebbi   | Kainji GS | 0.00574 | -0.00175 | 0.00147 | -0.00152 |
| Kainji GS  | Jebba TS | 0.00438 | -0.00699 | 0.00142 | 0.00682 |
| Gombe      | Jos     | 0.00340 | -0.00139 | -0.0024 | 0.00719 |
| Maiduguri  | Gombe   | 0.10640 | -0.00861 | 0.01532 | 0.01275 |
| Oshogbo    | Ayede   | 0.00556 | -0.00113 | 0.00374 | 0.00709 |
| Jebba TS   | Oshogbo | 0.00430 | 0.00578 | 0.00375 | -0.00685 |
| Jebba TS   | Oshogbo | 0.00430 | 0.00578 | 0.00375 | -0.00685 |
| Geregu     | Ajaokuta| 0.00161 | 0.00575 | 0.00150 | 0.00695 |
| Jos        | Makurdi | 0.00284 | 0.00526 | 0.00202 | 0.00389 |
| Ajaokuta   | Benin   | 0.00672 | -0.00174 | 0.00119 | -0.00435 |
| Ajaokuta   | Benin   | 0.00671 | -0.00174 | 0.00119 | -0.00435 |
| Benin      | Oshogbo | 0.00474 | -0.00195 | 0.00137 | -0.00437 |
| Kainji GS  | Jebba TS| 0.00378 | 0.00499 | 0.00142 | 0.00682 |
| Makurdi    | N. Heaven| 0.00319 | 0.00229 | 0.00610 | 0.00601 |
| Ayede      | Ikeja West | 0.00503 | -0.00197 | 0.00930 | 0.00292 |
| Oshogbo    | Ikeja West | 0.00589 | 0.00563 | 0.00971 | -0.00435 |
| Benin      | Ikeja West | 0.00237 | 0.00318 | 0.00162 | -0.00154 |
| Benin      | Sapele PS | 0.00527 | 0.00337 | 0.00410 | 0.00194 |
| Benin      | Onitsha | 0.00386 | -0.0019 | 0.00482 | -0.00733 |
| N. Heaven  | Onitsha | 0.00276 | 0.00199 | 0.00151 | -0.00153 |
| Ikeja West | Egbin GS | 0.00236 | 0.00148 | 0.00291 | -0.00117 |
| Benin      | Delta PS | 0.00366 | -0.00169 | 0.00141 | -0.00720 |
| N. Heaven  | Alaoji | 0.00336 | 0.00238 | 0.00118 | 0.00297 |
| Jebra GS   | Jebba TS | 0.00247 | 0.00483 | 0.00267 | -0.00193 |
| Onitsha    | Alaoji | 0.00448 | -0.0017 | 0.00156 | -0.0017 |
| Onitsha    | Okpai GS | 0.00831 | 0.00587 | 0.00138 | 0.00275 |
| Alaoji     | Afam GS | 0.00821 | 0.00573 | 0.00250 | 0.00650 |
| Alaoji     | Afam GS | 0.00821 | 0.00573 | 0.00250 | 0.00650 |
| Sapele PS  | Aladja | 0.00540 | 0.00361 | 0.00136 | -0.00379 |
| Delta PS   | Aladja | 0.00326 | 0.00375 | 0.00162 | -0.00198 |
| Egbin GS   | Aja | 0.00490 | -0.00016 | 0.0018 | -0.00118 |
| Egbin GS   | Aja | 0.00490 | -0.00016 | 0.0018 | -0.00118 |
| Egbin GS   | Egbin TS | 0.00328 | 0.00688 | 0.0011 | 0.00136 |
| Ikeja West | Akaegbu | 0.00485 | 0.00759 | 0.00376 | 0.00193 |
| Shiroro GS | Jebra TS | 0.00244 | -0.00025 | 0.00647 | -0.00425 |
| Egbin GS   | Akaegbu | 0.00374 | 0.00475 | 0.0018 | 0.00388 |
| Akumgba    | Egbin TS | 0.00451 | 0.00521 | 0.00168 | 0.00107 |
| Shiroro GS | Abuja | 0.00431 | 0.00349 | 0.00248 | 0.00571 |
| Shiroro GS | Abuja | 0.00431 | 0.00349 | 0.00248 | 0.00571 |
| Kaduna     | Shiroro GS | 0.00113 | 0.00462 | 0.00220 | 0.00411 |
| Kano       | Kaduna | 0.00237 | 0.00484 | 0.00214 | 0.00117 |
| Jos        | Kaduna | 0.00250 | 0.00321 | 0.00431 | 0.00214 |
| **Total losses** | | 0.00824 | 0.00767 | 0.00578 | 0.00418 |

Table 5 shows the real and the reactive power line losses of the Nigeria 330 kV transmission network before and after the transmission line was compensated for using the UPFC. Before compensation, the real power loss was 82.4MW while the reactive power loss was 76.7MVAR. After compensation with UPFC, the power loss reduced to 57.8MW for the real part and 41.8MVAR for the reactive part.

To show clearly the degree to which the transmission network has been improved, the graph of Figure. 7 is a plot of the 31 buses considered in this study.

**Figure. 7. Bar chart showing voltage profile after compensation**

Figure. 7 shows a bar chart that represents the voltage profile of the Nigeria 330 kV transmission network after compensation with UPFC. The result shows that the following buses, which hitherto experienced low voltages have been adequately restored to the operating range using the UPFC. They are: Abuja (0.9712pu), Gombe (0.96433pu), Jos (0.96763pu), Kaduna (0.95604pu), Kano (0.95843pu), Maiduguri (0.95604pu) and Makurdi (0.97349pu).

**VI. CONCLUSION**

The Nigerian transmission network is faced with efficiency issues which affect transmission line parameters such as the voltage magnitude and the real and reactive powers. These results to incessant power outages. In this study, a performance analysis of the Nigerian 330 kV network using UPFC to improve the voltage profile and reduce power losses was carried out. The UPFC was chosen because of its distinguished characteristic features that stand it out among other FACTS devices. Such features include its ability to modify the characteristics of the transmission line. The power flow analysis for the Nigeria 330 kV grid system was carried out using power systems analysis toolbox (PSAT), a power system software that is embedded in MATLAB. The Newton Raphson (N-R) load flow algorithm was used in carrying out the power flow because of its rate and accuracy of convergence.

The N-R load flow algorithm proved to be an excellent method of carrying out load flow study of the Nigeria 330 kV network. Through the study, the magnitude of the voltage drops, the active and
the reactive power losses in the line as well as their phase angles were identified. The UPFC was used to regulate the voltage magnitude and phase angle. The load flow study before compensation identified buses with low voltages as thus: Abuja (0.915214pu), Gombe (0.885320pu), Jos (0.892145), Kaduna (0.925412pu), Kano (0.814312pu), Maiduguri (0.800211pu) and Makurdi (0.892312pu). The simulation of the network with UPFC substantially improved the voltages at Abuja (0.97120pu), Gombe (0.96673pu), Kaduna (0.95664pu), Kano (0.95843pu), Maiduguri (0.95664pu) and Makurdi (0.97349pu). The result of the power flow analysis after compensation with UPFC showed a significant reduction in the total system voltage violations with all the bus voltages within the specified limit of 0.95 – 1.05pu.

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