Power Loss Reduction and Voltage Profile Improvement Using Optimal Placement of FACTS Devices

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ABSTRACT. The crucial role of an electric power system is to generate sufficient electricity to meet customer demands with an acceptable level of reliability in an economic manner. In recent years, Flexible AC Transmission Systems (FACTS) devices have been widely used to increase power system operation flexibility and controllability to meet this need. This paper presents an application of Differential Evolution (DE) to optimise the allocation of a Thyristor Controlled Series Capacitor (TCSC), a Static Var Compensator (SVC), and Unified Power Flow Controller (UPFC), as example FACTS devices. The objective of the research was to reduce power losses and improve the voltage profile in an IEEE 30-bus test system. The system performance was assessed with and without each FACTS device under different scenarios of load increase at up to 150% of the base case. The results obtained are encouraging in terms of reassessing electrical restructuring.

1. Introduction
Electric power production and distribution companies are constantly looking for new industrial technologies to contribute to improving energy supplies to consumers that can overcome the problems of increased demand for electric power and the disruption of recent fuel price increases. In recent years, many of these companies have increased their interest in the use of FACTS device technologies, which offer an effective way to improve the stability, reliability and capability of electric power transmission systems in traditional networks without the need to establish new transmission lines [1]. FACTS devices make power flow in transmission systems more flexible by controlling the active and reactive power flows in the transmission lines. The flow of electrical energy in AC transmission lines depends on the size of the wire, the line's intrinsic resistance, and the phase angle between the transmitting and receiving ends of the transmission line [2]. However, although the addition of FACTS devices generally improves the performance of electric power transmission networks, it also adds several technological and economic complications in terms of control, maintenance, and costs [3]. Identifying the optimal location and sizing of FACTS devices may, however, help address these issues, and thus a significant amount of research has been conducted to identify the best use of FACTS devices.

In [4], modelling of the best location for the installation of FACTS devices in an electric power transmission network was discussed, while in [5], FACTS devices were added to power systems suffering from congestion due to overloads; in that case, the locations and sizing of the FACTS devices were determined based on those factors considered to be most sensitive based on the nature of the load. In [6], an adaptive genetic algorithm was used to determine the best allocation of various types of FACTS devices, with the aim of that study being to reduce costs by reducing system losses. Researchers in [7] addressed increasing power transmission capacity by applying PSO technology to reducing system losses and improving line voltage, while in [8], the researchers sought to reduce system losses by adding various types of FACTS devices to power transmission systems. Simulations of these electrical systems were studied, and the flow of active and reactive energy determined; it was thus deduced that the economic cost of adding these devices was offset
by a reasonable percentage reduction in total energy losses. In [9], the performance of a power transmission system without the use of FACTS devices and with several types of such device was compared. An artificial intelligence technique was used to determine the best location and size for the relevant FACTS devices, which reduced losses and improved the voltage profile; in addition, the economic costs were calculated in each case and compared with those for the system without FACTS devices.

The current work is divided into several parts as follows: in section 2, a brief overview of FACTS technologies and types is presented, while in section 3, the basic principles of the DE improvement method are reviewed. The methodology used in this study is presented in section 4 and the results of the study are reported in section 5. Finally, these results are discussed in section 6.

2. FACTS Devices

The integration of FACTS devices with transmission systems offers many benefits, including increased transmission system reliability, increased transient and dynamic stability in a network, reduced loop fluctuations, increased supply quality to sensitive loads, increases in the fixed limits of transmission lines, and some environmental benefits [10].

FACTS devices are generally classified according to their purpose or according to their connection to the network; this means that they may be series controllers, shunt controllers, combined series-shunt controllers. Depending on their technological features, they are also divided into two generations: the first generation uses Thyristor ignition gate controls (TCR), while the second generation uses ignition semiconductors and portal-controlled extinction (GTO, IGBTs, MCTS, IGCTS, etc.). The primary difference between the two generations is the latter’s ability to facilitate reactive active exchange energy and power generation [11].

Three main FACTS devices, identified by their method of connection with the transmission networks, were analysed and studied as shown in Figure 1. The serial controllers were used in cases of disturbed voltages, with series voltage injected at the connection point to correct the voltage level. In the shunt controllers, an electric current is injected into the contact point to compensate for active power throughout the system, while in combined series-shunt controller FACTS devices, the electric current is injected at the shunt portion of the controllers and the series voltage is injected at the serial portion in the same controller [12]. The FACTS devices discussed in this paper are thus

- TCSC (Thyristor Controlled Series), which uses a series of capacitor modules running in parallel with a thyristor (TCR). The TCR controls the capacitive reactance smoothly and over a wide range, and the two-way thyristor pairs operate continuously to introduce inductive reactance on the line according to their instructions. This type of device is used to control line overloads.
- SVC (fixed VAR compensator), which is a device used to improve high-voltage electricity transmission lines by providing fast acting reactive energy. SVCs regulate voltage and increase the stability of the system. SVCs also have no moving parts other than separate circuit breakers. Previously, power compensation was done by adding a large number of capacitors simultaneously; the SVC instead uses the reactors to consume VAR from the system if the load is reactive, thus controlling the system voltage as the banks switch capacitor automatically.
- UPFC (Unified Power Flow Controller), which is one of the most widely used types of FACTS device in terms of transmission systems. These have the ability to set bus voltages within the required levels, controlling the transmission line reactance and phase angle between two buses independently. The UPFC controls these three parameters by including a control voltage in phase, a square voltage, and shunt compensation. The use of this type of device thus offers major advantages in terms of the dynamic operation of transmission lines based on its real-time and dynamic control compensation for AC power transmission systems.
3. Differential Evolution Techniques

Several artificial intelligence techniques may be used to identify optimal solutions to nonlinear problems. One of these techniques is the Differential Evolution (DE) technique, which is based on optimising random parameter algorithms [13]. Storn and Price laid down the basic principles of this innovative method for solving nonlinear optimisation problems in 1995, creating a less random approach to achieving the required results as compared to classical methods, and thus increasing efficiency. The DE method is generally used initially to find the optimum point in a D-dimensional parameter space. The first operation of the DE algorithm is the creation of an initial population (NP) of D-dimensional parameter vectors. Each vector in this population is randomly initialised within certain limits for each parameter. The vectors of the current generation are known as the target vectors, which are then mutated to produce donor vectors, a process implemented by randomly selecting three vectors from the population, with the scaling of any two of the vectors applied to the third vector. The new trial vectors are then generated using exponential or binomial crossover methods, and a comparison is made between the trial vector and the target vector to allow selection of the best vector to transfer to the next generation based on a pre-set fitness value. Figure 2 represents the basic stages used in the DE method.

The algorithm thus creates a random population of size (NP) and a floating point for each solution, allowing each individual to act as a candidate solution, as in Equation 1.

\[
P^{(G)} = [X_1^{(G)}, ..., X_i^{(G)}, ..., X_{NP}^{(G)}]
\]  

The DE method preserves the population \( P^{(G)} \) in each generation (NP) for each nominee solution (\( X_i \)). A nominee solution (\( X_i \)) is an integer value within the D-dimensional vector that depends on decision parameters (D), as given in equation 2.

\[
X_i^{(G)} = [X_{i,1}^{(G)}, ..., X_{i,j}^{(G)}, ..., X_{i,D}^{(G)}], i = 1, ..., N_P, \quad j = 1, ..., D
\]
4. The Proposed Approach

After installing FACTS devices in the most appropriate location in an electric power transmission lines, the entire system must maintain acceptable limits of active and reactive power. These limitations are described in equations 3 to 5 [14].

\[
\begin{align*}
    p_{ni}^{min} & \leq p_{ni} \leq p_{ni}^{max} \\
    q_{ni}^{min} & \leq q_{ni} \leq q_{ni}^{max} \\
    v_{i}^{min} & \leq v_{i} \leq v_{i}^{max}
\end{align*}
\]  

(3) (4) (5)

To achieve the objective of this research, which is to reduce the total losses of the system and improve the profile of the voltage, action steps as outlined in Figure 3 were applied.

![Flowchart of action steps](image-url)
5. Results

5.1 Optimal location

The active and reactive electrical energy of the IEEE 30 test system was calculated based on the power flow for each transmission line (41 lines) using the Newton-Raphael method; the transmission lines with the highest levels of active and reactive power were thus identified as candidate sites for the initial installation of FACTS devices. The total load of the test system was increased in three steps (100%, 125%, and 150%) from the base case by increasing the total load connected to the slack bus. Table 1 thus summarises the active and reactive power of the test system without any FACTS devices.

| Line no. | Bus | Base Case | Loading 100% | Loading 125% | Loading 150% |
|----------|-----|-----------|--------------|--------------|--------------|
|          | P   | Q         | P            | P            | P            |
| 1        | 1-2 | 0.902     | 0.013        | 0.905        | 0.014        |
| 2        | 1-3 | 0.477     | -0.003       | 0.479        | -0.002       |
| 3        | 2-4 | 0.288     | -0.058       | 0.290        | -0.051       |
| 4        | 3-6 | 0.446     | -0.027       | 0.446        | -0.025       |
| 5        | 2-5 | 0.158     | 0.029        | 0.160        | 0.031        |
| 6        | 2-6 | 0.378     | -0.051       | 0.380        | -0.049       |
| 7        | 4-6 | 0.392     | 0.024        | 0.394        | 0.026        |
| 8        | 5-7 | -0.130    | 0.029        | -0.128       | 0.031        |
| 9        | 6-7 | 0.363     | 0.033        | 0.365        | 0.035        |
| 10       | 6-8 | -0.027    | 0.013        | -0.024       | 0.015        |
| 11       | 6-9 | 0.151     | -0.110       | 0.154        | -0.108       |
| 12       | 6-10| 0.114     | -0.031       | 0.117        | -0.028       |
| 13       | 9-11| -0.179    | -0.225       | -0.175       | -0.222       |
| 14       | 9-10| 0.325     | 0.031        | 0.329        | 0.034        |
| 15       | 4-12| 0.268     | -0.068       | 0.271        | -0.065       |
| 16       | 12-13| -0.169   | -0.301       | -0.166       | -0.298       |
| 17       | 12-14| 0.076    | 0.019        | 0.079        | 0.023        |
| 18       | 12-15| 0.175    | 0.041        | 0.178        | 0.045        |
| 19       | 12-16| 0.067    | 0.016        | 0.070        | 0.019        |
| 20       | 14-15| 0.014    | 0.002        | 0.018        | 0.007        |
| 21       | 16-17| 0.031    | -0.042       | 0.034        | -0.038       |
| 22       | 15-18| 0.056    | 0.009        | 0.059        | 0.011        |
| 23       | 18-19| 0.024    | -0.010       | 0.027        | -0.080       |
| 24       | 19-20| -0.070   | -0.034       | -0.068       | -0.031       |
| 25       | 10-20| 0.093    | 0.044        | 0.097        | 0.047        |
| 26       | 10-17| 0.058    | 0.037        | 0.061        | 0.039        |
| 27       | 10-21| 0.160    | 0.033        | 0.164        | 0.037        |
| 28       | 10-22| 0.078    | 0.021        | 0.082        | 0.024        |
| 29       | 21-22| 0.015    | -0.020       | 0.018        | -0.017       |
| 30       | 15-23| 0.048    | 0.014        | 0.052        | 0.018        |
| 31       | 22-24| 0.062    | 0.020        | 0.065        | 0.025        |
| 32       | 23-24| 0.016    | -0.001       | 0.019        | -0.000       |
| 33       | 24-25| -0.009   | -0.007       | -0.005       | -0.005       |
| 34       | 25-26| 0.035    | 0.022        | 0.039        | 0.027        |
| 35       | 25-27| -0.044   | -0.031       | -0.040       | -0.028       |
| 36       | 28-27| 0.163    | -0.038       | 0.167        | -0.034       |
| 37       | 27-29| 0.061    | 0.015        | 0.067        | 0.012        |
| 38       | 27-30| 0.070    | 0.016        | 0.073        | 0.020        |
From Table 1, it is clear that lines 6, 7, and 4 have the highest active power flows in the system. These lines are connected between buses 2-6, 4-6, and 3-6, respectively; these lines are thus nominees for UPFC devices. Transmission lines 41, 25, and 18 have the largest reactive power flows, making them candidate locations for the installation of TCSC devices. To find the best locations to install SVC devices, the busses connected to the ends of the transmission lines that have the second-highest reactive capacities were identified. From Table 2, lines 27, 26, and 9 have the second highest reactive power flows in the test system, making buses 17, 7, and 2 the best locations for the proposed device. Table 2 shows the nominee buses and lines for the various types FACTS devices.

| Type of FACTS | 1st position | 2nd position | 3rd position |
|---------------|--------------|--------------|--------------|
| UPFC          | Line 6 (2-6) | Line 7 (4-6) | Line 4 (3-4) |
| TCSC          | Line 41 (6-28) | Line 25 (10-20) | Line 18 (12-15) |
| SVC           | Bus 17       | Bus 7        | Bus 21       |

5.2 Optimum size

To determine the optimum size of the UPFC, TCSC, and SVC devices, the DE optimisation method was applied with the parameters shown in Table 3. The total power losses of the test system with the FACTS devices added were then calculated. The data for the test system were taken from [15], where an IEEE 30-bus test system consisting of six generating units and 41 transmission lines was developed and tested. The total power losses of the system from that work are thus 17.5280 MW and 68.8881 MVar.

| Differential valuation parameters | Value |
|-----------------------------------|-------|
| Variable Size D*5                 | 15    |
| Maximum Generation (Gen max)      | 100   |
| Crossover Probability (Ωc)        | 0.9   |
| Mutation probability (Ωm)         | 0.2   |
| Initial size range                | 0-10  |

Table 4 illustrates the power losses in the test system with the relevant UPFC devices. Line 4, between buses 3-4, is clearly the optimum location for a UPFC device of 9.854 MW, as this causes the total active and reactive power losses of the test system to become 15.755, 16.201, and 16.761 MW and 61.227, 62.544, and 62.874 MVar, respectively, when the test system is increased by 100%, 125%, and 150%.

| UPFC Location | UPFC Size | Total losses | Total losses | Total losses |
|---------------|-----------|--------------|--------------|--------------|
|               | MW        | Loading 100% | Loading 125% | Loading 150% |
| Line 6 (2-6)  | 9.8624    | 15.817       | 61.457       | 16.201       | 62.544       | 16.761       | 62.874       |
| Line 7 (4-6)  | 9.7851    | 15.921       | 61.389       | 16.311       | 62.672       | 16.788       | 62.911       |

Table 2. Nominee locations for various FACTS devices.

Table 3. DE Parameters.

Table 4. Power losses of the test system with UPFC devices.
Table 5 illustrates the results of the test system with TCSC devices. Here, line 41, connected between busses 6-28, is the optimal placement of a device of 9,640 MW, whereby the total active power losses of the test system become 15.531, 15.764 and 15.934 MW, while the reactive power losses become 63.560, 63.865, and 64.706 MVar during successive load increases.

Table 5. Power losses of the test system with TCSC devices.

| TCSC Location | TCSC Size (MW) | Total losses Loading 100% (MW) | Total losses Loading 125% (MW) | Total losses Loading 150% (MW) |
|---------------|----------------|---------------------------------|---------------------------------|---------------------------------|
| Line 41 (6-28)| 9.640          | 15.531                          | 63.560                          | 15.934                          |
| Line 25 (10-20)| 9.476          | 15.592                          | 63.578                          | 16.247                          |
| Line 18 (12-15)| 9.600          | 15.603                          | 63.564                          | 16.312                          |

From table 6, it is clear that bus 21 is the optimal location for an SVC device of 9,720 MW. The total test system active and reactive power losses are then 14.897, 15.674, 15.864 MW, and 62.015, 63.278, and 64.214 MVar, respectively, with the various different loadings.

Table 6. Power losses of the test system with SVC devices.

| SVC Location | SVC Size (MW) | Total losses Loading 100% (MW) | Total losses Loading 125% (MW) | Total losses Loading 150% (MW) |
|---------------|----------------|---------------------------------|---------------------------------|---------------------------------|
| Bus 17        | 9.632          | 15.756                          | 62.456                          | 16.018                          |
| Bus 7         | 9.648          | 15.369                          | 62.315                          | 15.971                          |
| Bus 21        | 9.720          | 14.897                          | 62.015                          | 15.864                          |

As shown in Figure 4, the voltage profile of the whole test system is improved significantly after the installation of all different types of FACTS devices. However, the SVC device achieves the best improvement in the voltage profile of the test system.

Figure 4. Comparison of voltage profiles.
6. Conclusion
In recent years, there has been an increase in interest from electric power generation and distribution companies in FACTS devices, which can provide tremendous technological advantages when used correctly. In this research, three basic types of FACTS devices with different total loads were studied in order to assess their improvement of the performance of a test system. The addition of UPFC devices in the optimum location (line 4) reduced the active and the reactive losses of the system to 15.755, 16.198, and 16.743 MW and 61.227, 62.516, and 62.854 MVar, respectively, while the installation of TCSC devices in transmission line 44 reduced the losses to 15.531, 15.764, and 15.934 MW for active power and 63.560, 63.865, and 64.706 MVar for reactive power. Bus 21 was found to be the best place to install an SVC device, with total active and reactive power losses of 14.897, 15.674, and 15.864 MW and 62.015, 63.278, and 64.214 MVar, respectively, with varying loads.

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