Journal Homepage: - www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

ISSN NO. 2320-5407

Article DOI: 10.21474/IJAR01/18742
DOI URL: http://dx.doi.org/10.21474/IJAR01/18742

RESEARCH ARTICLE

OPTIMAL PLACEMENT OF UNIFIED POWER FLOW CONTROLLER USING PARTICLE SWARM OPTIMIZATION TECHNIQUE

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Manuscript Info

Manuscript History
Received: 19 March 2024
Final Accepted: 25 April 2024
Published: May 2024

Key words:-
Power Loss, Gauss-Seidel Method, UPFC, Load Growth, PSO Algorithm, Voltage Profile, FACTS

Abstract

The load growth in recent times due to advancements in technology and population increase has led to shortage of reactive power in the power system resulting in key issues such as voltage instability, large line losses, power outages among others. In this work, Particle Swarm Optimization (PSO) technique was used for optimal placement of Unified Power Flow Controller (UPFC) for power loss minimization using the IEEE 6-bus system as a test network. The load flow analysis was performed using Gauss-Seidel iterative method with and without inclusion of PSO-based UPFC. The PSO algorithm was used to find the optimum point for UPFC location and determined using the line with the least active power loss among other lines randomly selected by the PSO algorithm, with $0.95 \leq V \leq 1.10$ p.u defined as the voltage statutory limit. The simulation results revealed that the optimum point obtained was line 4-5, and the voltage profile were within the statutory limit with and without optimally placed UPFC. The total active power loss reduced from 495.5 to 273.9 MW, giving a reduction of 44.72 % with optimally placed UPFC. The total reactive power loss equally reduced from 1439 to 936.2 MVAr, producing a reduction of 34.94 % with optimally placed UPFC. These results obtained showed that PSO-based UPFC placement is suitable for power loss minimization and enhancement of the system voltage profile.

Introduction:-

There are three major units that constitute the electrical power system which are the generation, transmission, and distribution systems (Adebisi et al., 2021a). Power losses occur when the electrical energy generated are transmitted through transmission lines because of long-distance transmission (Adebisi et al., 2018; Patil et al., 2020). Other losses occur due to inadequate conductor sizing, line overloading, corona effect among others (Gupta, 2011). The recent load growth on power networks has further affected the system's performance, thereby making it inefficient. There are new technological methods, one of which is the use of Flexible Alternating Current Transmission System (FACTS) to minimize or reduce line losses to the barest minimum thereby improving the efficiency of the existing transmission networks.

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FACTS are power electronics-based devices which increases the capacity of the existing transmission network, offers power flow control flexibility, controllability, security of supply among others. Among all the solutions proffered to arrest the discomfort in power system, FACTS devices proved an effective remedy in optimizing the system available capacity, thereby increasing the system load ability, and enhancing the voltage profile (Adebisi et al., 2021b; Marefatjou and Soltani, 2013; Amin et al., 2021). FACTS devices are not cheap, and this explains the reason it is not widely used. It must also be optimally located on the power system network to prevent waste of energy and maximizing its available capacity, thereby providing maximum adequate compensation.

This work seeks to minimize power losses in transmission system using PSO based approach for optimal placement of UPFC. UPFC can control all the power flow parameters, and the parameters of control are the bus voltage, phase angle and line impedance/reactance (Mohanty and Barik, 2012). It synchronizes and combines the feature of two voltage source converters which are Static Synchronous Compensators (STATCOM) and Static Synchronous Series Compensator (SSSC) and exchange active and reactive power with the transmission lines. STATCOM and SSSC are connected in parallel and series through a shunt and series coupling transformers to the transmission lines respectively (Negi et al., 2017; Yugeswari et al., 2023). UPFC offers major benefits such as voltage stability, reduction in line losses, security of supply among others. The circuit diagram of UPFC is shown in Figure 1.

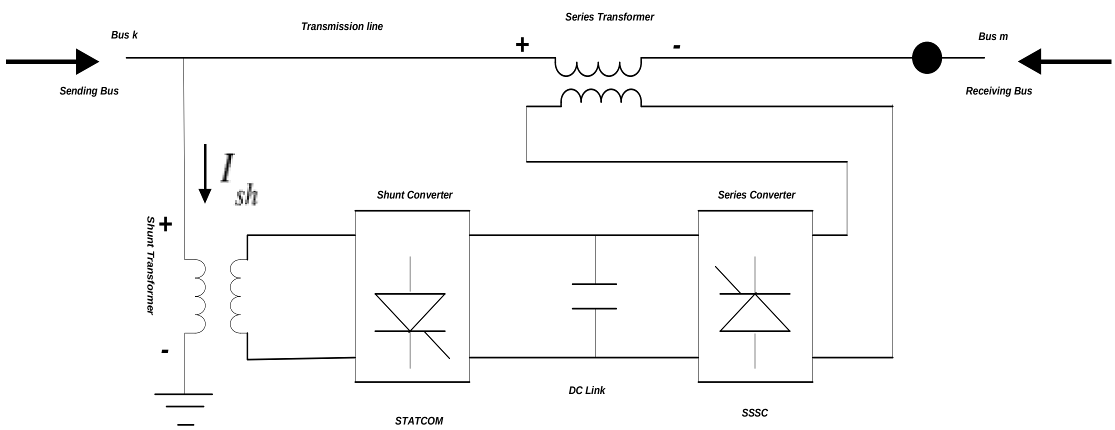

Figure 1:- Circuit diagram of UPFC.

Material and Methods:-

The load flow equations modelling the steady state performance of power systems were formulated without compensation and modified through inclusion of UPFC (with compensation). This was then integrated into the PSO algorithm for optimal placement of UPFC. The responses of the system without and with PSO-based UPFC were then analyzed and presented, and inferences were made.

Formulation of Load Flow Equations

This work considered a transmission line represented by a π model equivalent network shown in Figure 2 for the formulation of load flow equations.

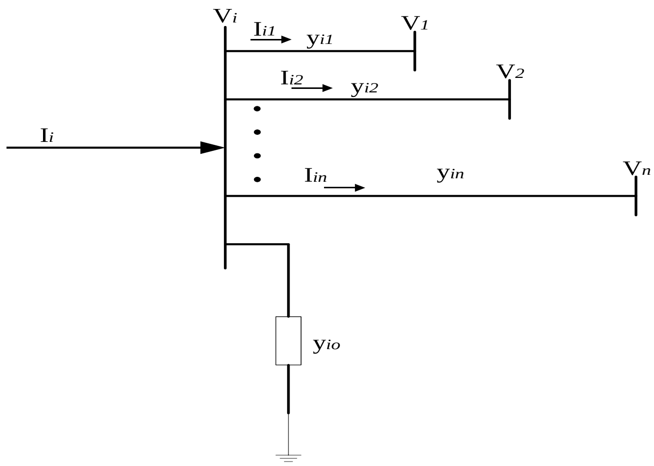

Figure 2:- A transmission line model.

Applying Kirchhoff's current law to bus i in Figure 2 gives Equation (1):

$$I_i = I_{i0} + I_{i1} + I_{i2} + \cdots + I_{iN} \quad (1)$$

The sum-total nodal current (I_i) of bus i in Figure 2 can be written as Equation (2) with the use of Ohm's law, and rearranging Equation (2) gives Equation (3):

$$I_i = y_{i0}V_i + y_{i1}(V_i - V_1) + y_{i2}(V_i - V_2) + \cdots + y_{iN}(V_1 - V_N) \quad (2)$$

$$I_i = (y_{i0} + y_{i1} + y_{i2} + \cdots + y_{iN})V_i - y_{i1}V_1 - y_{i2}V_2 - \cdots - y_{iN}V_N \quad (3)$$

The self-admittance (Y_{ii}) and mutual admittance (Y_{ik}) between bus i and k, is defined by Equation (4):

$$\left.\begin{array}{l} Y_{ii} = y_{i0} + y_{i1} + y_{i2} + \cdots + y_{iN} \\ Y_{i1} = -y_{i1} \\ Y_{i2} = -y_{i2} \\ \vdots \quad \vdots \quad \vdots \\ Y_{iN} = -y_{iN} \end{array}\right\} \quad (4)$$

By substituting Equation (4) into Equation (3) gives Equation (6):

$$I_i = Y_{ii}V_i + Y_{i1}V_1 + Y_{i2}V_2 + \cdots + Y_{iN}V_N \quad (5)$$

$$I_i = Y_{ii}V_i + \sum_{\substack{k=1 \\ k \neq i}}^{N} Y_{ik}V_k \quad (6)$$

where I_i, V_i and V_k denote current injected and voltage of bus i and k respectively, Y_{ik} and Y_{ii} denote mutual and self-admittance.

The injected complex power into bus i is given by Equation (7) and via complex conjugate modified into Equation (8) which further simplified into Equation (9) with the use of Equation (6) (Adebisi *et al*., 2017; Ohanu *et al*., 2022; Gupta, 2011):

$$S_i = P_i + jQ_i = V_i I_i^* \quad (7)$$

$$S_i^* = P_i - jQ_i = V_i^* I_i \quad (8)$$

$$\frac{P_i - jQ_i}{V_i^*} = Y_{ii}V_i + \sum_{\substack{k=1 \\ k \neq i}}^{N} Y_{ik}V_k \quad (9)$$

where S_i, P_i and Q_i denote apparent, real, and reactive power at bus i respectively, V_i^* and I_i^* denote complex conjugate of bus i voltage and current.

Making V_i the subject of the formula in Equation (9) produced Equation (10), and with the application of Gauss-Seidel method produced Equation (11):

$$V_i = \frac{1}{Y_{ii}}\left[\frac{P_i - jQ_i}{V_i^*} - \sum_{\substack{k=1\\k\neq i}}^{N} Y_{ik}V_k\right];\ i = 2,\ 3,\ldots,N \tag{10}$$

$$V_i^{r+1} = \frac{1}{Y_{ii}}\left[\frac{P_i - jQ_i}{\left(V_i^r\right)^*} - \sum_{\substack{k=1\\k\neq i}}^{N} Y_{ik}V_k^r\right];\ i = 2,\ 3,\ldots,N \tag{11}$$

where i and r denote the number of buses and iterations

By separating Equation (10) into real and imaginary parts yields Equations (12) and (13) respectively:

$$P_i = |V_i|^2 G_{ii} + \sum_{\substack{k=1\\k\neq i}}^{N} |Y_{ik}V_iV_k| cos(\theta_{ik} + \delta_k - \delta_i) \tag{12}$$

$$Q_i = |V_i|^2 B_{ii} + \sum_{\substack{k=1\\k\neq i}}^{N} |Y_{ik}V_iV_k| sin(\theta_{ik} + \delta_k - \delta_i) \tag{13}$$

where G_{ii} is self-conductance, δ_i is phase angle, B_{ii} is self-susceptance, and θ_{ik} is phase difference.

The net value of active and reactive power at bus i can be calculated using Equation (14), while the voltage-drop on the line between bus i and k can be calculated using Equation (15):

$$\left.\begin{aligned} P_i &= P_{G,i} - P_{D,i} \\ Q_i &= Q_{G,i} - Q_{D,i} \end{aligned}\right\} \tag{14}$$

$$\Delta V_{ik} = |V_i - V_K| \tag{15}$$

where P_i and Q_i are net value of real and reactive power, $P_{G,i}$ and $Q_{G,i}$ are active and reactive power generated, $P_{D,i}$ and $Q_{D,i}$ are active and reactive power demand, and ΔV_{ik} is voltage drop.

The active and reactive line losses between bus i and k were obtained from the mathematical manipulation of Equations (8) and (15) as Equations (16) and (17) respectively:

$$P_{Lik} = G_{ik}(V_i^2 + V_k^2 - 2V_iV_k\cos\theta_m) \tag{16}$$

$$Q_{Lik} = -V_i^2 B_{ik} - V_k^2 B_{ik} - 2B_{ik}V_iV_k\cos\theta_m \tag{17}$$

Load Flow Model of Unified Power Flow Controller

The UPFC model equivalent circuit is shown in Figure 3. The load flow models of the controller are derived and expressed by Equations (18) to (27) (Namrata, 2014):

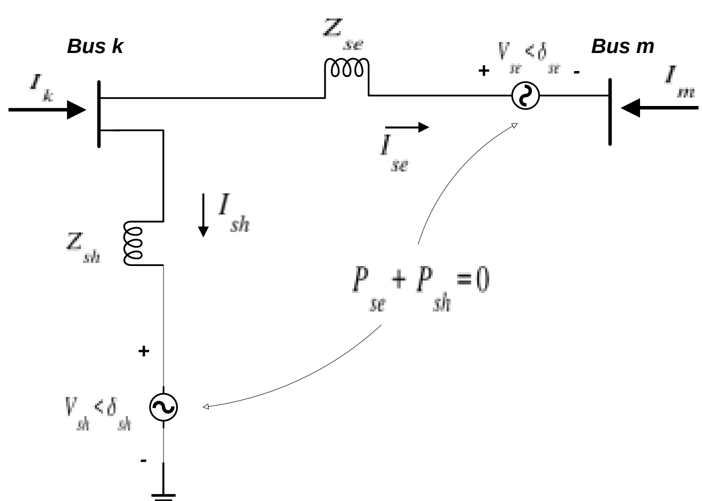

Figure 3:- UPFC model.

UPFC has two voltage source converters connected between two buses, one in series and the other in shunt. From Figure 3, Z_{se} and Z_{sh} represent the series and shunt impedances respectively, with subscript se representing series and subscript sh representing shunt.

The shunt (E_{sh}) and series (E_{se}) voltage sources are given by Equations (18) and (19) respectively:

$$E_{sh} = V_{sh}\left(\cos\delta_{sh} + j\sin\delta_{sh}\right) \quad (18)$$
$$E_{se} = V_{se}\left(\cos\delta_{se} + j\sin\delta_{se}\right) \quad (19)$$

where V_{sh} is controllable voltage magnitude with constraint of $(V_{sh\,min} \leq V_{sh} \leq V_{sh\,max})$, δ_{sh} is controllable phase angle with constraint of $\left(0 \leq \delta_{sh} \leq 2\pi\right)$, V_{se} is controllable voltage magnitude with constraint of $\left(V_{se\,min} \leq V_{se} \leq V_{se\,max}\right)$, and δ_{se} is controllable phase angle with constraint of $\left(0 \leq \delta_{se} \leq 2\pi\right)$.
Using the UPFC model shown in Figure 3, the real and reactive power Equations at bus k are given by Equations (20) and (21), and at bus m, are given by Equations (22) and (23) respectively:

$$P_k = V_k^2 G_{kk} + V_k V_m\left[G_{km}\cos\left(\theta_k - \theta_m\right) + B_{km}\sin\left(\theta_k - \theta_m\right)\right] + V_k V_{se}\left[G_{km}\cos\left(\theta_k - \delta_{se}\right) + B_{km}\sin\left(\theta_k - \delta_{se}\right)\right] + V_k V_{sh}\left[G_{sh}\cos\left(\theta_k - \delta_{sh}\right) + B_{sh}\sin\left(\theta_k - \delta_{sh}\right)\right] \quad (20)$$

$$Q_k = -V_k^2 B_{kk} + V_k V_m\left[G_{km}\sin\left(\theta_k - \theta_m\right) - B_{km}\cos\left(\theta_k - \theta_m\right)\right] + V_k V_{se}\left[G_{km}\sin\left(\theta_k - \delta_{se}\right) - B_{km}\cos\left(\theta_k - \delta_{se}\right)\right] + V_k V_{sh}\left[G_{sh}\sin\left(\theta_k - \delta_{sh}\right) - B_{sh}\cos\left(\theta_k - \delta_{sh}\right)\right] \quad (21)$$

$$P_m = V_m^2 G_{mm} + V_m V_k\left[G_{mk}\cos\left(\theta_m - \theta_k\right) + B_{mk}\sin\left(\theta_m - \theta_k\right)\right] + V_m V_{se}\left[G_{mm}\cos\left(\theta_m - \delta_{se}\right) + B_{mm}\sin\left(\theta_m - \delta_{se}\right)\right] \quad (22)$$

$$Q_m = -V_m^2 B_{mm} + V_m V_k\left[G_{mk}\sin\left(\theta_m - \theta_k\right) - B_{mk}\cos\left(\theta_m - \theta_k\right)\right] + V_m V_{se}\left[G_{mm}\sin\left(\theta_m - \delta_{se}\right) + B_{mm}\cos\left(\theta_m - \delta_{se}\right)\right] \quad (23)$$

The real and reactive power Equations for series converter are given by Equations (24) and (25), and for shunt converter are given by Equations (26) and (27) respectively:

$$P_{se} = V_{se}^2 G_{mm} + V_{se} V_k\left[G_{km}\cos\left(\delta_{se} - \theta_k\right) + B_{km}\sin\left(\delta_{se} - \theta_k\right)\right] + V_{se} V_m\left[G_{mm}\cos\left(\delta_{se} - \delta_m\right) + B_{mm}\sin\left(\delta_{se} - \theta_m\right)\right] \quad (24)$$

$$Q_{se} = -V_{se}^2 B_{mm} + V_{se} V_k\left[G_{km}\sin\left(\delta_{se} - \theta_k\right) - B_{km}\cos\left(\delta_{se} - \theta_k\right)\right] + V_{se} V_m\left[G_{mm}\sin\left(\delta_{se} - \theta_m\right) - B_{mm}\cos\left(\delta_{se} - \theta_m\right)\right] \quad (25)$$

$$P_{sh} = -V_{sh}^2 G_{sh} + V_{sh} V_k\left[G_{sh}\cos\left(\delta_{sh} - \theta_k\right) + B_{sh}\sin\left(\delta_{sh} - \theta_k\right)\right] \quad (26)$$

$$Q_{sh} = V_{sh}^2 B_{sh} + V_{sh} V_k\left[G_{sh}\sin\left(\delta_{sh} - \theta_k\right) - B_{sh}\cos\left(\delta_{sh} - \theta_k\right)\right] \quad (27)$$

Modelling of Particle Swarm Optimization

PSO uses a swarm of particles to locally search a given space, with each particle defined by a position and a velocity vector and moves in X-Y plane. During the search process, each particle communicates with each other to find solution to the optimization problem. 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}). The particle's best location is also known as local best. As the particles move in a search space, they communicate with one another to determine the best location found so far and move in that direction (Jumaat et al., 2011). PSO advantages include its robust system, ease of implementation, and fast convergence (Marefatjou and Soltani, 2013).

The initial position and velocity vector of the ith particle in a search space is given by Equation (28) and Equation (29) respectively (Marefatjou and Soltani, 2013):

$$X_i = \left(X_{i1}, X_{i2}, X_{i3} \ldots X_{id}\right)^T \quad (28)$$
$$F_i = \left(F_{i1}, F_{i2}, F_{i3} \ldots F_{id}\right)^T \quad (29)$$

The particle's velocity and position are given by Equations (30) and (32) respectively.

$$F_i^{k+1} = w \times F_i^k + c_1 \times r_1 \times \left(P_{best\,i} - x_i^k\right) + c_2 \times r_2 \times \left(G_{best\,i} - x_i^k\right) \quad (30)$$
$$w = w_{max} - \left(\left(w_{max} - w_{min}\right) \times k\right) / k_{max} \quad (31)$$
$$x_i^{k+1} = x_i^k + LF_i^{k+1} \quad (32)$$

where 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_{max} and k are maximum and current iteration.
The location of UPFC depends on which transmission line with UPFC placement brings about the least active power loss among other lines in the power network. Therefore, the objective function is to find the optimum point for UPFC location which give the least active power loss, and is expressed as Equation (33):

$$F_{obj} = min \sum_{i=1}^{NTL} P_{Loss} \quad (33)$$

Using Equation (16) in Equation (33) yields Equation (34):

$$P_{Loss} = \sum_{i=1, j=1}^{NTL} G_{ij}\left(V_i^2 + V_j^2 - 2V_i V_j \cos\left(\theta_i - \theta_j\right)\right) \quad (34)$$

where P_{Loss} is active power loss in the system, G_{ij} is conductance of line (i, j), V_i is voltage magnitude at bus i, V_j is voltage magnitude at bus j, $\theta_i - \theta_j$ is bus angle at bus i and bus j respectively, and NTL is number of transmission lines. Subject to voltage constraints ($V_i^{min} \leq V_i \leq V_i^{max}$), branch current constraints ($I_{bij} \leq I_{bij}^{max}$), and power flow constraints.

From Equation (30), make $G_{best\ i}$ the subject of the formula give Equation (35):

$$G_{best\ i} = \frac{F_i^{k+1} - \left(w \times F_i^k + c_1 \times r_1 \times \left(P_{best\ i} - x_i^k\right)\right) + c_2 \times r_2 \times x_i^k}{c_2 \times r_2} \quad (35)$$

Each particle is a potential solution to the optimization problem. The global best (G_{best}) is directly proportional to objective function. In this case, G_{best} is taken as the objective function value itself, and is expressed as Equation (36):

$$G_{best} = min(P_{Loss}) \quad (36)$$

There is continuous iterative process in Equations (30) and (32) until all the particles converge towards the G_{best}.

The flowchart for the PSO algorithm used for the placement of UPFC is shown in Figure 4.

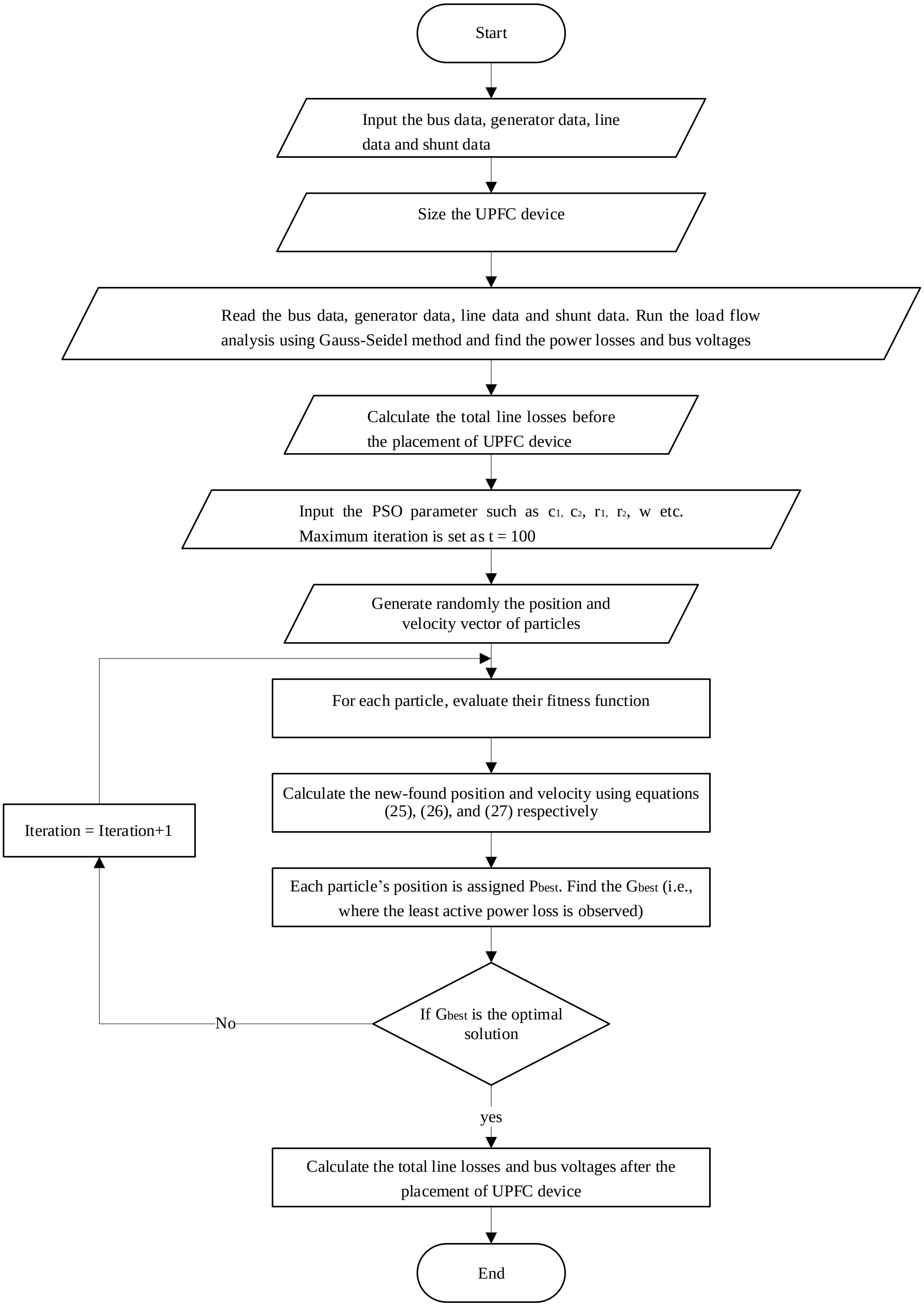

Figure 4:- Flowchart for PSO algorithm used for the placement of UPFC.

Implementation Software and Test Network

In this work, the load flow code was developed in Python environment (version 3.7), and a jupyter notebook was used to run the Python code. The test network used in this work was IEEE 6-bus system. The one-line diagram of an IEEE 6-Bus System is shown in Figure 5. It consists of six (6) buses and three (3) generation stations. The network data, generator data and transmission line data were taken from Alnaib (2020). The data is on 220 kV and 100 MVA base.

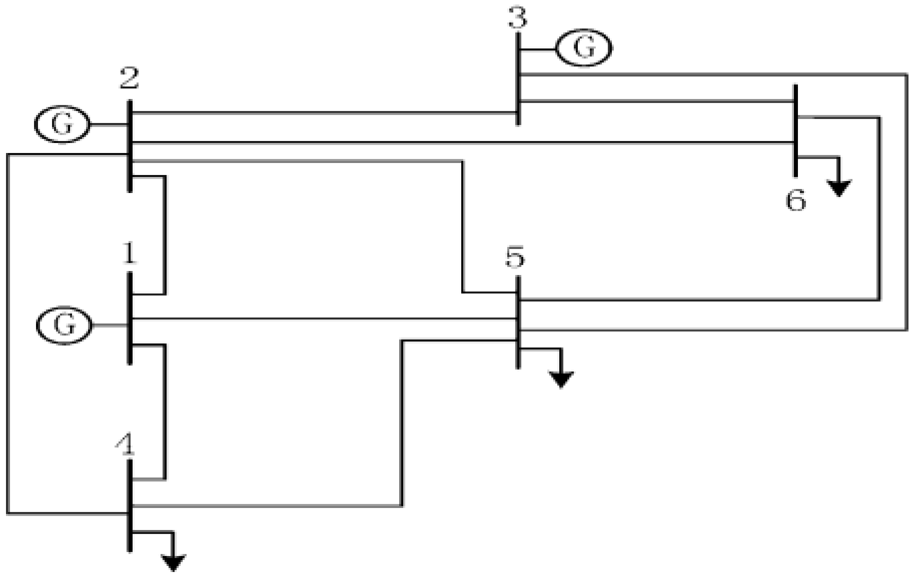

Figure 5:- IEEE 6-bus power system (Tong et al., 2017).

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 IEEE 6-bus power network are presented in this section. The parameters used for the PSO and UPFC sizing for the IEEE 6-bus power network is shown in Table 1 and Table 2 respectively.

Table 1:- The parameter value used for the PSO.

PSO Parameter	**Value**
c_1	0.1
c_2	0.2
r_1	0 to 1
r_2	0 to 1
w_{max}	0.8
w_{min}	0.2
Population size (N)	10
Maximum number of iterations	100

Table 2:- Parameters used for UPFC Design/Sizing.

UPFC Parameters	**IEEE 6 Bus**
Is	2
Ir	3
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	0.1
Vcrmin	0.001
Tvr	0.0
Tcr	[-87.13/57.3]

The PSO technique was used to find the optimal location for the UPFC device on the power system network, using active power loss as the selection criterion. The particles look for the line with UPFC placement in which the least active power loss is recorded. This is referred to as global best (G_{best}), and the UPFC device was placed/installed in this position. At G_{best} position, the effect of the compensation device (UPFC) is maximally felt in terms of having the least active and reactive power losses and enhanced voltage profile on the considered network.
The PSO algorithm has been programmed to randomly select some of the lines with UPFC placement to show the effect of UPFC device on different locations during the particle search.

The load flow results generated for IEEE 6-bus power network with UPFC placed on line 4-5 selected as the optimum point by the PSO algorithm are presented as follows:
Figure 6 shows UPFC placement at different locations on the IEEE 6-bus power network, while Figure 7 shows the comparison of the voltage profile without and with optimally placed UPFC device on line 4-5. Also, Figure 8 shows the comparison of the total active power loss without and with optimally placed UPFC, while Figure 9 shows the comparison of the total reactive power loss without and with optimally placed UPFC.

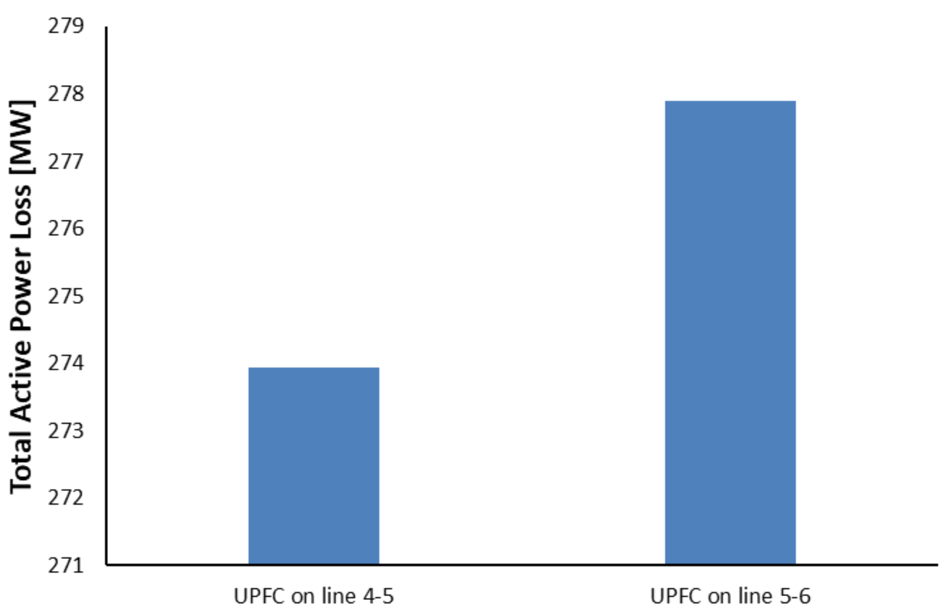

Figure 6:- Total active power loss with UPFC placement at different locations on the IEEE 6-bus power system network.

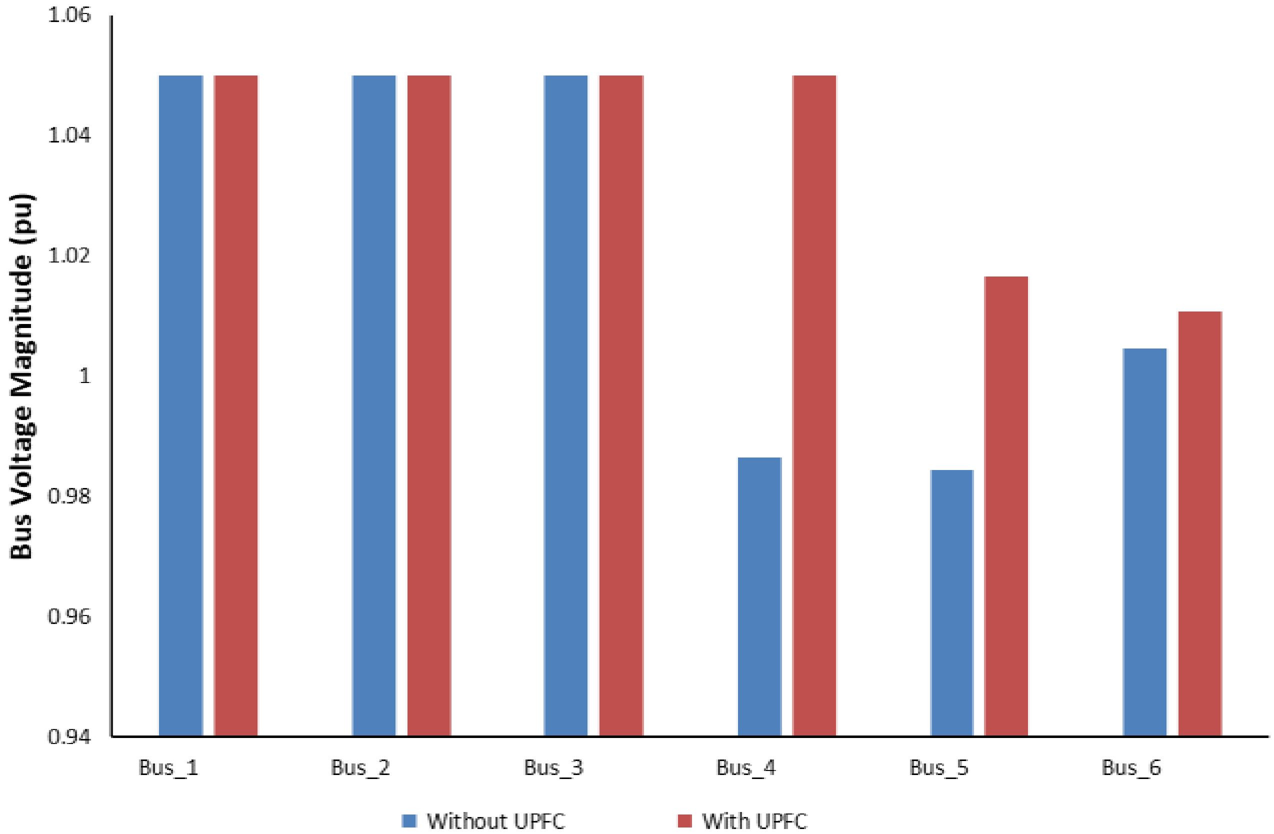

Figure 7:- Comparison of bus voltage magnitudes without and with optimally placed UPFC device on the IEEE 6-bus power system network.

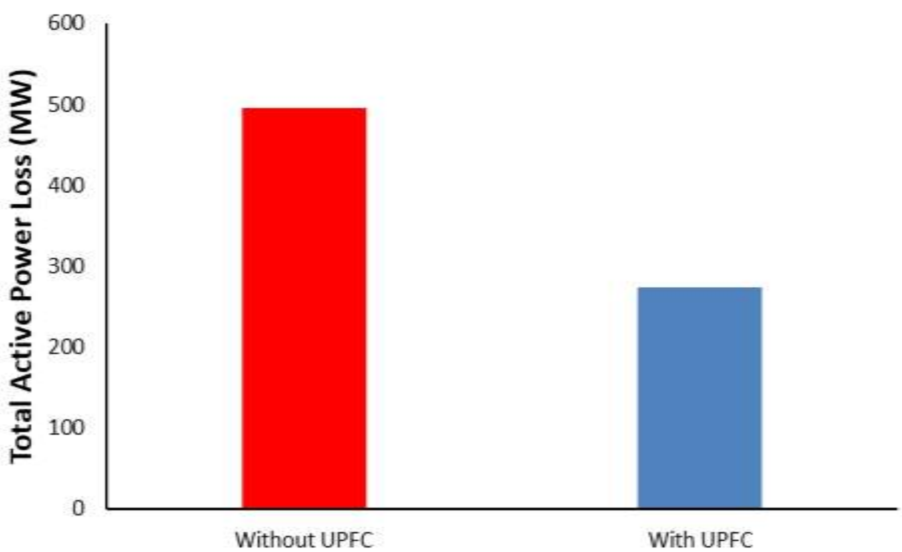

Figure 8:- Comparison of total active power loss without and with optimally placed UPFC device on the IEEE 6-bus power system network.

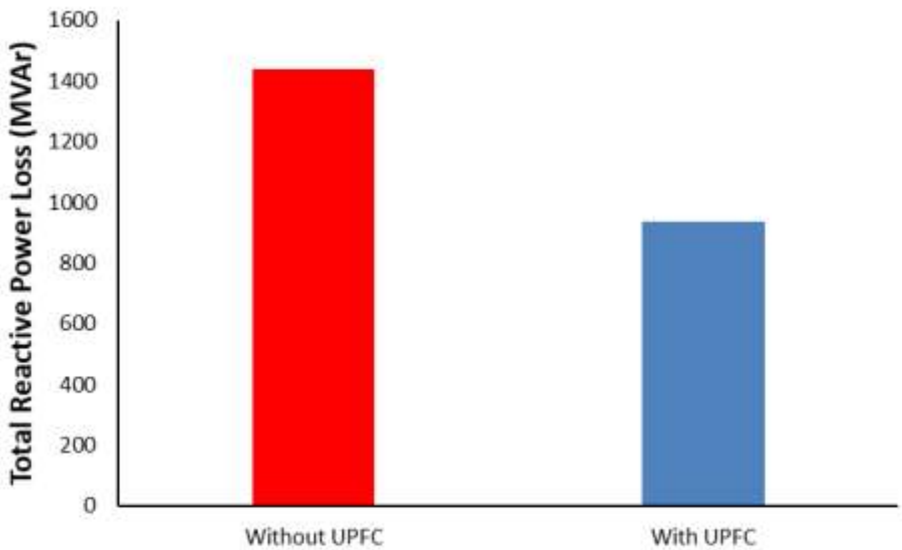

Figure 9:- Comparison of total reactive power loss without and with optimally placed UPFC device on the IEEE 6-bus power system network.

From Figure 6, the optimum point for UPFC placement as obtained from the load flow results was line 4-5. 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 $0.95 \leq V \leq 1.10$ p.u without and with optimally placed UPFC device on line 4-5.

From Figure 7, it was observed that without compensation applied to the test network, the voltage magnitude of all the buses were within the statutory limit, while with optimally placed UPFC device, the voltage magnitude of some of the buses already within the statutory limit still improved. The voltage magnitudes of buses 4, 5 and 6 improved from 0.9865, 0.9843, 1.0047 to 1.0500, 1.0165 and 1.0108 respectively.

From Figure 8, the total active power loss on IEEE 6-bus network was 495.50 MW without compensation, and reduced to 273.90 MW with optimally placed UPFC, equivalent to a percentage improvement of 44.72 %. Similarly, from Figure 9, the total reactive power loss was 1439.00 MVAr without compensation and decreased to 936.20 MVAr with UPFC optimally placed showing an improvement of 34.94 %.

The simulation results obtained from Amin et al. (2021), Mathad and Kulkarni (2020), Krishna and Reddy (2014), Amer et al. (2013) among others who have also worked on PSO technique for optimal location of UPFC using some other practical networks as case studies, reviewed that there is reduction in active and reactive power losses and enhancement of voltage profile which is in line with the results obtained from this research work.

Conclusion:-

The continual development in technology and increase in load has created a wide electricity gap between power demand and supply, leading to voltage instability, high transmission losses, frequent system collapse among others. There is a need to integrate FACTS technology into the power system network, of which benefits are improved system stability, security of supply of electricity, efficient use of the present transmission network among others. In this work, PSO technique was used for optimal placement of unified power flow controller for power loss minimization using the IEEE 6-bus system as a test network. The simulation results showed that UPFC when appropriately placed in a power system network via a suitable optimization technique such as particle swarm optimization will significantly minimize the power losses of the network.

Also, since particle swarm optimization technique is one of several possible modern optimization techniques. It will therefore be recommended that further study be conducted to examine the impacts of other modern optimization techniques such as genetic algorithm, differential evolution, evolutionary programming, ant colony among others on the power system network.

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