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Locating and Sizing of Unified Power Flow Controller in Power System Network for Power Loss Minimization Using Voltage Sensitivity Index and Bat Algorithm

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ABSTRACT

The search for an improved method of maximizing the power transfer capability of every transmission line in a power system network has become an important issue of concern, especially in these modern times when power systems have become large, complex and with ever increasing power demand. The emergence of the Flexible Alternating Current Transmission System (FACTS) technology has proffer alternative method for the improvement of power system network performance. Among the FACTS devices used today, the Unified Power Flow Controller (UPFC) is the most versatile because of its ability to control the voltage magnitude, phase angle and line impedance. To derive the maximum benefit from a FACTS device, its optimal size and location on the network must be determined. In this paper, Voltage Sensitivity Index (VSI) technique is applied for the optimal location of the UPFC while Bat Algorithm (BA) optimization technique is used for the UPFC sizing. The effectiveness of the work is validated on IEEE 14 bus test network. Results obtained show net active and reactive power losses reducing from 13593MW and 56910MVAr to 13491MW and 22.5715MVar respectively. Maximum bus voltage enhancement is from 1.0466pu to 1.0626pu (1.53%). These results are compared with the results of similar work available in recent literature.

Keywords **:— UPFC, Voltage Sensitivity Index, Bat Algorithm.**

I. INTRODUCTION

Electrical power supply is the bedrock and one of the most powerful driving force for development and technological innovations of the modern day society. As a result of this, the existing power system networks are continousely being expanded and upgraded in other to cater for the need of the ever growing power demands. There are several problems which can prevent optimal power system delivery. These problems have led to the continuous search for methods of improving power system performance in terms of its reliability, efficiency, quality, and stability. Very common among such methods are the use of Flexible Alternating Current Transmission Systems (FACTS) devices.

According to [1], FACTS device can be defined as a power electronics based device incoperated with other static controllers to enhance better controllability and increase maximum power transfer ability. These FACTS controllers can either be based on current sourced or voltage sourced and are catigorised under series connected controllers, shunt connected controllers, combine series-series controllers, and combine shunt and series controllers.

The most versatile device within the FACTs family is the unified power flow controller because it has the ability to adjusting the controllable parameters, namely;

i. Phase angle

ii. Bus voltage

iii. The transmission line reactance across two buses. It can do these either independently or in simultaneously [2].

The optimal location and setting of the UPFC in the network will unarguably improve the performance of the network. These challenges have been faced by researchers with more of them focusing on locating the UPFC [3], [4] and [5]. The work herein, considers the simultaneous locating and sizing of UPFC in a network. Voltage sensitivity index (VSI) is used to determine the location of the UPFC and the bat algorithm is exploited for sizing of the UPFC.

II. METHODOLOGY

This work is carried out in the following mainstream sequence:

1. Development and implementation of steady state power flow analysis based on Newton-Raphson for the study system in other to determine pre compensation (base case) bus voltages, power available on the buses and the power loss in each branch of the network.
2. Computation of voltage sensitivity indices (VSIs) for all the load buses of the study system to determine the

weakest bus which is the optimal location for UPFC placement in the network.

3. Determination of optimal size of the UPFC using bat algorithm.
4. Validate the effectiveness of the work on the IEEE 14 bus test network.

A. *Power Flow Analysis (PFA)*

The power system can operate in one of numerous voltage and power sets within the buses so as to befit standard requisites. Power Flow analysis, well documented in many books on power system, is the most frequently used method to determine these possible operational states through the knowledge *a priori* of certain variables of the system buses. The target of this type of problem is to obtain the system bus voltages – module and angle – so as to determine the power adjustments on the generation buses and the power flow in the system lines [6]. The power flow study provides the system status within the steady-state, that is, its parameters do not vary with the time variation. Once the steady-state of the system is determined, it is possible to estimate the capacity of power generation necessary to supply the power demand and the power losses in the system lines.

Power flow is basically solving the complex and nonlinear power balance equations given in (1) and (2).

$$P_i = \sum_{i=1}^{N} |V_i||V_j||Y_{ij}|\cos(\delta_i - \delta_j - \theta_{ij}), j = 1, \dots, N \quad 1$$

$$Q_i = \sum_{i=1}^{N} |V_i||V_j||Y_{ij}|\sin(\delta_i - \delta_j - \theta_{ij}), j = 1, \dots, N \quad 2$$

Where: $i = 1\dots$, N, N is the number of load buses; P_i = active power generated or injected on bus i; Q_i = reactive power generated or injected on bus i; $|V_i|$ = voltage module of bus i; δ_i = voltage angle of bus i, y_{ij} = element of the nodal admittance matrix Y_{bus}. The nodal admittance matrix is developed thus; if i = j, y_{ij} is the sum of the admittances that come out of the bus i; and if $i \neq j$, y_{ij} is the admittance between the buses i and j, multiplied by -1.

The power system buses are categorize into three depending on which variables are known and which variables are to be obtained through the power flow analysis. The bus types are,

- Load bus (PQ Bus): P_i & Q_i are specified and $|V_i|$ and δ_i are obtained through the PFA;
- Generator bus (PV Bus): P_i & $|V_i|$ are specified and Q_i and δ_i are obtained through the PFA;
- Slack bus (Vδ Bus): $|V_i|$ and δ_i are specified and P_i and Q_i are obtained through the PFA

Since the power balance equations are non-linear, their solutions are gotten through numerical computational methods such as Newton Raphson. These methods consist of the adoption of initial estimated values to the bus voltage magnitudes and angle, for instance, 1.0 pu, 0 rad, and then search for better approximations for the voltages in successive iterations. The iterative process will be stop depending on the required accuracy.

B. *Computation of Voltage Sensitivity Indices*

One effective way to know the location on a power system where instability is most likely to occur is to identify the weakest bus in the power systems. The weakest bus is the bus which lacks reactive power supports and the most to defend against voltage collapse. To identify the weak buses, several methods have been proposed in the literature [7] and applied as in [8]. Most of the methods of identifying weak bus are based on voltage sensitivity. Voltage sensitivity indices have been used as indicators of voltage stability and several indices of this kind have been proposed. The voltage sensitivity index that directly correlates the bus voltage and the bus reactive power is the reactive power voltage sensitivity index (*RPVS).* It gives the variation of node i voltage magnitude due to a unit reactive power injection to node j [9].

The computation of RPVS starts by considering the linearized form of the nonlinear power balance equations which is given in (3) [10]

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \quad 3$$

Where, matrix J is the Jacobean matrix, P_i and Q_i are as in equations (1) and (2), ΔP and ΔQ are vectors of real and reactive bus power changes, while $\Delta\delta$ and ΔV are vectors of changes in bus voltage angles and voltage magnitudes respectively.

From equation (3),

$$\Delta Q = \left(-J_3 \frac{J_2}{J_1} + J_4\right) \Delta|V| \quad 4$$

The reactive power is less sensitive to changes in phase angles and is mainly dependent on changes in voltage magnitudes. Similarly, real power change is less sensitive to the change in the voltage magnitude and is most sensitive to the change in phase angle. So, it is quite accurate to set J_2 and J_3 in equation (4) to zero resulting in equation (5)

$$\frac{\Delta|V|}{\Delta Q} = J_{4ij}^{-1} \quad 5$$

The RPVSI are computed as in equation (6).

$$RPVS_i = diag\{J_{4ij}^{-1}\} \quad 6$$

Bus with the smallest RPVS is the weakest in the system and most suitable bus for locating UPFC.

C. *Bat Algorithm*

Bat algorithm (BA) is a bio-inspired algorithm developed by Xin-She Yang in 2010 and has been found to be a very efficient optimization algorithm [12]. Meta-heuristic algorithms such as particle swarm optimization and simulated annealing have become powerful methods for solving many tough optimization problems. Bat Algoeithm (BA) is a much more powerful optimization algorithm because it combines major advantages of some popular heuristic algorithms [13]. It can deal with nonlinear, global optimization problems and has the advantages of simplicity, flexility and stability. It is based on the echolocation or bio-sonar characteristics of bats whereby the bats emits a loud and short pulse of sound, wait as the sound hits an object and the echo returns back to their ears. The bats then use the echoed pulse to compute how far they are from an object. In addition, this amazing orientation mechanism makes bats being able to distinguish the difference between an obstacle and a prey, allowing them to hunt even in a complete darkness.

Bats algorithm uses frequency tuning, whereby each bat is encoded with a velocity v_i^t and a location x_i^t at iteration *t*, in a *d*-dimensional solution space. The location can be considered as a solution vector to a problem of interest. Among the *n* bats in the population, the current best solution $x*$ found so far can be archived during an iterative search process.

Based on the above description and characteristics of bat echolocation, the bat algorithm was developed with the following three idealised rules:

- All bats use echolocation to sense distance, and also know the difference between food/prey and background barriers in some magical way.
- Bats fly randomly with velocity (v_x) at position (x_i) with a frequency (f) or wavelength (λ) and loudness (A_0) to search for prey. They can automatically adjust the wavelength (or frequency) of their emitted pulses and adjust the rate of pulse emission r ∈ [0,1], depending on the proximity of their target.
- Although the loudness can vary in many ways, we assume that the loudness varies from a large positive value A_0 to a minimum constant value A_{min}.

  In the application of the Bat algorithm, positions x_i and velocities v_i in a d-dimensional search space are updated. The new solutions x_i^t and velocities v_i^t at time step t are given by;

  $$f_i = f_{min} + (f_{max} - f_{min})\beta \quad 7$$

  $$V_i^t = V_i^{t-1} + (x_i^{t-1} - x^*)f_i \quad 8$$

  $$x_i^t = x_i^{t-1} + V_i^t \quad 9$$

  where $\beta \in [0,1]$ is a random vector drawn from a uniform distribution. x^* is the current global best location (solution) which is located after comparing all the solutions.

Once a solution is selected among the current best solutions, a new solution for each bat is generated locally using random walk.

$$x_{new} = x_{old} + \epsilon A^t \quad 10$$

ϵ Є [−1, 1] is a random number, while $A^t = < A_i^t >$ is the average loudness of all the bats at this step. In addition, the loudness A_i and pulse emission rates r_i can be varied during the iterations using the following equations.

$$A_i^{t+1} = \alpha A_i^t \quad 11$$

and

$$r_i^{t+1} = r_i^0[1 - \exp(-\gamma t)] \quad 12$$

where $0 < \alpha < 1$ and $\gamma > 0$ are constants.

For any $0 < \alpha < 1$ and $y > 0$, we have:

$A_i^t \rightarrow 0$. $r_i^t \rightarrow r_i^0$ as $t \rightarrow \infty$ The initial loudness A_0Є $[1, 2]$, while the initial emmision rate r_i^0 Є [0, 1].

The bat algorithm is summarized in the flow chart of Fig.1 [14]

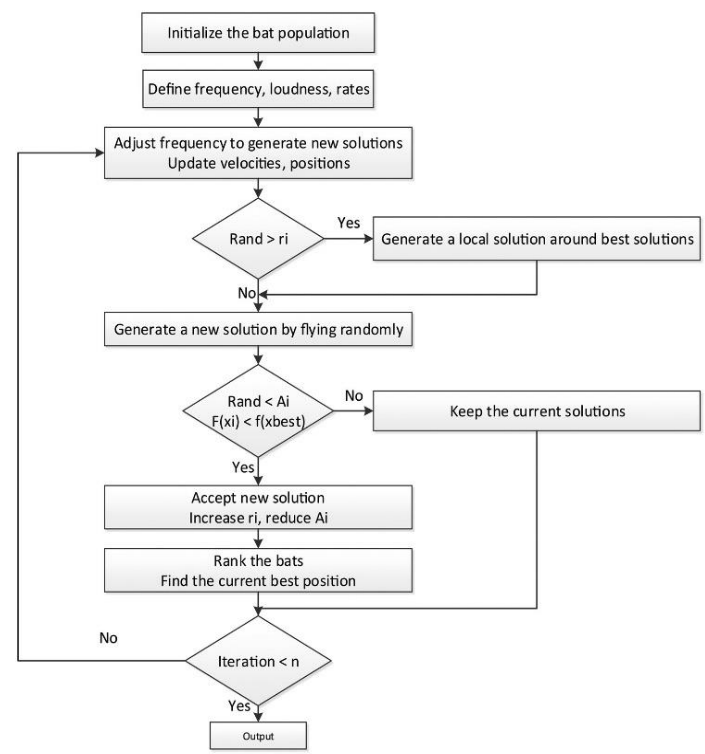

Fig. 1 The bat algorithm flowchart [14].

D. *Objective Function*

In this work, the aim is to minimize the real power losses in order to obtain maximum power transfer capability. Mathematically, the objective function can be written as [11],

$$f = \min(P_{loss}) \quad 13$$

Where $P_{loss} = \sum_{i=1}^{Ntl} G_{ij} [V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)$ 14

G_{ij} is the conductance of line *ij*, V_i and V_j are the magnitudes of sending end and receiving end voltages of the line. δ_i and δ_j are the phase angles of the end voltages. *Ntl* is the number of transmission lines.

The equality constraints:

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{Nb} V_j (G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)) = 0 \quad 15$$

$$Q_{Gi} - Q_{Ci} - Q_{Di} - V_i \sum_{j=1}^{Nb} V_j (G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j)) = 0 \quad 16$$

P_{Gi} is the real power generation at bus i, P_{Di} is the power demand at bus i, *Nb* is the number of PQ nodes in the system. Q_{Gi} is the reactive power generation at bus i, Q_{Di} is the reactive power demand at bus i, Q_{Ci} is the reactive power from compensation nodes.The inequality constraints are:

Voltage limits for generator buses:

$$V_{Gi}^{min} \leq V_{Gi} \leq V_{Gi}^{max} \quad 17$$

Where V_{Gi}^{min} is the minimum voltage at the generator bus, V_{Gi} is the actual voltage at the generator bus and V_{Gi}^{max} is the maximum voltage at the generator bus.

Real power generation limits:

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \quad 18$$

Where P_{Gi}^{min} is the minimum real power at the generator bus, P_{Gi} is the actual real power at the generator bus and P_{Gi}^{max} is the maximum real power at the generator bus.

Reactive power generation limits:

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \quad 19$$

Where Q_{Gi}^{min} is the minimum reactive power at the generator bus, Q_{Gi} is the actual reactive power at the generator bus and Q_{Gi}^{max} is the maximum reactive power at the generator bus.

UPFC limits:

$$V_{vr}^{min} \leq V_{vr} \leq V_{vr}^{max} \quad 20$$

Where V_{vr}^{min} is the minimum shunt converter voltage magnitude (p.u), V_{vr} is the actual shunt converter voltage (p.u) and V_{vr}^{max} is the maximum shunt converter voltage magnitude (p,u).

$$V_{cr}^{min} \leq V_{cr} \leq V_{cr}^{max} \quad 21$$

Where V_{cr}^{min} is the series converter voltage magnitude (p.u), V_{cr} is the actual series converter voltage magitude (p.u) and V_{cr}^{max} is the maximum series converter voltage magnitude (p.u)

The input parameters for the bat algorithm are given in Table I

TABLE I

INPUT PARAMETERS FOR BAT ALGORITHM

S/N	Parameters	Quantity
1	Number of iterations	50
2	Number of population	20
3	Pulse rate	0.9
4	Loudness	0.9

E. *Study System and Data Presentation*

The study system is the IEEE 14 bus system which has 5 generator buses, 9 load buses and 20 transmission lines. The one- line diagram of the study system is given in Fig. 2 with bus and branch data given in Tables II and III respectively.

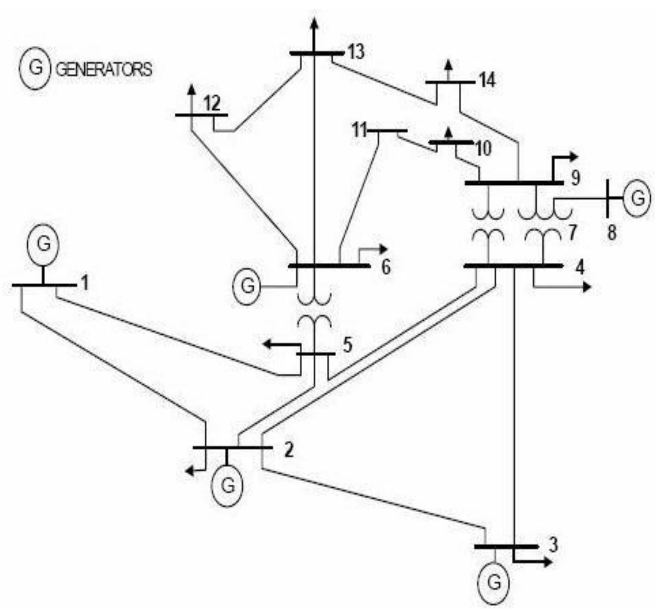

Fig. 2 One- line diagram of IEEE 14 bus system [15].

TABLE II BUS DATA OF IEEE 14 BUS NETWORK [15]

Bus No.	Bus Type	Volt Mag. (pu)	Angle Degree	P_G MW	Q_G MVAR	P_L MW	Q_L MVAR
1	Slack	1.06	0	232.4	-16.9	0	0
2	PV	1.045	-4.98	40	42.4	21.7	12.7
3	PV	1.01	-12.72	0	23.4	94.2	19
4	PQ	1.019	-10.33	0	0	47.8	-3.9
5	PQ	1.02	-8.78	0	0	7.6	1.6
6	PV	1.07	-14.22	0	12.2	11.2	7.5
7	PQ	1.062	-13.37	0	0	0	0
8	PV	1.09	-13.36	0	17.4	0	0
9	PQ	1.056	-14.94	0	0	29.5	16.6
10	PQ	1.051	-15.1	0	0	9	5.8
11	PQ	1.057	-14.79	0	0	3.5	1.8
12	PQ	1.055	-15.07	0	0	6.1	1.6
13	PQ	1.05	-15.16	0	0	13.5	5.8
14	PQ	1.036	-16.04	0	0	14.9	5

TABLE III LINE DATA FOR IEEE 14 BUS SYSTEM [15]

Line No.	From Bus	To Bus	Resistance (p.u)	Reactance (p.u)	Line Charging Susceptance (p.u)	Tap Ratio
1	1	2	0.01938	0.05917	0.0528	1
2	1	5	0.05403	0.22304	0.0492	1
3	2	3	0.04699	0.19797	0.0438	1
4	2	4	0.05811	0.17632	0.0374	1
5	2	5	0.05695	0.17388	0.034	1
6	3	4	0.06701	0.17103	0.0346	1
7	4	5	0.01335	0.04211	0.0128	1
8	4	7	0	0.20912	0	0.978
9	4	9	0	0.55618	0	0.969
10	5	6	0	0.25202	0	0.932
11	6	11	0.09498	0.1989	0	1
12	6	12	0.12291	0.25581	0	1
13	6	13	0.06615	0.13027	0	1
14	7	8	0	0.17615	0	1
15	7	9	0	0.11001	0	1
16	9	10	0.03181	0.0845	0	1
17	9	14	0.12711	0.27038	0	1
18	10	11	0.08205	0.19207	0	1
19	12	13	0.022092	0.19988	0	1
20	13	14	0.17093	0.34802	0	1

III. RESULTS

The results of the resarch work after modelling and simulation includes:

A. Optimal Location of UPFC

The computed reactive power voltage stability indices for the study system are given in Table IV

TABLE IV

VOLTAGE SENSITIVITY INDICES FOR STUDY SYSTEM

Load Bus Number	Voltage Stability Index
4	0.0827
5	0.0516
7	0.1116
9	0.0632
10	0.3421
11	0.0451
12	0.2723
13	0.0448
14	0.0260

In Table IV, the bus that has the smallest RPVS is the weakest in the system and most suitable bus for locating UPFC. Therefore the best location is bus fourteen.

B. Optimal Size of UPFC

The optimal size of UPFC was obtained using bat algorithm optimization. The obtimal size of the UPFC for the IEEE 14 bus network is 18.1737MVAr.

C. Validation of Proposed Technique

Power flow analysis using Newton Raphson method was run before and after UPFC compensation. The bus voltage enhancements expressed in percentages over the values before compensation are given in Table V.

TABLE V

BUS VOLTAGE IMPROVEMENT

Bus Number	Bus Voltage (pu)		
	Before UPFC	After UPFC	Enhancement (%)
1	1.0600	1.0600	0.00
2	1.0450	1.0450	0.00
3	1.0100	1.0100	0.00
4	1.0132	1.0147	0.15
5	1.0166	1.0175	0.09
6	1.0700	1.0700	0.00
7	1.0457	1.0517	0.57
8	1.0800	1.0900	0.93
9	1.0305	1.0364	0.57
10	1.0299	1.0348	0.48
11	1.0461	1.0486	0.24
12	1.0533	1.0619	0.82
13	1.0466	1.0626	1.53
14	1.0193	1.0297	1.02

Similarly, real and reactive power loss reduction in each branch of the network were calculated before and after compensation. The reduction in the power loss expressed in percent over the power before compensation are shown on Table VI.

TABLE VI

REDUCTION IN LINE REAL AND REACTIVE POWER LOSS

Line Number	From Bus	To Bus	Real Power Loss			Reactive Power Loss		
			Before UPFC	After UPFC	Reduction (%)	Before UPFC	After UPFC	Reduction (%)
1	1	2	4.3086	4.3041	0.10	13.1547	13.1410	0.10
2	1	5	2.7726	2.7695	0.11	11.4455	11.4326	0.11
3	2	3	2.3352	2.3294	0.25	9.8298	9.8140	0.16
4	2	4	1.6700	1.6703	-0.02	5.0670	5.0682	-0.02
5	2	5	0.9200	0.9148	0.57	2.8089	2.7931	0.56
6	3	4	0.3911	0.3846	1.66	0.9983	0.9817	1.66
7	4	5	0.4791	0.4884	-1.94	1.5113	1.5406	-1.94
8	4	7	0	0	0	1.9317	2.1045	-8.95
9	4	9	0	0	0	1.2920	1.3363	-3.43
10	5	6	0	0	0	5.7736	5.6347	2.41
11	6	11	0.1227	0.1027	16.30	0.2568	0.2151	16.24
12	6	12	0.0806	0.0607	24.69	0.1678	0.1264	24.67
13	6	13	0.2518	0.2060	18.19	0.4960	0.4058	18.19
14	7	8	0	0	0	0.6679	0.8322	-24.60
15	7	9	0	0	0	0.9573	0.9665	-0.96
16	9	10	0.0060	0.0062	-3.33	0.0160	0.0165	-3.13
17	9	14	0.0894	0.0955	-6.82	0.1902	0.2032	-6.83
18	10	11	0.0514	0.0387	24.71	0.1203	0.0905	24.77
19	12	13	0.0110	0.0105	4.55	0.0100	0.0095	5.00
20	13	14	0.1054	0.1328	-26.00	0.2146	0.2703	-25.96

D. Comparison of Proposed Technique with Similar Work in Literature

TABLE VII

COMPARISON OF PROPOSED WORK WITH SIMILAR WORK

Bus No.	Proposed			Aman and Jitendra [16]		
	Bus Voltage without UPFC	Bus Voltage with UPFC	% increase	Bus Voltage without UPFC	Bus Voltage With UPFC	% increase
1	1.0600	1.0600	0.00	1.060	1.0600	0.00
2	1.0450	1.0450	0.00	1.186	1.0450	-11.89
3	1.0100	1.0100	0.00	1.030	1.0100	-1.94
4	1.0132	1.0147	0.15	0.989	0.99795	0.90
5	1.0166	1.0175	0.09	0.918	1.0034	9.30
6	1.0700	1.0700	0.00	1.090	1.0700	-1.83
7	1.0457	1.0517	0.57	0.969	1.0349	6.80
8	1.0800	1.0900	0.93	1.110	1.0900	-1.80
9	1.0305	1.0364	0.57	0.989	1.0115	2.28
10	1.0299	1.0348	0.48	0.969	1.0109	4.32
11	1.0461	1.0486	0.24	0.967	1.0349	7.02
12	1.0533	1.0619	0.82	0.969	1.0461	7.96
13	1.0466	1.0626	1.53	0.987	1.0363	4.99
14	1.0193	1.0297	1.02	0.969	0.9968	2.87

These results show that the voltages on ten out of the fourteen buses were improved by the compensation with maximum improvement of 1.53%. Similarly, reduction in transmission loss were observed on most of the branches in the network.

IV. CONCLUSION

In this paper, reactive power voltage sensitivity (RPVS) indices are computed for the IEEE 14-bus system with an intent of identifying the weakest bus and hence the most appropriate location for UPFC Placement. Bus fourteen is found to be the weakest bus and hence the most suitable location. A Bat algorithm based technique was used to determine the optimal size of the UPFC compensator, which was found to be 18.1737MVAr. Simulation results on the compensated system show that the bus voltages increase on most of the buses. However, the enhancements are not much (maximum 1.53% on bus 13). This is because the test system has inherent compensators on buses 3, 6 and 8. Voltage profile improved on ten out of the fourteen buses. Maximum bus voltage improvement is from 1.0466pu to 1.0626pu (1.53%). Similarly, the maximum line real and reactive power loss reduction were both recorded in the 18th line. Maximum reduction in real and reactive power loss are from 0.0514pu to 0.0387pu (24.71%) and 0.1203pu to 0.0905pu (24.77%) respectively. When compared with the results of similar, this proposal has proven to be an edge above the other method because it improves the voltage on more of the buses than the other method.

The voltage profile enhancement obtained by the propose

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