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A Comparison of Generalized Unified Power Flow Controller and Load Tap Changing Transformer for Voltage Stability Enhancement in a Power System

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Authors' contributions

This work was carried out in collaboration between both authors. Author AO designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author IA coordinated and supervised this research. Author IA managed the analyses of the study. Authors AO and IA managed the literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

The continuous increase in power demand and huge power losses in modern power systems have been a growing concern to power utilities. Such phenomenon often results in epileptic power supply, power system instability, supply fluctuations and security problems in many parts of the globe. Identification of suitable places for the installation of reactive power compensators to minimize voltage drop and system power losses in a power system becomes imperative. In this paper, the Newton-Raphson iterative method was used for the power flow solution of the 28 bus Nigerian 330KV grid system. The Generalized Unified Power flow Controller (GUPFC) is installed at identified weak load buses of the Nigerian 28-bus power system to reduce the losses and voltage drop of the system. A comparative analysis of the GUPFC with Load Tap Changing Transformers (LTCT) is also performed. Result obtained shows that the GUPFC can largely (effectively) improve the system power stability and selectively balance the power flow of multi-lines power flows when placed at identified weak buses compared with LTCT. Thus, GUPFC can be used to reduce overall power losses along transmission lines as well as improve stability overall reliability of the power grid system.

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Keywords: Power flow; voltage stability; power loss; power system; load tap changing transformer.

1. INTRODUCTION

Electricity demand has been on the increase over the past few decades. Consequently, electrical power systems are forced to operate closer to stability limit [1]. Besides, the continuous and exponential increase in power demand results in overloading of transmission lines and critical stability issues such as voltage and power instability. Prolonged exposure of power systems to these challenges could further cause power loss and ultimately, total system breakdown and power outage [2]. Power outage disrupts daily economic activities, and this can be suicidal to an entire national economy. It therefore becomes imperative to enhance the power system's stability while simultaneously, providing maximum loading capacity. This could be implemented through the control of bus voltage magnitude, real and reactive power flow of multiline systems.

Integration of Flexible Alternating Current Transmission Systems (FACTS) device to power system is viable approach to improve active power flow and voltage stability in the design and operation of the system. The FACTS devices are power electronic appliances capable of managing congestion, enhancing security and available capability, controlling power flow, and improving overall performance of power system through selective control of power system parameters at any identified bus position [3,4,5,6]. Various FACTS controllers such as Static Synchronous Compensator (STATCOM), Static Var Compensator (SVC), Thyristor Controlled Series Capacitor (TCSC), and Unified Power Flow Controller (UPFC) among others have been exploited to address the system instability challenges in a power system by several authors. However, the single line FACTS devices are limited in the control of power flow and voltage stability enhancement of the system. Recently, the application of multi-lines FACTS controllers has been gaining significant attention of both researchers and power system utilities across the globe. Prominent among these include Interline Power Flow Controller (IPFC), Unified Power Flow Controller (UPFC) and Generalized Unified Power Flow Controller (GUPFC). Hence, in this work, the GUPFC performance is further investigated on power system voltage stability considering and compared with a conventional voltage control device of LTCT. The effectiveness of all the methodologies presented is tested on the Nigerian 330KV grid system. The main contribution of this work lies on the performance evaluation of the capability of both GUPFC and LTCT in controlling the system loss and voltage magnitude.

The remaining sections of this paper are as follows. Section II briefly describes GUPFC. Section III presents the mathematical formulation of the GUPFC based on two voltage source representation and that of the LTCT. Simulation results are presented and discussed in section IV. The conclusion and future work on this study is presented in Section V.

2. PROBLEM FORMULATIONS

A. Brief Description of the GUPFC

A GUPFC constitutes three converters, which include two converters connected in series and a parallel-connected shunt converter on two transmission lines at a bus. With this arrangement, the device can control five system parameters viz: the voltage magnitude, phase angle, line impedance, active and reactive power with equal voltage level [3]. A basic configuration of GUPFC is as shown in Fig. 1.

The shunt converter is coupled with an associated bus i in parallel through a shunt transformer. Mainly, the shunt converter supplies active power to the series converters while simultaneously, keep the common bus voltage within an acceptable limit. Conversely, the series converters are linked each with a series transformer to regulate the power flow in the transmission lines between the common bus and two other buses. With this structure, the GUPFC can reliably regulate about five system quantities such as voltage magnitude of bus i and independent apparent power flows of the multiline thereby, minimizing power losses on transmission lines. The electrical circuit of the GUPFC includes two controllable series injected voltage sources and a shunt injected voltage source presented in Fig. 2.

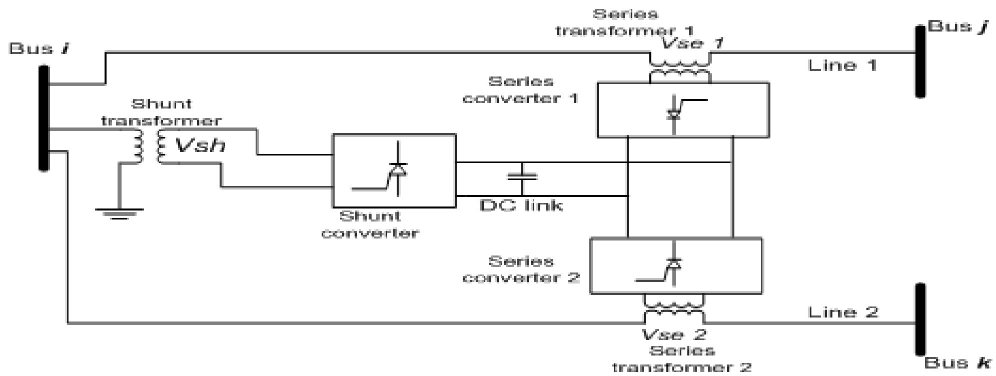

Fig. 1. Schematic layout of a GUPFC with three converters

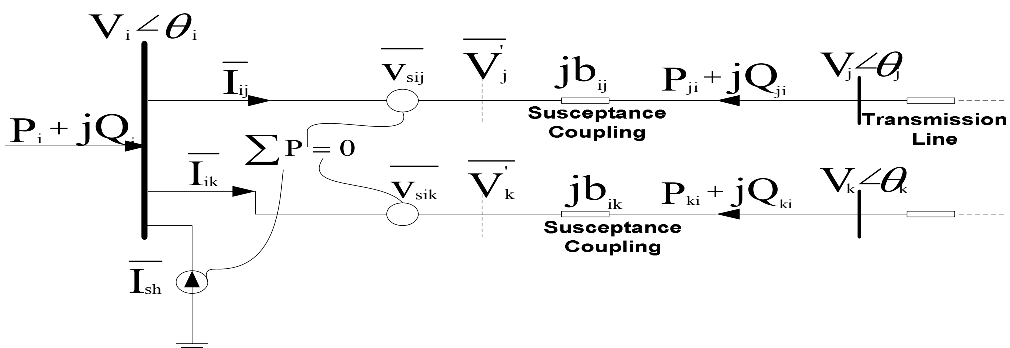

Fig. 2. The electrical circuit of GUPFC [6].

B. Power Flow Equation Using Newton Raphson Iterative Technique

Details mathematical formulation of the power flow solution using Newton Raphson iterative technique is presented in [7] and [8].

3. TWO VOLTAGE SOURCE MODEL OF GUPFC INJECTION POWER MODEL

A GUPFC can be described as a two series voltage sources indicating basic components of output voltage waveforms of the two series converters and a leaked impedance (reactance) of the coupling transformers. A two voltage-source model of the GUPFC device is presented in Fig. 3. The equivalent current source diagram for injected power at buses i, j $and\, k$ of the connected GUPFC, is also depicted in Fig. 4. The dual voltage sources V_{ser} depends on phase angles and magnitudes. The series voltages sources, V_{ser} is calculated as:

$$\mathrm{V_{ser}} \quad = \mathrm{rV_i e^{j\gamma}} \tag{1}$$

where r denotes voltage magnitude V_i in p.u at bus i and γ are defined within specified limits as defined as.

$$0 \le r \le r_{max}\ and\ 0 \le \gamma \le 2\pi$$

Where

$V_{Series}\ and\ \gamma$ represent phase angles (direction) and controllable voltage magnitude.

$$\mathrm{V_{Ser}} = \mathrm{rV_i e^{j\gamma}} = \mathrm{rV_i}(\cos \Upsilon + \sin \Upsilon) \tag{2}$$

where Υ represents the phase angle for which $0 \le \Upsilon \le \Upsilon_{max}\ (0 \le \Upsilon \le 2\pi)$

The equivalent current sources can be obtained by substituting the two series voltage sources by two current sources using Thevenin's theorem. At steady state condition, the GUPFC mathematical injection model is formulated by replacing voltage source V_{ser} with a current source I_{ser} in parallel to a susceptance $b_{ser} = {}^{1}/_{X_{ser}}$ Therefore, the series current I_{ser} is calculated as follow:

$$I_{ser} = -j\, b_{ser} V_{ser} \tag{3}$$

The current source I_{ser} corresponds to the injected powers $S_{i\,ser}$,$S_{j\,ser}$ and $S_{k\,ser}$

where:

$$S_{i\,ser} = 2V_i(-I_{ser})^* \tag{4}$$

$$S_{k\,ser} = V_j(I_{ser})^* \tag{5}$$

$$S_{j\,ser} = V_k(I_{ser})^* \tag{6}$$

The injection powers $S_{i\,ser}$,$S_{j\,ser}$ and $S_{k\,ser}$ can further be simplified as:

$$S_{i\,ser} = 2\,V_i[\,j\,b_{ser}\ r\,V_i e^{j\gamma}] * = -2\,b_{ser}\,r\,V_i^2 \sin\gamma - j\,2\,b_{ser}\,r\,V_i^2 \cos\gamma \tag{7}$$

$$P_{i\,ser} = -2\,b_{ser}\,r\,V_i^2 \sin\gamma \tag{8}$$

$$Q_{i\,ser} = -2\,b_{ser}\,r\ V_i^2 \cos\gamma \tag{9}$$

where $\theta_{ij} = \theta_i - \theta_j$ and $\theta_{ik} = \theta_i - \theta_k$,

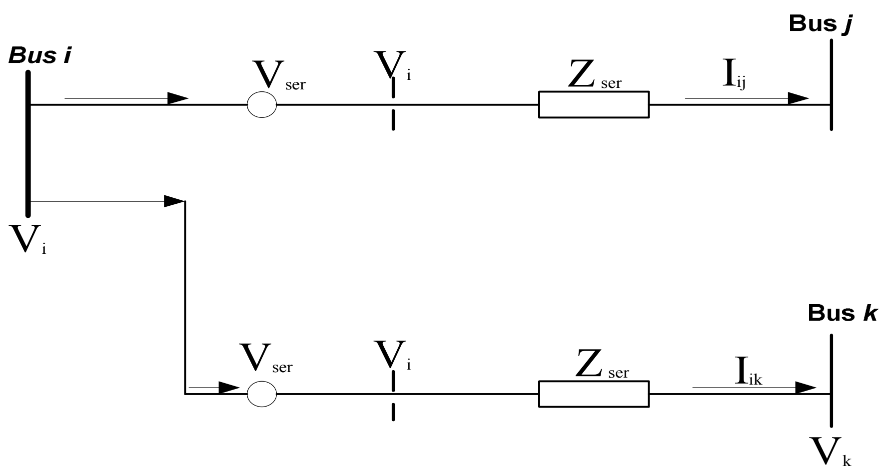

Fig. 3. Series connected voltage source representation of GUPFC [9]

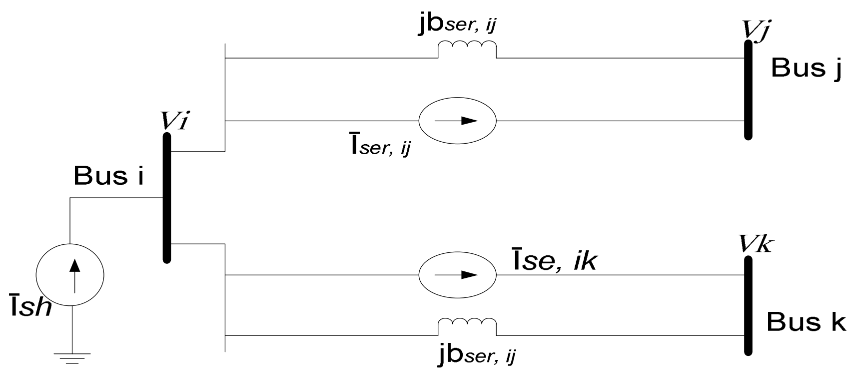

Fig. 4. Equivalent current sources [3]

Similarly, Eq.(6) becomes:

$$S_{j\,ser} = V_j[-\,j\,b_{ser}\,r\,V_i e^{j\gamma}] * = b_{ser} r\,V_i V_j \sin(\theta_{ij} + \gamma) + j\,b_{ser} r\,V_i V_j \cos(\theta_{ij} + \gamma) \tag{10}$$

Therefore,

$$P_{j\,ser} = b_{ser}\, r\, V_i\, V_j \sin(\theta_{ij} + \gamma) \tag{11}$$

$$Q_{j\,ser} = b_{ser}\, r\, V_i\, V_j \sin(\theta_{ij} + \gamma) \tag{12}$$

Also, Eq.(7) becomes:

$$S_{k\,ser} = V_k\,[-j\, b_{ser}\, r\, V_i\, e^{j\gamma}\,]* = b_{ser}\, r\, V_i\, V_k \sin(\theta_{ik} + \gamma) + j\, b_{ser}\, r\, V_i\, V_k \cos(\theta_{ik} + \gamma) \tag{13}$$

Therefore,

$$P_{k\,ser} = b_{ser}\, r\, V_i\, V_k \sin(\theta_{ik} + \gamma) \tag{14}$$

$$Q_{k\,ser} = b_{ser} r\, V_i\, V_k \cos(\theta_{ik} + \gamma) \tag{15}$$

A. Incorporation of GUPFC Injection Model in Power Flow Program

The Jacobian power flow matrix equation using Newton Raphson iterative technique is modified by the integration of suitable injection model powers as shown in Eq (16) [10].

$$[f(x)] = [J]\,[\Delta X] \tag{16}$$

where, $[f(x)]$ is the power mismatch $[\Delta X]$ is the solution vector and $[J]$ is the Jacobian matrix.

$$[f(x)] = [\Delta Pi\ \Delta Pj\ \Delta Pk\ \Delta Qi\ \Delta Qj\ \Delta Qk]^T \tag{17}$$

$$= [-Pref1 - Pref2 - Pi,cal\ Pref1 - Pj,cal\ Pref2 - Pk,cal - Qg(i) - Qi,cal\ Qref1 - Qj,cal\ Qref2 - Qk,cal\ ]^T \tag{18}$$

$$[\Delta X] = [\Delta\theta sh\ \Delta\theta ser1\ \Delta\theta ser2\ \Delta Vsh\ \Delta Vser1\ \Delta Vser2]^T \tag{19}$$

The group of nonlinear equations derived is solved using Newton-Raphson technique as follow:

1. At convergence of power flow program, phase angles and voltage magnitudes at both bus i, j and k i.e., $(Vi, \theta i, Vj, \theta j, Vk, \theta k)$ and injected imaginary power $Qg(i)$ from bus i at connected GUPFC are obtained.
2. Suitable initial values for the GUPFC control parameters, $V_{ser1}^0, \theta_{ser1}^0, V_{ser2}^0, \theta_{ser2}^0, V_{sh}^0$ and θ_{sh}^0 are assumed.
3. Solve the following linearized equations as follows:

$$[J] = \begin{bmatrix} \frac{\partial P_i}{\partial \theta_{sh}} & \frac{\partial P_i}{\partial \theta_{ser1}} & \frac{\partial P_i}{\partial \theta_{ser2}} & \frac{\partial P_i}{\partial V_{sh}} & \frac{\partial P_i}{\partial V_{ser1}} & \frac{\partial P_i}{\partial V_{ser2}} \\ \frac{\partial P_j}{\partial \theta_{sh}} & \frac{\partial P_j}{\partial \theta_{ser1}} & \frac{\partial P_j}{\partial \theta_{ser2}} & \frac{\partial P_j}{\partial V_{sh}} & \frac{\partial P_j}{\partial V_{ser1}} & \frac{\partial P_j}{\partial V_{ser2}} \\ \frac{\partial P_k}{\partial \theta_{sh}} & \frac{\partial P_k}{\partial \theta_{ser1}} & \frac{\partial P_k}{\partial \theta_{ser2}} & \frac{\partial P_k}{\partial V_{sh}} & \frac{\partial P_k}{\partial V_{ser1}} & \frac{\partial P_k}{\partial V_{ser2}} \\ \frac{\partial Q_i}{\partial \theta_{sh}} & \frac{\partial Q_i}{\partial \theta_{ser1}} & \frac{\partial Q_i}{\partial \theta_{ser2}} & \frac{\partial Q_i}{\partial V_{sh}} & \frac{\partial Q_i}{\partial V_{ser1}} & \frac{\partial Q_i}{\partial V_{ser2}} \\ \frac{\partial Q_j}{\partial \theta_{sh}} & \frac{\partial Q_j}{\partial \theta_{ser1}} & \frac{\partial Q_j}{\partial \theta_{ser2}} & \frac{\partial Q_j}{\partial V_{sh}} & \frac{\partial Q_j}{\partial V_{ser1}} & \frac{\partial Q_j}{\partial V_{ser2}} \\ \frac{\partial Q_k}{\partial \theta_{sh}} & \frac{\partial Q_k}{\partial \theta_{ser1}} & \frac{\partial Q_k}{\partial \theta_{ser2}} & \frac{\partial Q_k}{\partial V_{sh}} & \frac{\partial Q_k}{\partial V_{ser1}} & \frac{\partial Q_k}{\partial V_{ser2}} \end{bmatrix} \begin{bmatrix} \Delta\theta_{sh} \\ \Delta\theta_{ser1} \\ \Delta\theta_{ser2} \\ \Delta V_{sh} \\ \Delta V_{ser1} \\ \Delta V_{ser2} \end{bmatrix} \tag{20}$$

4. After evaluating the Jacobian matrix in Eq(20), the control parameters of GUPFC is then updated using Eq.(21).

$$X_1 = X^0 + \Delta X \tag{21}$$

where X represents control parameters of GUPFC (i.e. V_{ser2}, θ_{ser1} , θ_{ser2} , V_{ser1}).

B. Mathematical Formulation of the LTCT

Voltage magnitude of a power system can be regulated using tap changing transformers. Assuming a tap changing transformer as in Fig. 5, where yt represents its short circuit admittance, and a is the regulation between the primary and secondary voltages. Thus,

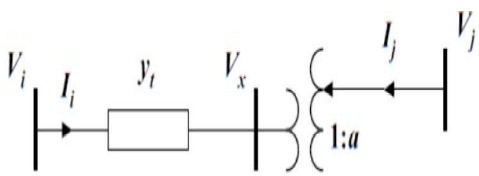

Fig. 5. LTCT schematic diagram

$$\begin{bmatrix} I_i \\ I_j \end{bmatrix} = \begin{bmatrix} y_t & -\frac{y_i}{t} \\ -\frac{y_t}{a^*} & \frac{y_t}{|a^2|} \end{bmatrix} \tag{22}$$

Details mathematical formulations and definition of parameters may be found in [11].

The model analysis by [12] is adapted to the Nigerian grid system considered in this work while incorporating LTCT into the system. Also, 10% tolerance of the LTCT nominal value was used.

4. RESULTS AND DISCUSSION

A. Line Losses and Power Flow Solution without incorporation of GUPFC

Simulation results of real and reactive power flows showing (indicating) line losses on each buses in the absence of GUPFC is presented in Table 1. The total real and reactive power losses across all lines without the incorporation of a FACTS device are $93.3MW$ and is $-762MVar$ respectively. In this scenario, convergence was reached after seventh iterations. In addition, the result of calculated power, voltage angle and voltage magnitude of power flow solution on each buses in the absence of GUPFC is shown in Table 2. The sum of active and reactive power are $93.3MW$ and $-2.22e+3\ MVar$ respectively. The voltage magnitudes on transmission lines $9, 13, 14\ and\ 16$ are $0.987p.u, 0.975\ p.u, 0.992\ p.u\ and\ 0.991\ p.u$ resp ectively. From these results, it is observed that the voltage magnitude is significantly low and thus, it becomes imperative to integrate GUPFC on the identified weak buses at the sending end while simultaneously, observing the voltage magnitude at the receiving end.

B. Line Losses and Power Flow Solution with Integration of GUPFC

Table 4 presents the power flow simulation results when GUPFC was incorporated to the identified weak busses for $330kV$ Nigerian $28-$bus system. The total active and reactive power losses with the integration of GUPFC are $90.1MW$ and $-791MVar$ rspectively. The optimal power flow solution converged after fourth iterations while maximum power mismatch was found to be 0.001. This was made possible through the redistribution of active power by the GUPFC across connected weak buses with low voltage magnitude. In addition, power flow on the connected GUPFC transmission lines has significantly improved. As a result of the incorporation of GUPFC, the active power flow on lines $9, 13\ and\ 16$ increased from $-340MW\ to\ -300MW, -88.9\ to\ -96.3, -131MW\ to\ -96.3MW$ respectively. In addition, the reactive power losses at busses $9, 13\ and\ 16$ reduced from $5.51MVar\ to\ 4.11MVar$, $0.393MVar\ to\ 0.343MVar$ and $0.114MVar\ to\ 2.24MVar$ respectively. The GUPFC regulates the voltage magnitude while concorently taking into consideration voltage magnitude boundaries, $V_{min} \leq V \leq V_{max}\ (i.e\ 1.0 \leq V \leq 1.1)$, as indicated in Table 5. In the power flow solution, 1.0 pu is considered as the reference per unit voltage V. It is deduced from Table 5, that a group of voltage magnitudes on buses 13, 14 and 16 have increased. Concisely, it is observed that the voltage magnitudes on lines $9, 13\ and\ 14$ increased from $0.987\ p.u\ to\ 1.00\ p.u$, $0.975\ p.u\ to\ 1.00\ p.u$, $0.992\ p.u\ to\ 0.991\ p.u$ respectively.

Table 1. Transmission line losses and flow without integration of GUPFC

Lines		PQ_{Send}			$PQ_{Received}$		Line Loss	
From	To	MW	Mvar	MVA	MW	Mvar	MW	Mvar
3	1	-137	-101	-238	137	99.2	0.158	-2.08
3	1	-137	-101	-238	137	99.2	0.158	-2.08
4	5	-172	-127	-300	173	126	0.307	-1.28
4	5	-172	-127	-300	173	126	0.307	-1.28
1	5	-164	166	1.98	166	-170	1.19	-3.58
1	5	-164	166	1.98	166	-170	1.19	-3.58
5	8	-152	-18.9	-171	154	-21.5	2.43	-40.4
5	8	-152	-18.9	-171	154	-21.5	2.43	-40.4
5	9	-63.8	92.6	28.8	64.6	-114	0.793	-21.1
5	10	-197	9.48	-187	201	-33.3	3.77	-23.8
6	8	-6.9	16.4	9.5	7	-57.9	0.102	-41.5
6	8	-6.9	16.4	9.5	7	-57.9	0.102	-41.5
2	8	334	-9.9	324	-329	19	4.35	-9.08
2	7	336	7.04	343	-335	-4.37	1.23	-2.66
7	24	238	-58	180	-237	54.6	1.36	-3.46
8	14	80.1	100	180	-79.1	-121	0.977	-20.5
8	10	-31.2	-5.5	-36.7	31.3	-46.3	0.129	-51.8
8	24	-213	-39	-252	214	34.6	0.857	-4.39
8	24	-213	-39	-252	214	34.6	0.857	-4.39
9	10	-340	-69.2	-410	346	87.9	5.51	18.7
15	21	-57.2	-8.45	-65.7	57.7	-56.4	0.426	-64.9
15	21	-57.2	-8.45	-65.7	57.7	-56.4	0.426	-64.9
10	17	-260	-15.4	-275	264	11.7	3.89	-3.75
10	17	-260	-15.4	-275	264	11.7	3.89	-3.75
10	17	-260	-15.4	-275	264	11.7	3.89	-3.75
11	12	216	147	363	-215	-148	0.625	-0.722
11	12	216	147	363	-215	-148	0.625	-0.722
12	14	289	66	355	-284	-58.9	5.04	7.06
13	14	-96.3	-58.1	-147	89.3	43.6	0.393	-14.5
13	14	-96.3	-58.1	-147	89.3	43.6	0.393	-14.5
16	19	-131	-69	-200	133	-24.5	2.24	-44.4
17	18	-247	41.6	-206	248	-42.1	0.114	0.061
17	18	-247	41.6	-206	248	-42.1	0.114	0.061
17	23	99.3	-35.9	63.4	-98.5	-36.9	0.866	-46.4
17	23	99.3	-35.9	63.4	-98.5	-36.9	0.866	-46.4
17	21	-253	33.7	-219	255	-45.8	1.91	-3.29
17	21	-253	33.7	-219	255	-45.8	1.91	-3.29
19	20	125	-18.6	106	-123	-38.7	1.14	-35.5
20	22	111	9.59	121	-110	-48.4	1.13	-38.8
20	22	111	9.59	121	-110	-48.4	1.13	-38.8
20	23	-146	-28	-174	147	13.2	0.764	-14.9
20	23	-146	-28	-174	147	13.2	0.764	-14.9
23	26	146	48.5	194	-145	-62.5	0.853	-14
23	26	146	48.5	194	-145	-62.5	0.853	-14
12	25	-143	-13.9	-157	145	-17.2	1.36	-31.1
12	25	-143	-13.9	-157	145	-17.2	1.36	-31.1
19	25	-164	14.8	-149	165	-37.2	1.49	-22.3
19	25	-164	14.8	-149	165	-37.2	1.49	-22.3
25	27	-365	64.4	-301	375	-22.4	10.1	41.8
25	27	-365	64.4	-301	375	-22.4	10.1	41.8
5	28	-373	-164	-536	375	172	2.5	8.39
5	28	-373	-164	-536	375	172	2.5	8.39
	Total						93.3	-762

Table 2. Calculated Power, voltage angle and voltage magnitude of power flow solution without integration of GUPFC

Bus Number	Voltage Magnitude (p.u)	Phase Angle (°)	Calculated Power (MW)	(MVAR)
1	1.05	0	-54.103	514.981
2	1.05	14.1	670.000	-17.689
3	1.05	-0.284	-274.400	-205.800
4	1.02	1.33	-344.700	-258.000
5	1.03	1.75	-633.200	-474.900
6	1.06	8.23	-13.800	-10.300
7	1.05	12.6	-96.500	-72.400
8	1.04	8.59	-383.300	-287.500
9	0.987	3.54	-275.800	-206.800
10	1.03	9.94	-201.200	-150.900
11	1.05	15	431.000	289.155
12	1.04	14.2	-427.000	-320.200
13	0.975	5.81	-177.900	-133.400
14	0.992	7.13	-184.600	-138.400
15	1.06	16.7	-114.500	-85.900
16	0.991	8.22	-130.600	-97.900
17	1.05	16.3	-11.000	-8.200
18	1.05	16.6	495.000	-84.223
19	1.05	14.4	-70.300	-52.700
20	1.04	10.4	-193.000	-144.700
21	1.05	19.5	624.700	-271.546
22	1.01	6.41	-220.600	-142.900
23	1.05	12.5	388.900	7.986
24	1.05	10.2	190.300	106.121
25	1.05	18.3	-110.000	-89.000
26	1.03	10.5	-290.100	-145.000
27	1.05	29.9	750.000	-78.590
28	1.05	3.96	750.000	334.322
Total Loss			93.300	-2.22e+3

C. Graphical Epresentation of the Voltage Magnitude and Active Power Loss with and without Incorporation of GUPFC

The effectivenes of GUPFC on active power loss along the transmission lines $11-12, 17$ and $32-33$ is demonstrated graphically in Fig. 5. Colour red and blue indicate active power losses output during power flow solution with and without inclusion of GUPFC respectively.

D. Graphical Representation of the Voltage Magnitude and Active Power Loss with and without GUPFC Implementation

Fig. 6 presents the active power loss outcome of the implementation of GUPFC illustrated in a graphical representation along the transmission lines $11-12, 17$ and $32-33$. The active (real) power losses obtained during the power flow solutions (simulations) with and without integration of GUPFC are indicated with red and blue colors respectively. Result of the comparison of the voltage magnitude obtained without and with GUPFC is as illustrated in Figs. 7 and 8.

E. Result of Voltage Profile with incorporation of LTCT

In this work, critical lines of the Nigerian 330KV grid systems were selected (5-9, 13-14, 16-19 and 20-22) as reported in Adebayo et al., 2012. The set of binding limits for the transformer tap ratio (LTCT) were taken as 0.9<1.0<1.1 which is 10% of the nominal value. Where high voltage drops were observed at the load buses, LTCT was used to regulate the voltage magnitude at such buses. Examples are the buses 9, 13, 16 and 22 as presented in Table 6. Installation of LCTC in the critical lines with respect to their load buses increased the voltage magnitude of the buses significantly when compared with the base case value of each of the selected load buses as shown in Table 6.

Table 3 .Transmission line losses and flows with the integration of GUPFC

Lines		PQ_{Send}			PQ_{Rec}		Line Loss	
From	To	MW	MVAR	MVA	MW	MVAR	MW	MVAR
3	1	-137	-101	-238	137	99.2	0.158	-2.08
3	1	-137	-101	-238	137	99.2	0.158	-2.08
4	5	-172	-127	-300	173	126	0.307	-1.29
4	5	-172	-127	-300	173	126	0.307	-1.29
1	5	-166	159	-6.59	167	-163	1.15	-3.88
1	5	-166	159	-6.59	167	-163	1.15	-3.88
5	8	-149	-20.8	-169	151	-20.6	2.31	-41.4
5	8	-149	-20.8	-169	151	-20.6	2.31	-41.4
5	9	-83.7	65.5	-18.2	84.4	-87.8	0.684	-22.3
5	10	-187	6.93	-180	-190	-33.8	3.38	-26.9
6	8	-6.9	16.5	9.58	7	-58.2	0.102	-41.7
6	8	-6.9	16.5	9.58	7	-58.2	0.102	-41.7
2	8	334	-16.5	318	-330	25.6	4.35	9.09
2	7	336	7.05	343	-335	-4.4	1.23	2.65
7	24	238	-58	180	-237	54.5	1.36	-3.48
8	14	80.6	64.4	145	-80	-88	0.633	-23.6
8	10	-24.7	-5.08	-29.7	24.8	-47.1	0.0974	-52.2
8	24	-213	-24.9	-238	214	20.4	0.84	-4.54
8	24	-213	-24.9	-238	214	20.4	0.84	-4.54
9	10	-300	-44.5	-345	305	52.4	4.11	7.82
15	21	-57.3	-8.45	-65.7	57.7	-56.4	0.426	-64.9
15	21	-57.3	-8.45	-65.7	57.7	-56.4	0.426	-64.9
10	17	-260	-13.4	-273	264	9.63	3.89	-3.73
10	17	-260	-13.4	-273	264	9.63	3.89	-3.73
10	17	-260	-13.4	-273	264	9.63	3.89	-3.73
11	12	216	131	347	-215	-132	0.583	-1.04
11	12	216	131	347	-215	-132	0.583	-1.04
12	14	288	32.4	320	-283	-28.1	4.74	4.28
13	14	-88.9	-25.3	-122	96.6	9.65	0.343	-15.6
14	14	-96.3	-25.3	-122	96.6	9.65	0.343	-15.6
16	19	-131	-68.9	-200	133	24.4	2.24	-44.5
17	18	-247	44.4	-203	248	-44.3	0.115	0.0651
17	18	-247	44.4	-203	248	-44.3	0.115	0.0651
17	23	98.6	-35.8	62.9	-97.8	-10.7	0.854	-46.4
17	23	98.6	-35.8	62.9	-97.8	-10.7	0.854	-46.4
17	21	-253	34	-219	255	-37.3	1.91	-3.29
17	21	-253	34	-219	255	-37.3	1.91	-3.29
20	20	126	-18.1	108	-125	-17.2	1.17	-35.3
20	22	111	9.58	121	-110	-48.4	1.13	-38.9
20	22	111	9.58	121	-110	-48.4	1.13	-38.9
20	23	-146	-27.9	-173	146	12.9	0.757	-14.9
20	23	-146	-27.9	-173	146	12.9	0.757	-14.9
23	26	146	48.5	194	-145	-62.5	0.853	-14
23	26	146	48.5	194	-145	-62.5	0.853	-14
12	25	-143	-12.9	-155	144	-18.4	1.34	-31.3
12	25	-143	-12.9	-155	144	-18.4	1.34	-31.3
19	25	-165	14.6	-150	166	-36.9	1.51	-22.3
19	25	-165	14.6	-150	166	-36.9	1.51	-22.3
25	27	-365	65.2	-300	375	-23.4	10.1	41.8
25	27	-365	65.2	-300	375	-23.4	10.1	41.8
5	28	-373	-154	-526	375	162	2.44	7.98
5	28	-373	-154	-526	375	162	2.44	7.98
	Total Loss						90.10	−791

Table 4. Phase angle and voltage magnitude of power flow solution with GUPFC

Bus Number	Voltage Magnitude (p.u)	Phase Angle (°)
1	1.05	0
2	1.05	14
3	1.05	-0.284
4	1.02	1.33
5	1.03	1.76
6	1.06	8.05
7	1.05	12.4
8	1.04	8.41
9	1	3.89
10	1.03	9.5
11	1.05	14.7
12	1.04	13.9
13	1	5.41
14	1.01	6.86
15	1.06	16.2
16	0.991	7.88
17	1.05	15.9
18	1.05	16.1
19	1.05	14
20	1.04	9.99
21	1.05	19.1
22	1.01	6.02
23	1.05	12.1
24	1.05	10
25	1.05	17.9
26	1.03	10.1
27	1.05	29.6
28	1.05	3.97

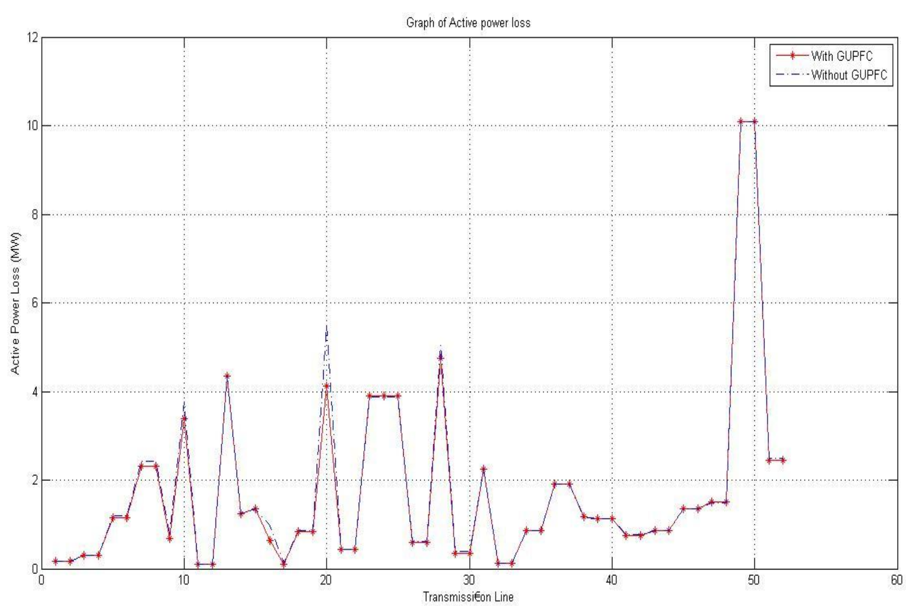

Fig. 6. Comparison of active power loss with and without GUPFC

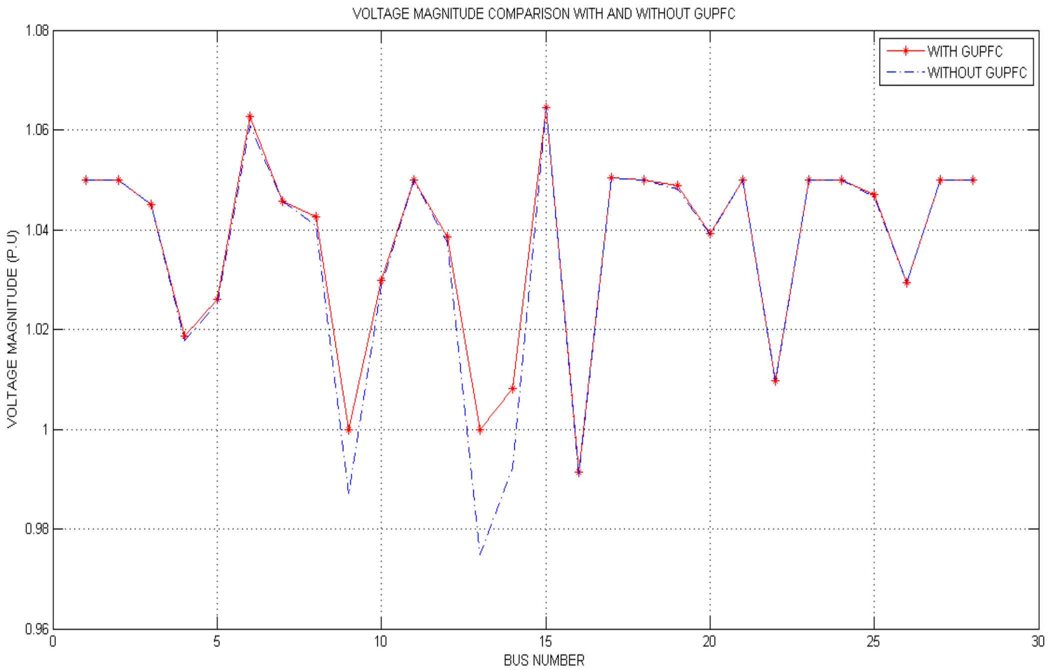

Fig. 7. Comparison of Voltage Magnitude with and without GUPFC

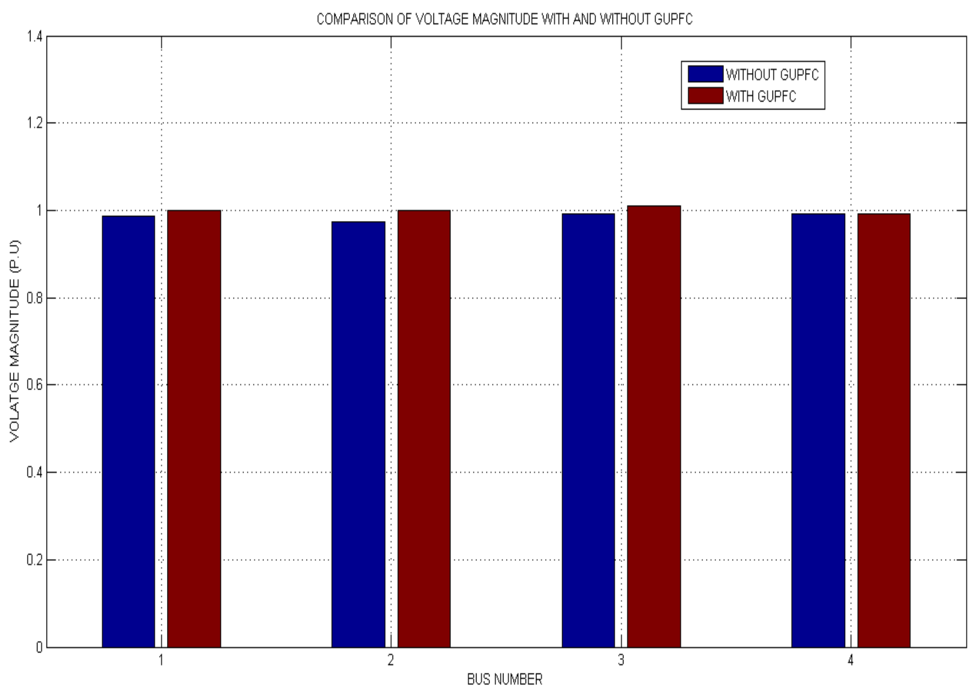

Fig. 8. Bar chart representation of only weak (defected) buses showing voltage magnitude variation with and without GUPFC

Table 5. Voltage magnitude with LTCT

Line From To	Tapping	Bus No	Base Case Voltage Mag. (p.u)	Voltage Mag. (p.u)
5-9	0.978	9	0.987	0.993
13-14	1.02	13	0.985	0.991
16-19	1.09	16	0.9678	0.986
20-22	0.90	22	0.9345	0.990

Table 6. Results of the summary of comparison between LTCT and GUPFC

Bus No	Base Case voltage mag (p.u)	With LTCT Voltage Mag. (p.u)	With GUPFC Voltage Mag (p.u)
9	0.987	0.993	1.00
14	0.985	0.991	1.00
16	0.9678	0.986	0.991
22	0.9345	0.990	1.01

Table 7 shows the result of the comparison of voltage magnitude obtained when GUPFC and LTCT devices were installed separately at the target lines/buses. It could be observed that the use of GUPFC has significance impact in the control of voltage magnitude compared to LTCT. For instance, the voltage magnitude of bus 9 increased from its base case value of 0.987pu to 0.993pu when LTCT was installed. Whereas, with the insertion of GUPFC, the voltage magnitude was regulated to 1.00pu.

4. CONCLUSION

In the current study, power flow analysis was performed in MATLAB 2014a environment. The effectiveness of all the methodologies presented was tested on a practical Nigerian 28-bus power system. Buses with low voltages were identified and GUPFC was applied at the identified weak buses. In the same vein, LTCTs were installed at the critical lines with respect to their load buses to control the voltage magnitude of the target load buses. The GUPFC was also used to minize the system losses. The efficacy of GUPFC and LTCT devices in controlling the voltage magnitude proved to give satisfactory results by increasing the voltage magnitude at the identified load buses sufficiently to meet the binding limit. The reinforcement of the network by incorporating GUPFC and LTCT can greatly enhance voltage stability of the power system. This work could go a long way in assisting electrical power utilities during planning and operation of the power system.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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