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Original Research Article

Power Loss Minimization in Transmission System using Particle Swarm Optimization-Based Unified Power Flow Controller

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ABSTRACT

Flexible Alternating Current Transmission System (FACTS) devices have been identified as viable alternatives in power systems to address the shortcomings of the conventional solutions for mitigating poor bus voltages, high line losses, persistent outages among others. This work examines the effect of Unified Power Flow Controller (UPFC) which is one of the versatile members of the FACTS family used for the minimization of power losses in a transmission system network via Particle Swarm Optimization (PSO) technique. The load flow analysis was performed using Gauss-Seidel method with the integration of PSO-based UPFC. Simulations were done in Python environment (version 3.7) using the Nigerian 330 kV, 34-bus power network as a test case. Simulation results revealed that line 5-10 was the optimal point for the placement of UPFC on the Nigerian 34-bus power network, and the voltage profile fell within the statutory limit with and without UPFC placed at the optimal point. The total active power loss reduced by 83.04 % with optimally placed UPFC, from 3943.10 to 668.60 MW, and the total reactive power loss reduced by 3.00 % with optimally placed UPFC, from 30012.40 to 29111.60 MVAr. The obtained results indicated that UPFC has the capacity to appreciably reduce system losses.

1. INTRODUCTION

Power system is an interconnection network of generating plants, transmission lines, distribution lines, loads and other essential components. Over the years, electrical energy demand has increased exponentially causing a wide gap between power supply and demand leading to shortage of reactive power in the system, resulting in poor power quality delivery to consumer's load, voltage instability among others (Lokanadham, 2010; Oyedoja, 2014; Ayodele *et al.*, 2016; Noor *et al.*, 2018). One way of enhancing the performance of the power system is by construction of new transmission lines and building more generating plants, but will require large intensive capital investment, which is not always available. Another is by adequate reactive power compensation which seems to be the reasonable solution to power problem due to insufficient capital. The traditional method of compensation is by using reactors and capacitor banks to absorb or inject reactive power in the system network (Pabla, 2004; Tarik and Sercan, 2006; Saravana, 2015). But this method seems to be ineffective as it requires an operator to switch in these devices. Another challenge associated with these mechanical devices is wear and tear. One novel method proposed that has been in literature is the use of Flexible Alternating Current Transmission System (FACTS) (Jumaat *et al.*, 2011; Saravana, 2015; Agrawal *et al.*, 2016).

FACTS are power electronics-based devices, that are technologically advanced, fast acting devices, with the ability to control grid parameters such as line impedance, nodal voltage, phase angle and can significantly increase the available transmission capacity (Saravana, 2015; Zayandehroodi et al., 2015; Ayodele *et al.,*2016). Many research efforts have been conducted on using some of these FACTS devices to boost the voltage profile and minimize power losses with appreciable results obtained (Mathad and Kulkarni 2020; Amin *et al.,* 2021). Hence, its use for power system performance enhancement should be accorded the deserved attention.

The goal of this work is to minimize power loss in transmission system using particle swarm optimization-based unified power flow controller (UPFC) with the Nigeria 34-bus power system network considered as a test case. The UPFC is the latest among the FACTS devices and offers major advantages such as versatility, real time control of transmission systems among others, and can be used in the power delivery industry to solve various challenges (Negi *et al.*, 2017).

2. METHODOLOGY

2.1. Formulation of Load Flow Equations

A medium transmission line is usually represented by a nominal π equivalent network as shown in Figure 1, as it provides a more accurate representation of network impedance, voltage drops, computational efficiency etc. in load flow equations (Gupta, 2011; Theraja and Theraja, 2000).

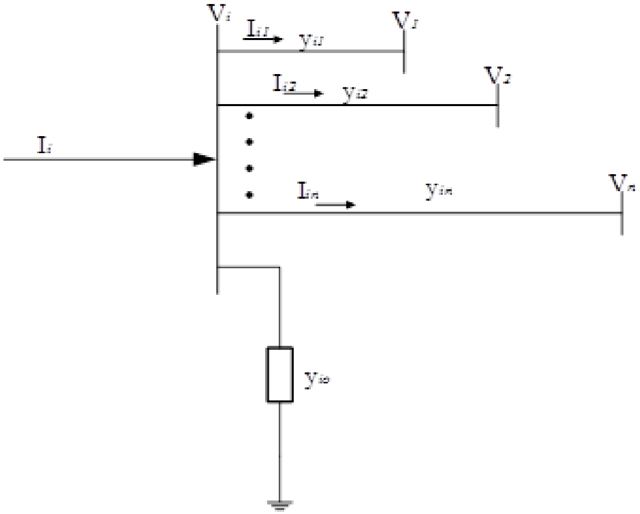

Figure 1: A transmission line model

Applying Kirchhoff's current law to bus i in Figure 1 gives Equation (1), and the injected complex power given by Equation (2), and further modified into Equation (3), and with the application of Gauss-Seidel method produced Equation (4) (Gupta, 2011):

$$I_i = Y_{ii}V_i + \sum_{\substack{k=1 \\ k\neq i}}^{N} Y_{ik}V_k \tag{1}$$

$$S_i = P_i + jQ_i = V_i I_i^* \tag{2}$$

$$\frac{P_i - jQ_i}{V_i^*} = Y_{ii}V_i + \sum_{\substack{k=1 \\ k\neq i}}^{N} Y_{ik}V_k \tag{3}$$

$$V_i^{r+1} = \frac{1}{Y_{ii}}\left[\frac{P_i - jQ_i}{\left(V_i^r\right)^*} - \sum_{\substack{k=1 \\ k\neq i}}^{N} Y_{ik}V_k^r\right];\ i = 2,\ 3,\ldots,N \tag{4}$$

where I_i is injected current into bus i, Y_{ii} is self-admittance, V_i is voltage of bus i, Y_{ik} is mutual admittance, V_k is voltage of bus k, S_i is apparent power, Q_i is reactive power, P_i is real power, I_i^* and V_i^* are complex conjugate of bus i current and voltage, i and r are the number of buses and iterations respectively

By separating Equation (4) into real and imaginary parts yields Equations (5) and (6) respectively, and the voltage-drop on the line, say bus i and bus k can be calculated using Equation (7):

$$P_i = \left|V_i\right|^2 G_{ii} + \sum_{\substack{k=1 \\ k\neq i}}^{N} \left|Y_{ik}V_iV_k\right| cos\left(\theta_{ik} + \delta_k - \delta_i\right) \tag{5}$$

$$Q_i = \left|V_i\right|^2 B_{ii} + \sum_{\substack{k=1 \\ k\neq i}}^{N} \left|Y_{ik}V_iV_k\right| sin\left(\theta_{ik} + \delta_k - \delta_i\right) \tag{6}$$

$$\Delta V_{ik} = \left| V_i - V_K \right| \tag{7}$$

where G_{ii} is self-conductance, δ_i is phase angle, B_{ii} is self-susceptance, θ_{ik} is phase difference, and ΔV_{ik} is voltage drop between bus i and k.

The active and reactive line losses were obtained from the mathematical manipulation of Equations (2) and (7) as Equations (8) and (9) respectively:

$$P_{Lik} = G_{ik}\left(V_i^2 + V_k^2 - 2V_iV_k\cos\theta_m\right) \tag{8}$$

$$Q_{Lik} = -V_i^2 B_{ik} - V_k^2 B_{ik} - 2B_{ik}V_iV_k\cos\theta_m \tag{9}$$

2.2. UPFC Load Flow Model

The load flow model of UPFC is expressed by Equations (10) to (22), and the equivalent circuit shown in Figure 2 (Namrata, 2014).

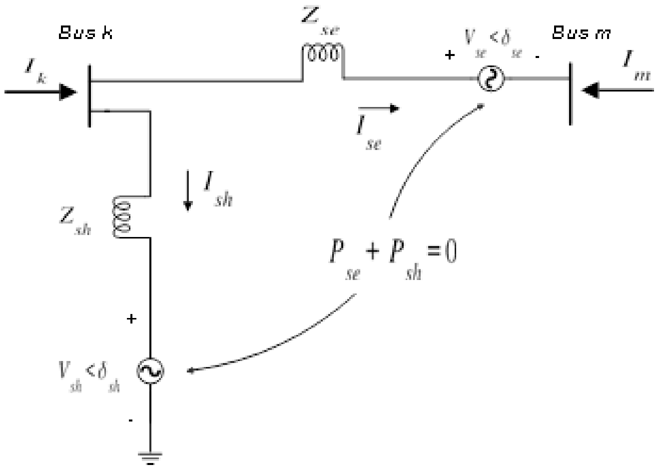

Figure 2: UPFC model

The shunt (E_{sh}) and series (E_{se}) voltage sources are given by Equations (10) and (11) respectively:

$$E_{sh} = V_{sh}\left(\cos\delta_{sh} + j\sin\delta_{sh}\right) \tag{10}$$

$$E_{se} = V_{se}\left(\cos\delta_{se} + j\sin\delta_{se}\right) \tag{11}$$

where V_{sh} , V_{se} is controllable voltage magnitude, and δ_{sh} , δ_{se} is controllable phase angle.

The real and reactive power equations at bus k, and at bus m, are expressed as Equations (12) and (13), and Equations (14) and (15) respectively:

$$P_k = V_k^2 G_{kk} + V_k V_m\left[G_{km}\cos\left(\theta_k - \theta_m\right) + B_{km}\sin\left(\theta_k - \theta_m\right)\right] + V_k V_{se}\left[G_{km}\cos\left(\theta_k - \delta_{se}\right) + B_{km}\sin\left(\theta_k - \delta_{se}\right)\right] + V_k V_{sh}\left[G_{sh}\cos\left(\theta_k - \delta_{sh}\right) + B_{sh}\sin\left(\theta_k - \delta_{sh}\right)\right] \tag{12}$$

$$Q_k = -V_k^2 B_{kk} + V_k V_m\left[G_{km}\sin\left(\theta_k - \theta_m\right) - B_{km}\cos\left(\theta_k - \theta_m\right)\right] + V_k V_{se}\left[G_{km}\sin\left(\theta_k - \delta_{se}\right) - B_{km}\cos\left(\theta_k - \delta_{se}\right)\right] + V_k V_{sh}\left[G_{sh}\sin\left(\theta_k - \delta_{sh}\right) - B_{sh}\cos\left(\theta_k - \delta_{sh}\right)\right] \tag{13}$$

$$P_m = V_m^2 G_{mm} + V_m V_k\left[G_{mk}\cos\left(\theta_m - \theta_k\right) + B_{mk}\sin\left(\theta_m - \theta_k\right)\right] + V_m V_{se}\left[G_{mm}\cos\left(\theta_m - \delta_{se}\right) + B_{mm}\sin\left(\theta_m - \delta_{se}\right)\right] \tag{14}$$

$$Q_m = -V_m^2 B_{mm} + V_m V_k\left[G_{mk}\sin\left(\theta_m - \theta_k\right) - B_{mk}\cos\left(\theta_m - \theta_k\right)\right] + V_m V_{se}\left[G_{mm}\sin\left(\theta_m - \delta_{se}\right) + B_{mm}\cos\left(\theta_m - \delta_{se}\right)\right] \tag{15}$$

The real and reactive power equations for series and shunt converters are expressed as Equations (16) and (17), and Equations (18) and (19) respectively:

$$P_{se} = V_{se}^2 G_{mm} + V_{se} V_k\left[G_{km}\cos\left(\delta_{se} - \theta_k\right) + B_{km}\sin\left(\delta_{se} - \theta_k\right)\right] + V_{se} V_m\left[G_{mm}\cos\left(\delta_{se} - \delta_m\right) + B_{mm}\sin\left(\delta_{se} - \theta_m\right)\right] \tag{16}$$

$$Q_{se} = -V_{se}^2 B_{mm} + V_{se} V_k\left[G_{km}\sin\left(\delta_{se} - \theta_k\right) - B_{km}\cos\left(\delta_{se} - \theta_k\right)\right] + V_{se} V_m\left[G_{mm}\sin\left(\delta_{se} - \theta_m\right) - B_{mm}\cos\left(\delta_{se} - \theta_m\right)\right] \tag{17}$$

$$P_{sh} = -V_{sh}^2 G_{sh} + V_{sh} V_k\left[G_{sh}\cos\left(\delta_{sh} - \theta_k\right) + B_{sh}\sin\left(\delta_{sh} - \theta_k\right)\right] \tag{18}$$

$$Q_{sh} = V_{sh}^2 B_{sh} + V_{sh} V_k\left[G_{sh}\sin\left(\delta_{sh} - \theta_k\right) - B_{sh}\cos\left(\delta_{sh} - \theta_k\right)\right] \tag{19}$$

2.3. Particle Swarm Optimization

PSO uses a swarm of particles to locally search a given space and moves in X-Y plane. During the search process, each particle communicates with each other to find solution to the problem, and the best location found by each particle is known as particle best location (P_{best}), while the best position found by the team (swarm) so far is known as team best location (T_{best}) or global best (G_{best}). Its major advantages are fast convergence, ease of implementation, more robust among others (Jumaat *et al.*, 2011; Marefatjou and Soltani, 2013).

The PSO algorithm used for the placement of UPFC in this work is given as follows:

i. Input the bus data, generator data, line data and shunt data
ii. Size the UPFC device
iii. Read the bus data, generator data, line data and shunt data. Run the load flow analysis using Gauss-Seidel method and find the power losses and bus voltages
iv. Calculate the total line losses before the placement of UPFC device
v. Input the PSO parameter such as c_1 and c_2, r_1 and r_2, w among others. Maximum iteration is set as t = 100
vi. Generate randomly the initial search points (positions) and velocities of the particles with population size representing a solution to the objective function
vii. For each particle, evaluate their fitness function
viii. Find the optimal location for the UPFC device, where the least active power loss is recorded
ix. Each particle's position is assigned P_{best}. Find the G_{best} (i.e., where the least active power loss is observed)
x. Calculate the new-found position and velocity using Equations (20), (21), and (22) respectively:
xi.

$$F_i^{k+1} = w \times F_i^k + c_1 \times r_1 \times \left(P_{best\,i} - x_i^k\right) + c_2 \times r_2 \times \left(G_{best\,i} - x_i^k\right) \tag{20}$$

$$w = w_{max} - \left(\left(w_{max} - w_{min}\right) \times k\right) / k_{max} \tag{21}$$

$$x_i^{k+1} = x_i^k + LF_i^{k+1} \tag{22}$$

xii. Continue to evaluate $Iteration = Iteration + 1$
xiii. Check if $Iteration = Iteration_{max}$ (i.e., if the number of iterations reach the maximum limit) proceed to the next step, if not, go back to step xi
xiv. Set best of P_{best} as G_{best}
xv. If G_{best} is the optimal solution proceed to step xv, otherwise, go back to step vi
xvi. Calculate the total line losses and bus voltages after the placement of UPFC device
xvii. End

From Equations (20), (21), and (22), $F_i^{k+1}$and x_i^{k+1} are the velocity and position of particle i at iteration k+1, F_i^k and x_i^k are the velocity and position of particle i at iteration k, $i = 1, 2, \ldots, N$ and N is swarm size, w is inertial weight, r_1 and r_2 are variables between 0 and 1, c_1 and c_2 are acceleration constant, L is constriction factor, w_{max} and w_{min} are maximum and minimum inertia weight, k and k_{max} are current and maximum number.

2.4. Implementation Software and Test Network

In this work, the load flow code was developed in Python environment (version 3.7), and the Nigerian 34-Bus, 330 kV power system network was used as the test network. The single line diagram of the Nigerian 34-Bus, 330 kV power system network is shown in Figure 3. The network data, generator data and transmission line data were taken from National Control Centre, Oshogbo. The relevant parameter is as attached in the appendix. The data is on 330 kV, 50 Hz and 100 MVA base.

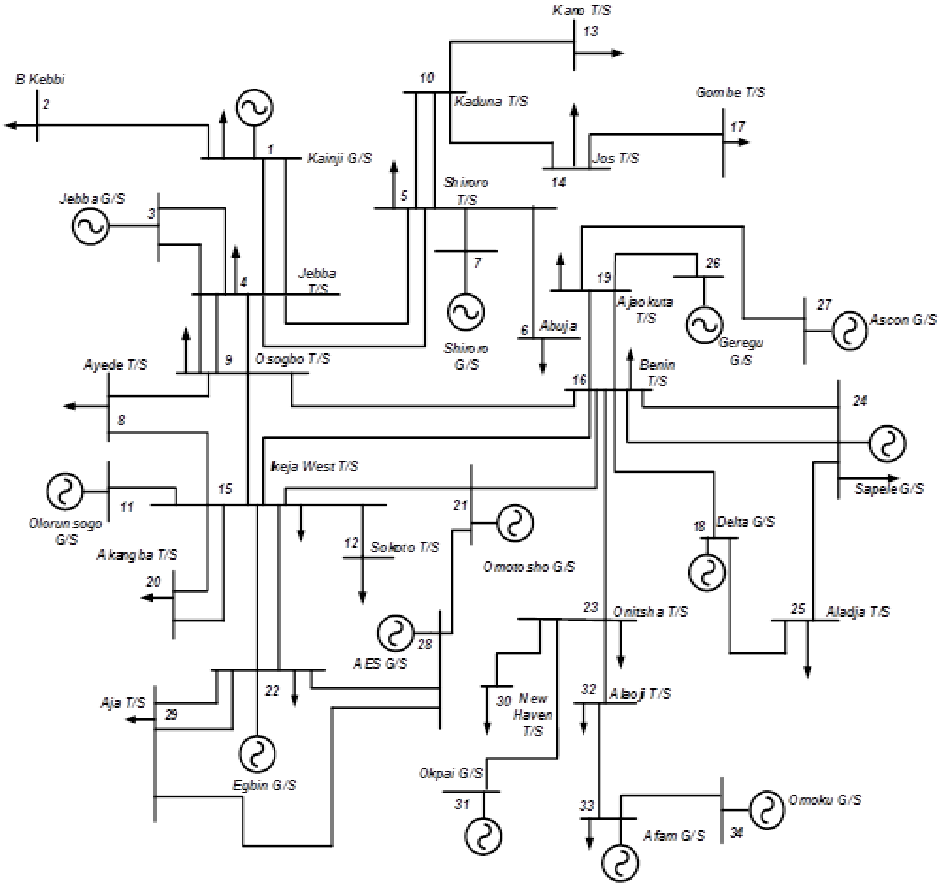

Figure 3: The Nigerian 34-bus power system (National Control Centre, Power Holding Company of Nigeria, 2014)

3. RESULTS AND DISCUSSION

The load flow results without and with optimally placed UPFC device programmed in Python environment via the PSO algorithm, applied on the Nigerian 34-Bus, 330 kV power system network are presented in this section. The parameters used for the UPFC sizing for the Nigerian 34-Bus, 330 kV power system network is as attached in the appendix. Active power loss was used as the selection criterion for optimal location of UPFC device on the power network. The generated load flow results with UPFC placed on line 5-10 (Shiroro-Kaduna TS line) selected as the optimum point by the PSO algorithm are presented as follows:

Figure 4 shows UPFC placement at different locations on the Nigeria 34-bus power network, while Figure 5 shows the comparison of the voltage profile without and with optimally placed UPFC device on line 5-10 (Shiroro-Kaduna TS line). Figure 6 shows the comparison of the total real power loss without and with optimally placed UPFC, while Figure 7 shows the comparison of the total reactive power loss without and with optimally placed UPFC.

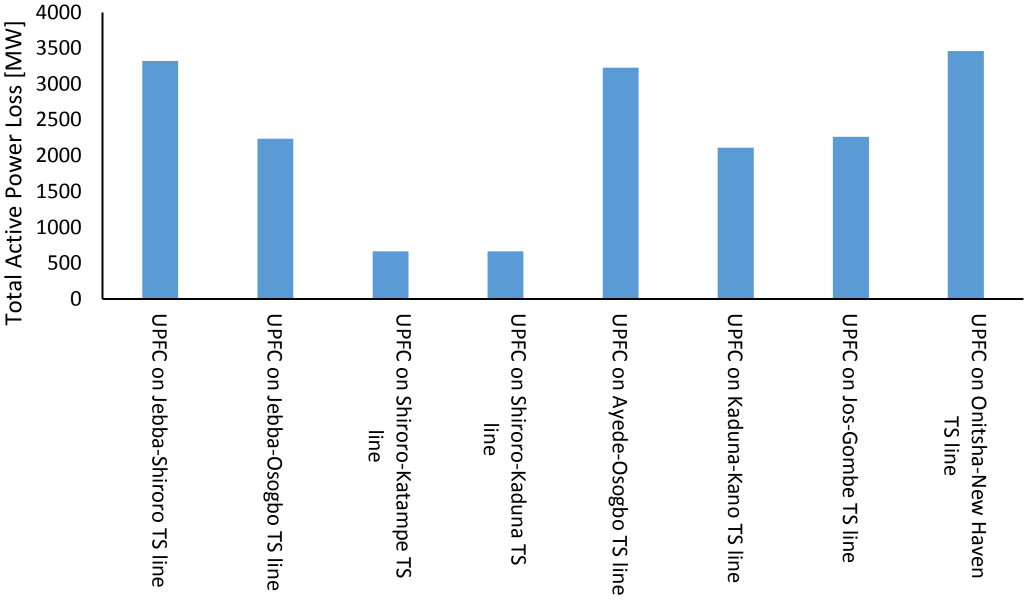

Figure 4: Total active power loss with UPFC placement at different locations on the Nigerian 34-bus power system network

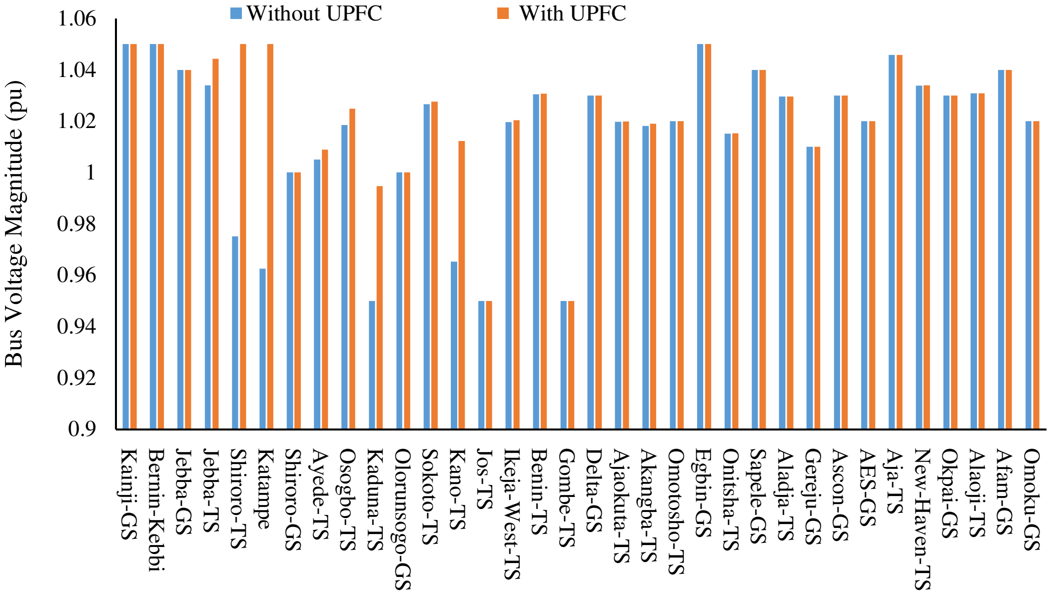

Figure 5: Comparison of bus voltage magnitudes without and with optimally placed UPFC device on the Nigerian 34-bus power system network

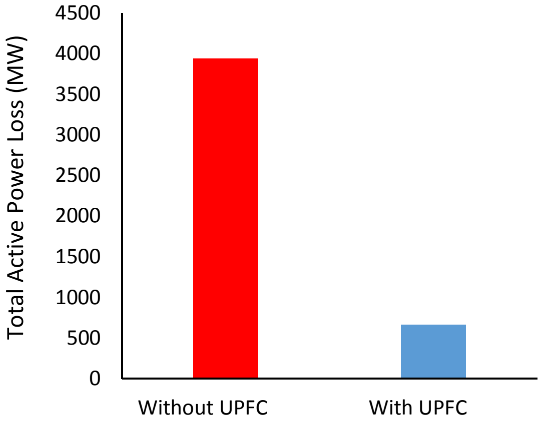

Figure 6: Comparison of total active power loss without and with optimally placed UPFC device on the Nigerian 34-bus power system network

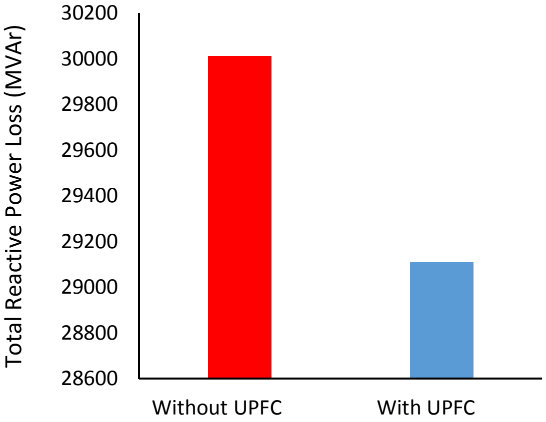

Figure 7: Comparison of total reactive power loss without and with optimally placed UPFC device on the Nigerian 34-bus power system network

From Figure 4, the optimum point for UPFC placement as obtained from the load flow results was line 5-10 (Shiroro-Kaduna TS line). This is where the least active power loss was observed. The bus voltage magnitudes of all the buses in per unit were within the statutory limit defined by $0.95 \leq V \leq 1.05$pu without and with optimally placed UPFC device on line 5-10 (Shiroro-Kaduna TS line). From Figure 5, it was observed that without compensation applied to the test network, the voltage magnitude of Jebba-TS (1.0340), Shiroro-TS (0.9751), Katampe (0.9626), Ayede-TS (1.0051), Osogbo-TS (1.0186), Kaduna-TS (0.9500), Sokoto-TS (1.0267) and Kano-TS (0.9653) already within the statutory limit still improved with optimally placed UPFC device to Jebba-TS (1.0444), Shiroro-TS (1.0500), Katampe (1.0500), Ayede-TS (1.0089), Osogbo-TS (1.0249), Kaduna-TS (0.9947), Sokoto-TS (1.0276), Kano-TS (1.0124) and some other buses have their voltage profile improved.

In Figure 6, it was observed that the total real power loss on Nigerian 34-bus network was 3943.10 MW without compensation, and reduced to 668.60 MW with optimally placed UPFC, equivalent to a percentage improvement of 83.04 %. Similarly, in Figure 7, the total reactive power loss was 30012.40 MVAr without compensation and decreased to 29111.60 MVAr with UPFC optimally placed showing an improvement of 3.00 %.

The load flow results obtained from Amin *et al.* (2021), Mathad and Kulkarni (2020) among others who have also worked on PSO technique for optimal location of UPFC using other practical networks as test cases, showed that there is reduction in active and reactive power losses and enhancement of voltage profile which is in consonant with the results obtained from this study.

4. CONCLUSION

Much research has been carried out in power system using various FACTS devices with appreciable results. However, the approach used for the placement of these FACTS devices are usually trial and error, hence underutilizing the capacity of the controller. This work employed an artificial intelligent technique known as PSO to find the best placement for UPFC on the Nigerian 330 kV, 34-bus power network, and the obtained results established that the technique when adopted could offer a significant improvement in the voltage stability and power losses of the system to produce more spares of electrical energy that could be used to address growing demand of end-users.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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APPENDICES

APPENDIX I: Bus parameters of the Nigeria 34-Bus, 330 kV power system network

Bus identification			Bus load	
Bus name	Bus no	Bus type	Pd (MW)	Qd (MVAR)
Kainji G.S	1	3	00.00	00.00
Bernin Kebbi	2	1	40.00	- 10.00
Jebba G.S	3	2	00.00	00.00
Jebba T.S	4	1	140.00	30.00
Shiroro T.S	5	1	90.00	30.00
Abuja (katampe)	6	1	160.00	70.00
Shiroro G.S	7	2	00.00	00.00
Ayede T.S	8	1	130.00	70.00
Oshogbo T.S	9	1	300.00	90.00
Kaduna T.S	10	1	210.00	40.00
Olorunsongo G.S	11	2	00.00	00.00
Sokoto T.S	12	1	50.00	-20.00
Kano T.S	13	1	100.00	-30.00
Jos T.S	14	1	120.00	60.00
Ikeja West T.S	15	1	500.00	50.00
Benin T.S	16	1	250.00	43.00
Gombe T.S	17	1	70.00	38.00
Delta G.S	18	2	00.00	00.00
Ajaokuta T.S	19	1	200.00	55.00
Akangba T.S	20	1	150.00	35.00
Omotosho T.S	21	2	00.00	00.00
Egbin G.S	22	2	00.00	00.00
Onitsha T.S	23	1	300.00	45.00
Sapele G.S	24	2	00.00	00.00
Aladja T.S	25	1	100.00	58.00
Geregu G.S	26	2	00.00	00.00
Ascon G.S	27	2	00.00	00.00
AES G.S	28	2	00.00	00.00
Aja T.S	29	1	120.00	80.00
New Heaven T.S	30	1	130.00	-78.00
Okpai G.S	31	2	00.00	00.00
Alaoji TS	32	1	200.00	67.00
Afam G.S	33	2	00.00	00.00
Omoku G.S	34	2	00.00	00.00

APPENDIX II: Generator parameters of the Nigeria 34-Bus, 330 kV power system network

Bus no	Generator		Reactive limits					
	Pg (MW)	Qg (MVAR)	Qmax (MVAR)	Qmin (MVAR)	Vg (p.u)	R (p.u)	X (p.u)	H
1	00.00	00.00	0	0	1.06	0.0020	0.0901	9.920
3	300.00	40.00	110	0	1.04	0.0080	0.3000	3.390
7	400.00	60.00	140	0	1.0	0.0240	0.3000	3.240
11	150.00	50.00	114	0	1.0	0.0036	0.2200	4.000
18	280.00	45.00	100	0	1.03	0.0020	0.1240	12.400
21	240.00	55.00	104	0	1.02	0.0036	0.2200	4.000
22	700.00	68.00	108	0	1.05	0.0040	0.3080	3.090
24	180.00	00.00	132	0	1.04	0.0030	0.1060	12.690
26	190.00	-35.00	126	0	1.01	0.0061	0.3400	1.245
27	150.00	51.00	100	0	1.03	0.0036	0.3000	1.242
28	130.00	80.00	150	0	1.02	0.0051	0.2100	1.249
31	150.00	00.00	100	0	1.03	0.0061	0.3000	4.000
33	200.00	59.00	140	0	1.04	0.0010	0.0610	28.050
34	300.00	65.00	125	0	1.02	0.0051	0.1900	1.350

APPENDIX III: branch parameters of the Nigeria 34-Bus, 330 kV power system network

Bus		Transmission line data		
From Bus	To Bus	R (p.u)	X (p.u)	B (p.u)
1	2	0.0121836	0.0916336	1.21
1	4	0.0015918	0.0119716	0.31
3	4	0.0001572	0.0094178	0.00
4	5	0.0047827	0.0360219	0.09
4	9	0.0020565	0.0154692	0.07
5	6	0.0018864	0.0141884	0.36
5	7	0.0003144	0.0188355	0.00
5	10	0.0018864	0.0141884	0.37
8	9	0.0053843	0.0404961	0.33
8	15	0.0053343	0.0405651	0.45
9	15	0.0065432	0.0426547	0.55
9	16	0.0098648	0.0741936	0.98
10	13	0.0090394	0.0679862	0.52
10	14	0.0077425	0.0582316	0.77
11	15	0.0020643	0.0103951	0.31
12	15	0.0040534	0.0305160	0.41
14	17	0.0104150	0.0783319	0.01
15	16	0.0110045	0.0827653	0.09
15	20	0.0003527	0.0026574	0.05
15	21	0.0055023	0.0413829	0.35
15	22	0.0012184	0.0091634	0.20
16	18	0.0063843	0.0404961	0.15
16	19	0.0038336	0.0288242	0.76
16	21	0.0055023	0.0413829	0.55
16	23	0.0053843	0.0404961	0.38
16	24	0.0009826	0.0073898	0.19
18	25	0.0010218	0.0076553	0.10
19	26	0.0005109	0.0038427	0.38
19	27	0.0006105	0.0038427	0.40
22	28	0.0005109	0.0036458	0.30
22	29	0.0002749	0.0020654	0.20
23	30	0.0037730	0.0283768	0.37
23	31	0.004913	0.0036949	0.09
23	32	0.00605225	0.0455212	0.02
24	25	0.0024760	0.0186223	0.24
28	29	0.0034640	0.0206114	0.30
32	33	0.0009825	0.0073898	0.09
33	34	0.0005109	0.0038427	0.30

APPENDIX IV: Parameters used for UPFC design/sizing

UPFC parameters	Nigerian 34 bus
Is	14
Ir	17
Xvr	0.1
Xcr	0.1
Vvrtarget	1.0
Vstat	1
Psp	0.4
Qsp	0.02
Pstat	1
Qstat	1
Flow	[-1]
Vcr	0.04
Vvr	1.0
Vvrmax	1.05
Vvrmin	0.95
Vcrmax	0.2
Vcrmin	0.001
Tvr	0.0
Tcr	[-87.13/57.3]