Optimal location of UPFC devices for minimizing Losses in Transmission Line

Ihssan A Amin\textsuperscript{1}, Dhari Y Mahmood\textsuperscript{2} and Ali H Numan\textsuperscript{3}

\textsuperscript{1} Electrical Engineering Department University of Technology Baghdad, Iraq
\textsuperscript{2} Electrical Engineering Department University of Technology Baghdad, Iraq
\textsuperscript{3} Electromechanical Engineering Department University of Technology Baghdad, Iraq

Abstract. The fast increase in world loads has made electrical networks more complex and difficult to operate within their capacities. This has contributed to many issues like the failure of the loss of the power. Flexible alternating current transmission systems (FACTS) are therefore considered to be the best solution to this problem, the Unified Power Flow Controller (UPFC) device is the most important of FACTS devices because of its ability to reduce overall line losses and increase the power system's transmission capacity. To increase the advantages of this device we need to find the optimal location for it. In the search process code to determine the optimal placement of UPFC device to minimizing losses in the transmission line in the standard Institute of Electrical and Electronic Engineers (IEEE 14 bus) test system using Particle Swarm Optimization (PSO) by using [MATLAB program/M-file]. This paper deals with the optimization of two UPFC compensator parameters in the power system with the aim of reducing losses and increasing the transmission line load limit by using a modified version of the PSO algorithm. The power system simulation results show that the UPFC's optimal location has been able to minimize the losses from the transmission line.

1. Introduction
The electric power systems in the world are usually interconnected, instead of independent power. The interconnected approach delivers electricity to customers with minimum cost at maximum reliability through utilizing load distribution, resource availability and fuel prices. Power transmission lines are one of the components of the system responsible for the transmission of energy from production centers to load centers. These lines must have maximum reliability for power transmission. With the increase in electricity demand and the need for more power transmission, new transmission lines will have to be built or existing lines equipped. The first one seems to be impractical due to problems with the power system. However, the latter is applicable and has fewer problems. The equipment is equipped with modern reactive power compensation equipment (FACTS).

2. FACT device
Since the 1960s, discussions of dynamic stability have received much attention. In certain power systems, two or more methods may need to be used simultaneously\cite{1}. But in any case, the proposed method must also be economically justified. High voltage transmission lines have an important role in improving dynamic and transient stability due to their controllability. With the advancement of power electronics and the development of high-voltage and high-voltage equipment, direct current transmission lines and alternating current flexible elements (FACTS) have been justified economically. FACTS devices have the capability of controlling the active and reactive power transmission components in lines, so controlling when these components can achieve both transient and dynamic stability modification.
3. Introduction to UPFC devise

The UPFC is a member of the second generation FACTs family devices was proposed by gyugi in 1992[2]. The latest generation of FACTS devices is a device called the UPFC with unique power and voltage control capabilities in the transmission line, effectively attenuate the transient oscillations of the power system as well as reduce energy transmission losses. In one sentence, UPFC is a versatile power transfer device that is expected to be widely used in power systems because of its unique capabilities.

This device can insert a voltage with any phase and magnitude referred to the line voltage in series with the transmission line. The UPFC consists of a three-phase transformer and a PWM converter in the series and parallel part. The active power can easily flow between the two transmission lines. The converters can exchange reactive power at the terminals independently. The controllers, provides controlling signals to the converters (IGBT gates) to provide the suitable series voltages and drawing the shunt current simultaneously. Figure (1) shown the UPFC structure[3][4].

![Figure 1. The UPFC structure](image1)

![Figure 2. UPFC system: (a) UPFC Configuration, (b) UPFC equivalent circuit](image2)
From the circuit shown in Figure (2.b), The voltages source to converters of UPFC are[5][6]:

$$E_{VR} = V_{VR}(\cos\delta_{VR} + j\sin\delta_{VR})$$  \hspace{1cm} (1)

$$E_{CR} = V_{CR}(\cos\delta_{CR} + j\sin\delta_{CR})$$  \hspace{1cm} (2)

Where $V_{VR}$ and $\delta_{VR}$ are the controllable magnitude ($V_{VR_{min}} \leq V_{VR} \leq V_{VR_{max}}$) and phase angle ($0 \leq \delta_{VR} \leq 2\pi$) of the voltage source representing the shunt converter. The magnitude $V_{CR}$ and phase angle $\delta_{CR}$ of the voltage source representing the series converter are controlled between limits ($V_{CR_{min}} \leq V_{CR} \leq V_{CR_{max}}$) and ($0 \leq \delta_{CR} \leq 2\pi$) respectively.

The phase angle of the series-injected voltage determines the mode of power flow control. "If $\delta_{CR}$ is in phase with the nodal voltage angle $\theta_k$, the UPFC regulates the terminal voltage. If $\delta_{CR}$ is in quadrature with respect to $\theta_k$, it controls active power flow, acting as a phase shifter. If $\delta_{CR}$ is in quadrature with the line current angle then it controls active power flow, acting as a variable series compensator. At any other value of $\delta_{CR}$, the UPFC operates as a combination of voltage regulator, variable series compensator, and phase shifter. The magnitude of the series-injected voltage determines the amount of power flow to be controlled." The equivalent circuit shown in Figure (2) and equations (1) and (2), the active and the reactive power equations are:

At bus k:

$$P_k = V_k^2 G_{kk} + V_k V_n [G_{kn} \cos(\theta_k - \theta_n) + B_{kn} \sin(\theta_k - \theta_n)]$$  \hspace{1cm} (3)

$$Q_k = -V_k^2 B_{kk} + V_k V_n [G_{kn} \sin(\theta_k - \theta_n) - B_{kn} \cos(\theta_k - \theta_n)]$$  \hspace{1cm} (4)

At bus n:

$$P_n = V_n^2 G_{nn} + V_n V_k [G_{nk} \cos(\theta_n - \theta_k) + B_{nk} \sin(\theta_n - \theta_k)]$$  \hspace{1cm} (5)

$$Q_n = -V_n^2 B_{nn} + V_n V_k [G_{nk} \sin(\theta_n - \theta_k) - B_{nk} \cos(\theta_n - \theta_k)]$$  \hspace{1cm} (6)

- **Series converter:**

$$P_{CR} = V_{CR}^2 G_{nn} + V_{CR} V_k [G_{kn} \cos(\delta_{CR} - \theta_k) + B_{kn} \sin(\delta_{CR} - \theta_k)]$$  \hspace{1cm} (7)

$$Q_{CR} = -V_{CR}^2 B_{nn} + V_{CR} V_k [G_{kn} \sin(\delta_{CR} - \theta_k) - B_{kn} \cos(\delta_{CR} - \theta_k)]$$  \hspace{1cm} (8)

- **Shunt converter:**

$$P_{VR} = V_{VR} V_k [G_{VR} \cos(\delta_{VR} - \theta_k) + B_{VR} \sin(\delta_{VR} - \theta_k)] - V_{VR}^2 G_{VR}$$ \hspace{1cm} (9)

$$Q_{VR} = V_{VR} V_k [G_{VR} \sin(\delta_{VR} - \theta_k) - B_{VR} \cos(\delta_{VR} - \theta_k)] + V_{VR}^2 B_{VR}$$ \hspace{1cm} (10)

where $P_k$ and $P_n$ are the active powers at bus k and bus n.
\( Q_k \) and \( Q_n \) are the reactive powers at bus \( k \) and bus \( n \).

\( P_{cr} \), \( Q_{cr} \) are the active and reactive power of series converter.

\( P_{vR} \), \( Q_{vR} \) are the active and reactive power of shunt converter.

\( V_k \) and \( V_n \) are the voltage magnitudes at bus \( k \) and bus \( n \).

\( \theta_k \) and \( \theta_n \) are the power angles at bus \( k \) and bus \( n \).

\( G_{nk} \) and \( G_{kn} \) are the conductance of the line between bus \( k \) and bus \( n \).

\( B_{hn} \) and \( B_{kk} \) are the substations at bus \( k \) and bus \( n \).

\( B_{nk} \) and \( B_{kn} \) are the conductance of the line between bus \( k \) and bus \( n \).

The converters of UPFC are assumed lossless converter values in voltage sources model, this shows that both converters will not be involved in generation (or absorbing) power for its losses, and the demanded of active power by the series converter at its output is supplied from the (AC) power system by the shunt converters via the common \((D.C)\) link. The voltage of the capacitor \( V_{dc} \) of a \((D.C)\) link will remain constant. Thus, the active power supplied to the shunt converter, \( P_{cr} \) equals the active power demanded by the series converters, \( P_{vR} \). Then the following constraint on equality must be guaranteed.

\[ \Delta P_{bb} = P_{vR} + P_{cr} = 0 \]  

Moreover, if the connecting transformers are supposed to hold no resistance, then the active power on bus \( k \) equals the active powers on bus \( n \).

\[ P_{vR} + P_{cr} = P_k + P_n = 0 \]  

The UPFC power equations, in linearized form, have combined with the (A.C) network equations. For the situation where UPFC dominates the following parameters:

1) Voltage magnitude at the shunt converter terminal (bus \( k \)).
2) Active power flow from bus \( n \) to bus \( k \).
3) Reactive power injected at bus \( n \), and taking bus \( n \) to be a PQ bus, then, the linearized form of this combination of equations can be written as:

\[
\begin{bmatrix}
\Delta P_k \\
\Delta P_n \\
\Delta Q_k \\
\Delta Q_n \\
\Delta P_{nk} \\
\Delta Q_{nk} \\
\Delta P_{bb}
\end{bmatrix} =
\begin{bmatrix}
\frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial \theta_n} & \frac{\partial P_k}{\partial V_{vR}} & V_n & \frac{\partial P_k}{\partial V_n} & \frac{\partial P_k}{\partial \delta_{CR}} & \frac{\partial P_k}{\partial \delta_{VR}} \\
\frac{\partial P_n}{\partial \theta_k} & \frac{\partial P_n}{\partial \theta_n} & 0 & \frac{\partial P_n}{\partial V_n} & \frac{\partial P_n}{\partial V_n} & \frac{\partial P_n}{\partial \delta_{CR}} & \frac{\partial P_n}{\partial \delta_{VR}} \\
\frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial \theta_n} & \frac{\partial Q_k}{\partial V_{vR}} & \frac{\partial Q_k}{\partial V_n} & \frac{\partial Q_k}{\partial V_n} & \frac{\partial Q_k}{\partial \delta_{CR}} & \frac{\partial Q_k}{\partial \delta_{VR}} \\
\frac{\partial Q_n}{\partial \theta_k} & \frac{\partial Q_n}{\partial \theta_n} & 0 & \frac{\partial Q_n}{\partial V_n} & \frac{\partial Q_n}{\partial V_n} & \frac{\partial Q_n}{\partial \delta_{CR}} & \frac{\partial Q_n}{\partial \delta_{VR}} \\
\frac{\partial P_{nk}}{\partial \theta_k} & \frac{\partial P_{nk}}{\partial \theta_n} & 0 & \frac{\partial P_{nk}}{\partial V_n} & \frac{\partial P_{nk}}{\partial V_n} & \frac{\partial P_{nk}}{\partial \delta_{CR}} & \frac{\partial P_{nk}}{\partial \delta_{VR}} \\
\frac{\partial Q_{nk}}{\partial \theta_k} & \frac{\partial Q_{nk}}{\partial \theta_n} & 0 & \frac{\partial Q_{nk}}{\partial V_n} & \frac{\partial Q_{nk}}{\partial V_n} & \frac{\partial Q_{nk}}{\partial \delta_{CR}} & \frac{\partial Q_{nk}}{\partial \delta_{VR}} \\
\frac{\partial P_{bb}}{\partial \theta_k} & \frac{\partial P_{bb}}{\partial \theta_n} & \frac{\partial P_{bb}}{\partial V_{vR}} & V_n & \frac{\partial P_{bb}}{\partial V_n} & \frac{\partial P_{bb}}{\partial \delta_{CR}} & \frac{\partial P_{bb}}{\partial \delta_{VR}}
\end{bmatrix}
\begin{bmatrix}
\Delta \theta_k \\
\Delta \theta_n \\
\Delta V_{vR} \\
\Delta V_n \\
\Delta \delta_{CR} \\
\Delta \delta_{VR} \\
\Delta \delta_{vR} \\
\end{bmatrix}
\]

(13)

4. Particle Swarm Optimization (PSO)

In 1995, a particle swarm optimization algorithm was proposed by Kennedy and Eberhart. This algorithm is located in the congestion intelligence branch. That is, the principle of this algorithm is to share information and experiences with each other. Figure (3) shown The search-point principle in
PSO[7]. PSO was created by simulating simplistic versions of society. The system functions as follows:

1) Research into swarms such as fish schooling and a flock of birds is based on the process.
2) It is based on a simple's concepts. Therefore, it requires few memories and the computation time is be short.
3) It was originally developed with continuous variables for nonlinear optimization problems. Nevertheless, the diagnosis of problems with discrete variables is conveniently extended.

![Figure 3. The search-point principle in PSO](image)

This modification may be expressed by the velocity equation, and the velocity of each agent can be changed by the following equation[8]:

\[ V_{id}^{k+1} = w V_{id}^k + C_1 \times rand(P_{best id} - X_{id}^k) + C_2 \times rand(G_{best id} - X_{id}^k) \]  
\[ X_{id}^{k+1} = X_{id}^k + V_{id}^{k+1} \quad i = 1, 2, ..., n \]

Where,
- \( X_{id}^k \) and \( X_{id}^{k+1} \) are current and modified searching point respectively,
- \( V_{id}^k \) and \( V_{id}^{k+1} \) are current and modified velocity respectively,
- \( V_{pbest} \) and \( V_{gbest} \) are velocity based on \( p_{best} \) and \( g_{best} \) respectively,
- \( n \) number of the particles in a group
- \( m \) members in a particle
- \( P_{best} \) the best position of the ith particle
- \( G_{best} \) the best particle among all the particle in the group
- \( w_i \) weight function velocity of the agent \( i \),
- \( c_i \) the weight factors for each term.

The following function is used for weight:

\[ w(i) = w_{max} - \left( \frac{w_{max} - w_{min}}{k_{0\ max}} \right) \times k_0 \]

Where:
- \( w_{min} \) and \( w_{max} \) are the minimum, maximum weight respectively.
- \( k_{0\ max} \), \( k_0 \) are the maximum and current iteration respectively.

In general, the steps of the particle swarm algorithm are as follows (Figure 4) show the flowchart about this step.

1) Random production of the initial population and its evaluation
2) Choosing the best personal memories and the best collective memories
3) Updating the speed and location and evaluating new responses
4) Multiply the coefficient $w$ by the attenuation rate of 0.96.
5) If the algorithm stopping conditions are not met, the second step is to return.

Figure 4. Flowchart of modified particle swarm optimization algorithm
Start

Modeling the Iraqi power system in MATLAB

Adjust the PSO parameters (Pop, Iterations, C1, C2, V, w)

The particles are randomly quantified (Each particle determines the place of installation of UPFCs)

Ite=1

Is there any transmission line between two chosen buses for the UPFCs installation?

Yes

Perform load flow for each particle and calculate the loss

Objective function=Loss

Choose personal best (Pbest) and Global best (Gbest)

Calculate velocity (V) for each particle and update particle position (new location for UPFC installation)

Ite=Ite+1

Is Ite>Iterations

Yes

Select the best location for UPFC installation (Gbest)

End

No

Loss=1e10

No

Ite=1

Figure 5. Flowchart of modified PSO for UPFC placement
The steps to perform optimization by PSO algorithm (figure 5) for the optimal location of the UPFC and the minimizing the losses in transmission line as follows:

Step 1: Modeling the IEEE 14 bus system in MATLAB (Transmission Lines, Generators, loads parameters of IEEE 14 bus system are coded in MATLAB with matrixes).

Step 2: Adjust parameters of the PSO algorithm (Population, Max_it, C1, C2, V_min, V_max, ω).

Step 3: The particles are randomly quantified (Each particle determines places of UPFCs installation).

Step 4: If there is no transmission line between two chosen buses, consider Loss equal to a large number (Loss=1e10) and jump to step six.

Step 5: Perform load flow and calculate loss for each particle (Objective function=Loss).

Step 6: Calculate the velocity (V) for each particle, and update the particle position (new location for UPFC installation).

Step 7: If the number of iteration is less than Max_it jump to Step 4. Otherwise go to Step 8.

Step 8: End of simulation.

5. Simulation Results

The main goal of this work is to minimizing the power system losses in the Transmission Line by using optimum location of UPFC device.

The 14-bus test system IEEE consists of nine loads bus in “buses no 4, 5, 7, 9, 10, 11, 12, 13, 14”, five generators bus in “buses no. 1, 2, 3, 6, 8” and twenty transmission lines where the lines “4-7, 4-9 and 5-6” are with tap changing transformers. The single line diagram for this test system is shown in the Figure (6)[9].

![Figure 6. Single line diagram of the IEEE 14-bus test system](image-url)
The PSO algorithm proposes to install two UPFC in buses 7-8 and 4-5, respectively. Under these circumstances, the system's active losses decreased by 15.13% to 3.0288 MW and the reactive losses decreased to 9.2075 MVar which reduced 28.90%, (as shown in table (1,2,3)) compared to pre-compensation conditions as shown in Figure (7), (8) and (9).

Table 1. Active and Reactive Power Losses without UPFC

| NO. bra. | Form bus | To bus | $P_{Losses}$ (MW) | $Q_{Losses}$ (MVar) |
|----------|----------|--------|-------------------|---------------------|
| 1        | 1        | 2      | 0.0015            | 1.4230              |
| 2        | 1        | 5      | 0.0855            | 0.0521              |
| 3        | 2        | 3      | 0.0518            | 0.1396              |
| 4        | 2        | 4      | 0.0076            | 0.4262              |
| 5        | 2        | 5      | 0.1266            | 0.8065              |
| 6        | 3        | 4      | 0.0440            | 0.0727              |
| 7        | 4        | 5      | 0.3019            | 0.3587              |
| 8        | 4        | 7      | 0                 | 0.0062              |
| 9        | 4        | 9      | 0                 | 0                   |
| 10       | 5        | 6      | 0                 | 1.6672              |
| 11       | 6        | 11     | 0.0234            | 0.6003              |
| 12       | 6        | 12     | 0.5981            | 1.0210              |
| 13       | 6        | 13     | 0.6520            | 0.0218              |
| 14       | 7        | 8      | 0                 | 0                   |
| 15       | 7        | 9      | 0                 | 1.3118              |
| 16       | 9        | 10     | 0.6965            | 0.2299              |
| 17       | 9        | 14     | 0.1271            | 0.4117              |
| 18       | 10       | 11     | 0.1114            | 0.0376              |
| 19       | 12       | 13     | 0.1866            | 0.6193              |
| 20       | 13       | 14     | 0.0142            | 0.0012              |
Table 2. Active and Reactive Power Losses with UPFC

| NO. bra. | Form bus | To bus | $P_{losses}$ (MW) | $Q_{losses}$ (MVar) |
|---------|----------|--------|------------------|-------------------|
| 1       | 1        | 2      | 0.0651           | 0.1962            |
| 2       | 1        | 5      | 0.0873           | 0.3579            |
| 3       | 2        | 3      | 0.3067           | 1.2902            |
| 4       | 2        | 4      | 0.0002           | 0.0009            |
| 5       | 2        | 5      | 0.2595           | 0.7906            |
| 6       | 3        | 4      | 0.5139           | 1.3111            |
| 7       | 4        | 5      | 1.0195           | 3.2159            |
| 8       | 4        | 7      | 0                | 0.2024            |
| 9       | 4        | 9      | 0                | 0.1432            |
| 10      | 5        | 6      | 0                | 0.6308            |
| 11      | 6        | 11     | 0.2977           | 0.6235            |
| 12      | 6        | 12     | 0.0003           | 0.0007            |
| 13      | 6        | 13     | 0.1789           | 0.3523            |
| 14      | 7        | 8      | 0                | 0.0156            |
| 15      | 7        | 9      | 0                | 1.6157            |
| 16      | 9        | 10     | 0.1378           | 0.3662            |
| 17      | 9        | 14     | 0.3120           | 0.6638            |
| 18      | 10       | 11     | 0.4385           | 1.0266            |
| 19      | 12       | 13     | 0.1627           | 0.1472            |
| 20      | 13       | 14     | 0.00004          | 0.000007          |

Table 3. Total Active and Reactive Power Losses with and without UPFC

| $P_{losses}$ (MW) | Without UPFC | With UPFC |
|-------------------|--------------|-----------|
| 3.7809            | 3.0288       |

| $Q_{losses}$ (MVar) | Without UPFC | With UPFC |
|---------------------|--------------|-----------|
| 12.9499             | 9.2075       |

Figure 7. Active Power Losses with and without UPFC
6. Conclusion

Through the results shown, we concluded the following important points and summarized as follows:

1. The optimal design of FACTS devices plays a key role in ensuring that these devices function properly.
2. The optimal location for two UPFC devices by using (PSO) controller-based IEEE 14-bus test system was between buses (7-8) and (4-5).
3. These locations will be minimizing the active and reactive power losses under normal operating condition.

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