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Solving the Power System State Estimation Problem Embedded with UPFC Using Glowworm Swarm Optimization Algorithm

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Abstract

In this paper, the state estimation (SE) problem is formulated as a general nonlinear programming problem with equality constraints and boundary limits on the state variables. The objective of this paper is to incorporate the Unified Power Flow Controller (UPFC) into the SE algorithm. UPFC has the potential to independently control the voltage, active and reactive power flows in the system. In this paper, the Glowworm Swarm Optimization (GSO) is used to store the proposed SE problem. The proposed SE algorithm embedded with UPFC has been examined on IEEE 14 bus test system.

Keywords: State estimation, FACTS devices, Evolutionary algorithms, Load flow, Unified power flow controller.

NOMENCLATURE

h(.)	Vector of nonlinear functions relating measurement and state vectors.
N_b	Total number of buses.
P_i	Active power injection at ith bus.
P_{Gi}, Q_{Gi}	Active and reactive power generations at ith bus.
P_{is}, Q_{is}	Injected active and power generations.
q	Number of network PQ buses.
m	Number of measurements.
n	Number of state variables.
P_{Li}, Q_{Li}	Active and reactive power load demands at ith bus.
I_{sh}	Shunt current due to line charging.
Q_i	Reactive power injection at ith bus.
R^{-1}	Diagonal matrix with the weights of the individual measurements in the objective function.
V_i	Voltage magnitude at ith bus.
δ_i	Load angle at ith bus.
Y_{ij}	i-jth element of admittance (Y-bus) matrix (g_{ij}+b_{ij}).
N_l	Number of load buses.
S^0	Complex power injection when there was no UPFC.
N_g	Number of generator buses.
X	Equivalent impedance of transmission line
δ_1-δ_2	Phase angle difference between two ends of transmission line.
z	Measurement vector.
ρ	Luciferin decay constant ($0 < \rho < 1$).
ϵ	Measurement errors vector.
γ	Luciferin enhancement constant.
β	Constant parameter.
n_t	Threshold parameter.

INTRODUCTION

Power system state estimation (SE) is an important tool for the supervision and control applications. Based on the redundant measurements in the network, the state estimation (SE) provides the most likely state of the power system [1]. The SE processes a set of measurements to get the best estimate of the current state of the power system. The set of measurements includes the telemetered and pseudo-measurements. Telemetered measurements are the online telemetered data of power injections, line flows, bus voltages, etc. Pseudo-measurements uses the manipulated data like guessed substation load demand or MW generation based on the historical data. Normally, the SE problem is solved using the weighted least square (WLS) approach. However, this WLS technique does not enforce explicitly the equality and limit constraints. But, these constraints contain reliable information about the physical restrictions and equipment limits and can be used to increase the quality of SE result.

Nowadays, it has been found that the Artificial Neural Networks (ANNs) are well suited as computational tools for solving certain classes of complex problems. ANN computations may be carried out in parallel, and special hardware devices are being designed and manufactured which take advantage of this capability. The objective of good estimation of state variables of power system is with little error. The Flexible AC Transmission System (FACTS) devices are used in power systems to control the utilization of the power transfer capability, and to improve the stability and security of the power systems. However, in the literature, there is very limited efforts have been made to study the impact of FACTS devices on the SE of power systems.

An effective and novel sequential approach is developed in Reference [2] for SE of power system with FACTS conrollers and multi-terminal DC systems. The SE problem of power systems incorporating various FACTS devices, i.e., Static Var compensators (SVCs), thyristor controlled series compensators (TCSCs), and unified power flow controllers (UPFCs) is solved using the predictor-corrector interior point (IP) algorithm is proposed in Reference [3]. Reference [4] presents an approach to incorporate the FACTS controllers, i.e., SVC and TCSC into a WLS-SE algorithm. Reference [5] focuses on how to improve the SE result of the Independent System Operator (ISO) or the member companies by exchanging the estimated or raw data with neighboring ISOs (or member companies). Reference [6] deals with the issues of modeling SVC and STATCOM when solving the power system SE problem. A least absolute value SE for power system using Recursive Least Squares by including the Unified Power Flow Controller (UPFC) is proposed in [7]. In Reference [8], the modified version of SE formulation is presented to incorporate the detailed models of UPFC.

A SE model with Interline Power flow Controller (IPFC) is proposed in Reference [9], where the power injection model is used and the effect of IPFC on power flow is transferred to the lines which are connected to it. In Reference [10], the IPFC is used in the SE problem as one of the versatile FACTS device. An algorithm considering the correlated measurements, multiple load levels and accuracy evaluation of state estimation to allocate meters in distribution networks to increase the accuracy of the SE is proposed in Reference [11]. A practical method to incorporate the synchronized phasor measurements into a WLS-SE algorithm, which is suitable for electric networks containing FACTS controllers is presented in Reference [12]. A practical approach to incorporate the FACTS controllers into a WLS-SE algorithm by simultaneously upgrading the estimated values of state variables of these devices and the state variables of rest of the electric network, for a unified solution in a single-frame of reference is proposed in Reference [13]. References [14-16] proposes an algorithm for SE in power systems including the FACTS controllers and PMUs. A new SE approach with interphase power controllers (IPC) is presented in Reference [17]. In Reference [18], a Hopfield neural network is used to solve the power system SE problem.

In the recent years, after the establishment of power markets with transmission open access, the significance and the use of FACTS controllers has reduced the congestion in the system and obtained the increased overall grid operation. Hence, there is a requirement to integrate the FACTS devices into the existing power system applications. In this paper, an approach for solving the SE problem of power system containing UPFC by using the GSO algorithm. Here, the steady state model of UPFC is presented and then the GSO is used to solve the state estimation problem. The proposed SE model embedded with UPFC has been examined on IEEE 14 bus test system.

FLEXIBLE AC TRANSMIOSSION SYSTEM (FACTS)

As a result of rights of way issues, recent environmental legislation, increase in construction cost and deregulation policies, there is an increasing recognition of the necessity to utilize existing transmission system assets to the maximum extent possible, and this can be achieved with the help of FACTS controllers. Some advantages which FACTS devices can offer includes:

- Controls the power flows through the transmission lines.
- Reduces the power system oscillations.
- Secure loading of transmission lines closer to their maximum power flow limits.
- Prevention of cascading outages.

The active power transmitted over a transmission line is expressed by,

$$P = \frac{V_1 V_2}{X}\sin(\delta_1 - \delta_2) \qquad (1)$$

where V_1 and V_2 are the voltages at the ends of the transmission line. From the above equation, it is evident that the transmitted power is a function of three parameters: the magnitude of sending and receiving end voltages, impedance and voltage angle difference. Different type of facts devices can be used to control one or more of these parameters to control the existing power system network. The fast response of FACTS devices improves the controllability of the system and hence makes the system more versatile.

FACTS technology has been developed rapidly developed in the last few years. Static Var Compensation (SVC) is a shunt device to maintain a healthy voltage profile in the system. Thyristor Controlled Series Compensation (TCSC) is a series controller used to control the line flows. The combined series-shunt controllers are the combination of separate series and shunt controllers, which are controlled in a coordinated manner. UPFC is a most comprehensive device which offers new horizons in terms of power system control, with the potential to independently control the bus voltage, active and reactive powers [19]. The UPFC consist of two converters one connected in shunt and another one is connected in series with transmission lines. The active power is exchanged among series and shunt converters through a DC link. From the literature, it is found that unified power flow controllers are very powerful and can give flexible and effective power flow control in power system.

Static Modeling of UPFC

Suppose, there is n numbers of lines connected at bus i. Let us assume that UPFC be placed at the ith end if the line k having impedance $r_{ij}+jx_{ij}$ connected between buses i and j. UPFC has 3 controllable parameters, i.e., magnitude and angle of inserted voltage (V_{s1}, φ_{s1}) in line-k and the magnitude of the current (I_q). The circuit diagram of UPFC is presented in Figure 1 [20].

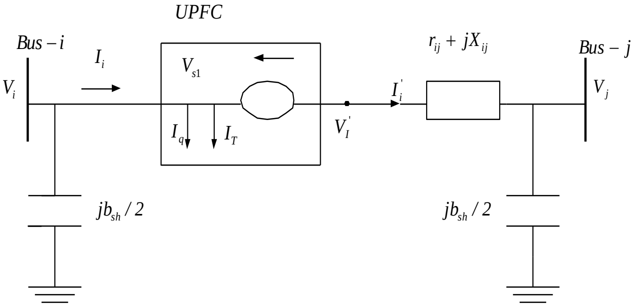

Figure 1: Circuit diagram of UPFC.

From this figure, it can be written as [20],

$$I_{ij} = (V_i + V_{s1} - V_j)y_{ij} \tag{2}$$

$$Arg(I_q) = Arg(V_i) \pm \pi/2\,, Arg(I_T) = Arg(V_i) \tag{3}$$

$$I_T^* = \frac{Re[V_{s1}I_{ij}^*]}{V_i} \tag{4}$$

The power injection at ith bus is expressed as,

$$S_i = P_i + jQ_i = V_iI_{ij}^* + V_i(I_T + jI_q)^* + \sum_{\substack{i=1\\ \neq j}}^{n} V_iI_{in}^* + V_iI_{sh}^* \tag{5}$$

Figure 2 depicts the power injection model of UPFC.

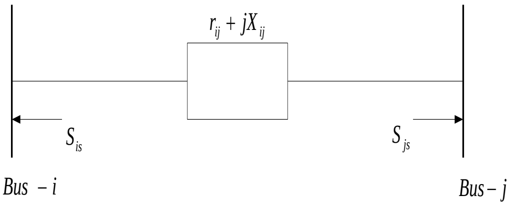

Figure 2: Injection model of UPFC.

The complex power injected at buses i and j are expressed as,

$$S_{ig} = S_i^0 - S_i = \left\{V_iV_{s1}^*y_{ij}^* + V_i(I_T + jI_q)^*\right\} \tag{6}$$

$$S_{jg} = S_j^0 - S_j = V_jV_{s1}^*y_{ij}^* \tag{7}$$

The active and reactive power injections at ith bus are expressed as,

$$P_{ig} = -Re\left\{V_iV_{s1}^*y_{ij}^*\right\} - V_iI_T^{\ *} \tag{8}$$

$$Q_{ig} = -Im\left\{V_iV_{s1}^*y_{ij}^*\right\} + V_iI_q \tag{9}$$

From Equation (4), we have

$$\begin{aligned} V_iI_T = V_{s1}^2g_{ij} + V_{s1}V_i\left[g_{ij}cos(\varphi_{s1} - \delta_i) + b_{ij}sin(\varphi_{s1} - \delta_i)\right] \\ - V_{s1}V_j\left[g_{ij}cos(\varphi_{s1} - \delta_j) + b_{ij}sin(\varphi_{s1} - \delta_j)\right] \end{aligned} \tag{10}$$

The real and imaginary values of $V_iV_{s1}^*y_{ij}^*$ can be written as,

$$Re\left(V_iV_{s1}^*y_{ij}^*\right) = V_iV_{s1}\left(g_{ij}cos(\delta_i - \varphi_{s1}) + b_{ij}sin(\delta_i - \varphi_{s1})\right) \tag{11}$$

$$Im\left(V_iV_{s1}^*y_{ij}^*\right) = V_iV_{s1}\left(g_{ij}sin(\delta_i - \varphi_{s1}) - b_{ij}cos(\delta_i - \varphi_{s1})\right) \tag{12}$$

The active and reactive power injections at ith bus is expressed as,

$$\begin{aligned} P_{ig} = -V_{s1}^2g_{ij} - 2V_{s1}V_ig_{ij}cos(\varphi_{s1} - \delta_i) + \\ V_{s1}V_j\left[g_{ij}cos(\varphi_{s1} - \delta_j) + b_{ij}sin(\varphi_{s1} - \delta_j)\right] \end{aligned} \tag{13}$$

$$\begin{aligned} Q_{ig} = V_iI_q + V_iV_{s1}[g_{ij}sin(\varphi_{s1} - \delta_i) \\ + b_{ij}cos(\varphi_{s1} - \delta_i)] \end{aligned} \tag{14}$$

Similarly, the real and reactive powers injections at jth bus is expressed as,

$$P_{jg} = V_jV_{s1}\left(g_{ij}cos(\varphi_{s1} - \delta_j) - b_{ij}sin(\varphi_{s1} - \delta_j)\right) \tag{15}$$

$$Q_{jg} = -V_jV_{s1}\left(g_{ij}sin(\varphi_{s1} - \delta_j) + b_{ij}cos(\varphi_{s1} - \delta_j)\right) \tag{16}$$

Therefore, as shown in Figure 4, the UPFC is represented as the injected complex powers S_{ig} and S_{jg} at buses i and j, respectively into the network.

LOAD FLOW EMBEDDED WITH UPFC

Generally, the Newton-Raphson (NR) method and fast decoupled load flow (FDLF) are used for the load flow with UPFC. In this paper, NR load flow is used to model the UPFC [19]. The modified Jacobian matrix (J) and power mismatch equations are deduced based on the injection model of UPFC to control the active and reactive powers and voltages magnitude in any combination. The effect of UPFC on power system can be modeled as injected power flow at two related buses and hence they have no effect on the node admittance matrix (Y). The load flow equations at ith bus for the system with *n* buses and without UPFC can be represented as,

$$P_{is} = P_{Gi} - P_{Li} = V_i \sum_{j=1}^{n} V_j (G_{ij} cos\delta_{ij} + B_{ij} sin\delta_{ij}) \tag{17}$$

$$Q_{is} = Q_{Gi} - Q_{Li} = V_i \sum_{j=1}^{n} V_j (G_{ij} sin\delta_{ij} - B_{ij} cos\delta_{ij}) \tag{18}$$

For each PV and PQ buses, the active and reactive power mismatches are expressed as,

$$\Delta P_i = P_{is} - V_i \sum_{j=1}^{n} V_j (G_{ij} cos\delta_{ij} + B_{ij} sin\delta_{ij}) \tag{19}$$

$$\Delta Q_i = Q_{is} - V_i \sum_{j=1}^{n} V_j (G_{ij} sin\delta_{ij} - B_{ij} cos\delta_{ij}) \tag{20}$$

The power mismatch equations at buses k and p are expressed as,

$$\Delta P_k = P_{ks} - P_{kg} - V_k \sum_{j=1}^{n} V_j (G_{kj} cos\delta_{kj} + B_{kj} sin\delta_{kj}) \tag{21}$$

$$\Delta Q_k = Q_{ks} - Q_{kg} - V_l \sum_{j=1}^{n} V_j (G_{kj} sin\delta_{kj} - B_{kj} cos\delta_{kj}) \tag{22}$$

$$\Delta P_p = P_{ps} - P_{pg} - V_p \sum_{j=1}^{n} V_j (G_{pj} cos\delta_{pj} + B_{pj} sin\delta_{pj}) \tag{23}$$

$$\Delta Q_p = Q_{ps} - Q_{pg} - V_p \sum_{j=1}^{n} V_j (G_{pj} sin\delta_{pj} - B_{pj} cos\delta_{pj}) \tag{24}$$

The mismatch equations in matrix form is expressed as,

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = [J_1] \begin{bmatrix} \Delta\delta \\ \Delta V/V \end{bmatrix} + [J_2] \begin{bmatrix} \Delta\delta \\ \Delta V/V \end{bmatrix} \tag{25}$$

$$[J] = [J_1] + [J_2] \tag{26}$$

STATE ESTIMATION PROBLEM EMBEDDED WITH UPFC

The state vector of an electric network includes the complex voltages at the buses. Unmeasured transformer tap settings may also be included into the state vector. The measurement vector consists of power injections, power flows, current and voltage magnitudes and transformer tap settings. However, for the SE problem embedded with UPFC, the control parameters of UPFC, i.e., magnitude and angle of inserted voltage (V_{s1}, φ_{s1}) in line-k and the magnitude of the current (I_q), are included in the state vector set. The static state estimator measurement model is represented by,

$$z = h(x) + \epsilon \tag{27}$$

The error-free data is modeled as the equality constraints, and they are represented as,

$$g(x)=0 \tag{28}$$

The limits on some network variables are modeled as inequality constraints, and they are represented as,

$$f(x) \le 0 \tag{29}$$

The objective of SE is to minimize the weighted squared error between the calculated and measured quantities. By considering system is observable and with m>n, the SE problem is formulated as,

$$\min \frac{1}{2} [z - h(x)]^T R^{-1} [z - h(x)] \tag{30}$$

Subject to the conventional SE and UPFC embedded SE equality and inequality constraints.

Equality constraints:

These are the active reactive power balance equations, and they are expressed as,

$$P_i = \sum_{m=1}^{N_b} V_i V_m (g_{im} \cos\delta_{im} + b_{im} \sin\delta_{im}) = 0 \tag{31}$$

$$Q_i = \sum_{m=1}^{N_b} V_l V_m (g_{lm} \sin\delta_{lm} - b_{lm} \cos\delta_{lm}) = 0 \tag{32}$$

Equality constraints due to UPFC:

During the steady state operation of UPFC (by neglecting the UPFC losses), it doesn't absorbs or injects active power into the system. Hence, the sum of active powers injected to the end buses of UPFC inserted should be zero. It is expressed as [20],

$$P_{ig}+P_{jg}=0 \tag{33}$$

***Inequality Constraints**:*

The bus voltage magnitudes are limited by,

$$V_i^{\min} \le V_i \le V_i^{\max} \tag{34}$$

The phase angle at each bus is limited by,

$$\delta_i^{\min} \le \delta_i \le \delta_i^{\max} \tag{35}$$

The line flow limits are expressed as,

$$P_{li}^{\max} \geq P_{li} \qquad (36)$$

The constraint on reactive power generation is expressed as,

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \qquad (37)$$

Inequality constraints due to UPFC:

The control parameters of UPFC must be within their limits. The voltage magnitude (V_T) and phase angle (ϕ_T) of series voltage of UPFC must lie within their limits. They are expressed as,

$$0.5 \geq \bar{V}_{s1max} \geq 0 \qquad (38)$$

$$\bar{I}_{q\max} \geq 0 \qquad (39)$$

$$0 \leq \bar{V}_{s1} \leq \bar{V}_{s1max} \qquad (40)$$

$$\bar{\mathrm{I}}_{\mathrm{q\,min}} \leq \bar{\mathrm{I}}_{\mathrm{q}} \leq \bar{\mathrm{I}}_{\mathrm{q\,max}} \qquad (41)$$

$$0 \leq \varphi_{s1} \leq 2\pi \qquad (42)$$

The above objective function is solved using the GSO and the description of GSO is presented next:

GLOWWORM SWARM OPTIMIZATION (GSO) ALGORITHM

GSO [21-22] is a novel swarm optimization algorithm which is developed from the natural glowworm's activities in the night. The Glowworms exercise in group in nature, their interaction and inter-attraction with each other by one's luciferin. If the glowworm emits luciferinmore light, it can attract more glowworms move toward it. Through simulate this natural phenomena, combined with the characteristics of natural glowworm populations, each glowworm at the owns field of view in search for the glowworm which release the strongest luciferin, also move to the strongest glowworm. Recently, this GSO has been successfully applied to various optimization problems such as, multi-modal, multi-source position, multi-source tracking, collective robotics and harmful gas leak location, etc. [23-24].

Basic Glowworm Swarm Optimization:

In the glowworm algorithm, physical entities that are randomly distributed in the workspace. The agents in the glowworm algorithm carry a luminescence quantity called *luciferin*along with them. Agents are thought of as glowworms that emit a light whose intensity is proportional to the associated luciferin and have a variable decision range r^i_d bounded by a circular sensor range $rs(0 < r^i_d < r^i_s\ )$. Each glowworm is attracted by the brighter glow of other neighboring glowworms.

Luciferin-update phase*:* During the luciferin update phase, each glowworm adds, to its previous luciferin level, a luciferin quantity proportional to the measured value of the sensed profile at that point. In the case of a function optimization problem, this would be the value of the objective function at that point [25]. The luciferin update rule is expressed as,

$$\ell_j(t+1)=\max\{0,(1-\rho)\,\ell_j(t) + \gamma J_j(t+1)\} \qquad (43)$$

Movement-phase: During this phase, each glowworm decides, using a probabilistic mechanism, to move towards a neighbor that has a luciferin value more than its own. That is, they are attracted to neighbors that glow brighter. For each glowworm i, the probability of moving towards a neighbor j is expressed as,

$$P_j(t) = \frac{l_j(t)}{\Sigma_{k\in N_i(t)} l_k(t)} \qquad (44)$$

The discrete-time model of the glowworm movements can be expressed as,

$$x_i(t+1) = x_i(t) + s\,(\frac{x_j\,(t) - x_i(t)}{||x_i(t) - x_i(t)||}) \qquad (45)$$

Local-decision range update rule: When the glowworms depend on only local information to decide their movements, it is expected that the number of peaks captured would be a strong function of the radial sensor range. A suitable function is chosen to adaptively update the local-decision domain range of each glowworm, and it is expressed as,

$$r_d^i(t+1) = \min\left[r_s, max\left[0, r_d^i(t) + \beta(n_t - |N_i(t)|)\right]\right] \qquad (46)$$

The description of GSO algorithm is presented next:

Glowworm Swarm optimization Algorithm:

Step 1: Read the input data.

Step 2: Select the parameters of GSO algorithm.

Step 3: Initialize local decision range r_o, initial luciferin value ℓ_o.

Step 4: Initialize the glowworm within the limits of each variable.

Step 5: Run the SE with UPFC, and determine the luciferrin value of all glowworms.

Step 6: Determine the neighborhood glowworms having brighter glow and are in the local decision range.

Step 7: Determine the probability of glowworm moving towards a neighbor.

Step 8: Update the glowworm movement and check the limits.

Step 9: Update the local decision range of all glowworms.

Step 10: Repeat the Steps 5 to 9, until the maximum number of iterations are reached.

RESULTS AND DISCUSSION

In this paper, IEEE 14 bus test system [26-27] is used to test the effectiveness of the proposed SE approach embedded with UPFC. The proposed SE algorithm is solved in MATLAB R2016a. Here, the UPFC is placed between the buses 6 and 12. As mentioned, the UPFC is inserted in the system by modifying the existing the NR power flow. The considered parameters of UPFC are V_{s1}, φ_{s1} and I_q are 0.1, 0.5 and 0.1 respectively. The GSO parameters selected are: Luciferin decay constant (ρ) is 0.95, radial range of luciferin sensor is

0.005, constant parameter (β) is 0.0005, luciferin enhancement constant (γ) is 0.95, neighborhood threshold is 4, and the local decision domain range is 0.0005.

The measurement set for the IEEE 14 bus system is depicted in Figure 3. Table 1 presents the injection and line flow measurements for IEEE 14 bus test system.

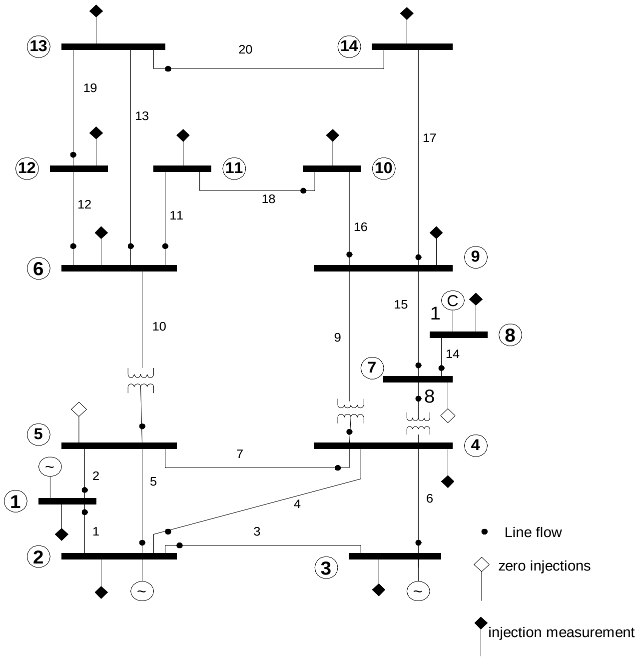

Figure 3: Schematic diagram with measurement set for IEEE 14 bus test system.

In this paper, first the load flow is carried out by with and without UPFC in the IEEE 14 bus test system. For the simulation studies, the UPFC is placed line number 12 (i.e., the line connected between the buses 6 and 12). Table 2 presents the bus voltage magnitudes and phase angles for IEEE 14 bus system with and without UPFC in the system. Table 3 presents the line flows in the system. From these two tables, it can be observed that the voltages are improved and the line flows are optimized. The active and reactive power losses obtained without UPFC are 13.41MW and 43.02MVAR, respectively. Whereas, the active and reactive power losses obtained with UPFC are 12.24MW and 38.53MVAR, respectively. From these results, it can be observed that the active and reactive power losses are reduced by placing the UPFC in the system.

Table 1: Injection and line flow measurements for IEEE 14 bus system.

Injection measurements	Bus number	P (in p.u.)	Q (in p.u.)	Line flow measurements	From bus -To bus	P (in p.u.)	Q (in p.u.)
z_1	1	1.52	-0.058	z_{13}	1-2	1.0434	-0.0090
z_2	2	0.18	-0.250	z_{14}	1-5	0.4886	0.0068
z_3	3	-.9522	-0.16	z_{15}	2-3	0.6171	0.0609
z_4	4	-0.1583	-0.0039	z_{16}	2-4	0.3372	-0.0613
z_5	6	-0.1954	-0.234	z_{17}	2-5	0.2537	-0.0447
z_6	8	0.1496	0.0017	z_{18}	3-4	-0.3436	-0.0251
z_7	9	0.0883	0.0210	z_{19}	4-5	-0.3594	0.0869
z_8	10	-0.0057	-0.048	z_{20}	4-7	0.2105	-0.1870
z_9	11	-0.0963	-0.1603	z_{21}	4-9	0.1218	-0.0846
z_{10}	12	-0.5602	0.1396	z_{22}	5-6	0.3675	-0.1954
z_{11}	13	-0.1978	-0.058	z_{23}	6-11	0.0347	0.0307
z_{12}	14	-0.1173	-0.0508	z_{24}	6-12	0.2758	0.1488
---	---	---	---	z_{25}	6-13	0.3149	0.1104
---	---	---	---	z_{26}	7-8	0	0.0000
---	---	---	---	z_{27}	7-9	0.2100	-0.0834
---	---	---	---	z_{28}	9-10	0.0914	0.0464
---	---	---	---	z_{29}	9-14	0.2118	0.0532
---	---	---	---	z_{30}	10-11	0.0001	-0.0124
---	---	---	---	z_{31}	12-13	-0.1267	-0.0285
---	---	---	---	z_{32}	13-14	0.0434	0.0084

Table 2: Load flow results (voltages and phase angles) for IEEE 14 bus system with and without UPFC.

Bus Number	**Without UPFC**		**With UPFC**	
	Voltage (p.u.)	**Angle (degree)**	**Voltage (p.u.)**	**Angle (degree)**
1	1.06	0	1.06	0
2	1.046	-4.82	1.047	-3.15
3	1.012	-12.45	1.023	-9.69
4	1.024	-9.99	1.038	-6.42
5	1.025	-8.46	1.039	-5.58
6	1.071	-13.89	1.088	-10.02
7	1.065	-13.56	1.076	-8.71
8	1.092	-13.25	1.094	-8.72
9	1.056	-14.65	1.072	-9.81
10	1.051	-14.86	1.073	-10.14
11	1.054	-14.56	1.075	-10.18
12	1.051	-14.78	1.068	-12.70
13	1.051	-14.85	1.059	-11.71
14	1.031	-15.72	1.039	-12.38

Table 3: Line flows for IEEE 14 bus system with and without UPFC.

Line number	**From bus (i)**	**To bus (j)**	**Without UPFC**	**With UPFC**
			Line flow S_{ij} (in p.u.)	**Line flow S_{ij} (in p.u.)**
1	1	2	1.056+j0.074	1.0406-j0.009
2	1	5	0.494+j0.056	0.487+j 0.008
3	2	3	0.621+j0.078	0.619+j0.065
4	2	4	0.348-j0.034	0.338-j0.064
5	2	5	0.265-j0.014	0.253-j0.048
6	3	4	-0.339-j0.013	-0.345-j0.024
7	4	5	-0.356+j0.097	-0.358+j0.088
8	4	7	0.209-j 0.161	0.206-j0.187
9	4	9	0.118-j0.075	0.116-j0.087
10	5	6	0.356-j0.115	0.342-j0.196
11	6	11	0.017+j0.008	0.036+j0.035
12	6	12	0.077+j0.023	0.276+j0.149
13	6	13	0.178+j0.064	0.315+j0.113
14	7	8	0.00-j0.00	-0.00+j0.00
15	7	9	0.215-j0.065	0.218-j0.087
16	9	10	0.109+j0.069	0.097+j0.048
17	9	14	0.198+j0.058	0.217+j0.054
18	10	11	0.019+j0.009	0.002-j0.015
19	12	13	0.017+j0.005	-0.127-j0.029
20	13	14	0.057+j0.005	0.048+j0.009

Table 4: State estimation results using the proposed approach.

Bus number	**True States**		**Proposed Approach**	
	V (in p.u.)	**Angle (in deg.)**	**V (in p.u.)**	**Angle (in deg.)**
1	1.063	0	1.0629	0
2	1.048	-4.961	1.0478	-4.9607
3	1.013	-12.744	1.0128	-12.7437
4	1.024	-10.511	1.0238	-10.509
5	1.032	-9.101	1.0316	-9.1008
6	1.070	-15.205	1.0695	-15.2049
7	1.054	-13.568	1.0536	-13.5676
8	1.088	-13.584	1.0875	-13.5839
9	1.038	-15.180	1.0379	-15.1798
10	1.035	-15.458	1.0352	-15.4575
11	1.049	-15.453	1.0489	-15.4528
12	1.081	-14.454	1.0808	-14.4536
13	1.053	-15.452	1.0531	-15.4518
14	1.028	-16.342	1.0278	-16.3418

Table 4 presents the SE results using the proposed approach and the true states of the system. From this Table, it can be observed that the proposed approach estimates the state variables with more accuracy and negligible error in comparison with the true states of the system.

From the above simulation results, it can be concluded that the voltages improve while the overall system losses reduce along with control of line power by placing a UPFC in the system. And also, the proposed approach estimates the state variables with more accuracy and negligible error in comparison with the true states of the system.

CONCLUSIONS

In this paper, the Glowworm swarm optimization (GSO) has been applied for solving the state estimation (SE) problem including the unified power flow controller (UPFC) using the power injection model. The states of a power system are required to be estimated in real time. The enforcing of limits and equality constraints increases the quality of state estimation results and produces the solution, which reflects correctly the physical behavior of a power system. The simulation studies are carried out on IEEE 14 bus test system to test the effectiveness of the proposed SE algorithm. From the simulation results, it can be concluded that the voltages improve while the overall system losses reduce along with control of line power by placing a UPFC in the system. And also, the proposed approach estimates the state variables with more accuracy and negligible error in comparison with the true states of the system.

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