Power Flow Control incorporating TCSC using Differential Evolution

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Abstract—Optimal power flow aims to optimize the generation cost, active power loss via optimal adjustment of power system control variables, while at the same time satisfying various equality and inequality constraints. In recent years FACTS devices have made the power systems operation more flexible and secure. In this paper, the focus is to obtain the optimal solution using differential evolution, when thyristor controlled series capacitors (TCSC) are used at fixed location in the system. The proposed strategy is tested on IEEE 14 bus system and load flow is carried out with Newton Raphson method. The results obtained are compared for the system with and without TCSC. and shows improvement in results.

Index Terms— Differential Evolution, Generator Fuel Cost FACTS, Optimal power flow.

I. INTRODUCTION

As power industry is moving to a competitive market, its operation is strongly influenced. Optimization methods have been widely used in power system operation, analysis and planning. One of the most significant application is optimal power flow (OPF). So when we consider the case of power system operation and planning, Optimal Power Flow (OPF) plays an important role. The OPF mainly aims to optimize the selected objective function such as fuel cost, active power loss via optimal adjustment of power system control variables, keeping the equality and inequality constraints in limit. Equality constraints are basically the power flow equations, while inequality constraints are the limits on control variables and control variable includes the generator active powers, the generator bus voltage magnitudes, the transformer tap settings and reactive power of VAR sources. Mathematically, OPF is modelled as a nonlinear programming (NLP) problem, which usually minimizes the total generating unit fuel cost and total load bus voltage deviation from a specified point subject to a set of equality and inequality constraints and thus losses can be reduced to a significant amount by keeping the equality and inequality constraints in limit. Now as the demand for the power transfer increases, the power system becomes increasingly more difficult to operate and insecure with unscheduled power flows and thus handling the losses. Rapid development of self-commutated semiconductor devices has made it possible to design power electronic equipment. This equipment is well known as flexible AC Transmission System (FACTS) which has been introduced by Hingorani [1] in 1988. FACTS Technology is concerned with the management of active and reactive power to improve the performance of electrical networks and thus minimizing the losses. FACTS includes various types of series and shunt type VAR compensators. Series and shunt VAR compensators have the capability to change the performance characteristics of electrical networks. In both of them, the reactive power through the system can significantly improve the performance of the power system. So, as discussed earlier OPF is modelled as a nonlinear programming (NLP) problem and when we incorporated FACTS in it and considered as a control variable, it becomes even more nonlinear and complex. Various researchers developed algorithms to solve optimal power flow incorporating FACTS devices. T.S.Chung et al. [2] presented a Hybrid Genetic Algorithm (GA) method to solve OPF incorporating FACTS devices. GA is integrated with conventional OPF to select the best control parameters to minimize the total generation fuel cost and keep the power flows within the security limits. TCPS and TCSC are modeled. The proposed method was applied on modified IEEE 14 bus system and it converged in a few iterations. L.J.Cai et al. [3] proposed optimal choice and allocation of FACTS devices in multi-machine power systems using genetic algorithm. The objective is to achieve the power system economic generation allocation and dispatch in deregulated electricity market. The locations of the FACTS devices, their types and ratings are optimized simultaneously. UPFC, TCSC, TCPST and SVC are modeled and their investment costs are also considered.

The remaining part of the paper is organized as follows. Section II presents the modeling of TCSC. Section III represents the problem formulation of OPF using TCSC. Section IV gives the brief idea about Differential Evolution. Section V gives overview of proposed algorithm. Implementation of DE to solve OPF problem incorporating TCSC and results is presented in Section VI. Finally conclusion is drawn in Section VII.

II. MODELLING OF TCSC

Transmission lines are invariably represented by π equivalent parameters and is located as lumped component in the entwark. The series compensator Thyristor controlled Series Compensator (TCSC) is a static capacitor/ reactor with impedance $X_C$. Fig. 1 shows a transmission line incorporating a TCSC. [4][5] between bus nodes $i$ and $j$ and updated admittance between nodes $i$ and $j$ will be expressed as in equation (1):

$$\Delta y_{ij} = y'_{ij} - y_{ij} = (g'_{ij} + jb'_{ij}) - (g_{ij} + jb_{ij}) \quad \ldots(1)$$

$$g_{ij} = \frac{r_{ij}}{\sqrt{r_{ij}^2 + x_{ij}^2}}; \quad y_{ij} = -\frac{x_{ij}}{\sqrt{r_{ij}^2 + x_{ij}^2}}$$

$$g'_{ij} = \frac{r_{ij}}{\sqrt{r_{ij}^2 + (x_{ij} + x_C)^2}}; \quad b'_{ij} = -\frac{x_{ij} + x_C}{\sqrt{r_{ij}^2 + (x_{ij} + x_C)^2}}$$
With the addition of TCSC in the line between bus i and bus j of a general power system, the new system admittance matrix $Y_{bus}$ can be updated as:

$$Y'_{bus} = Y_{bus} + A$$ ... (2)

$$A = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & \Delta y_{ij} & 0 & \cdots & -\Delta y_{ij} \\
0 & 0 & 0 & 0 & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
0 & -\Delta y_{ij} & 0 & \cdots & \Delta y_{ij} \\
0 & 0 & 0 & 0 & 0
\end{pmatrix}$$

### III. PROBLEM FORMULATION

The objective function of power flow problem is the minimization of total generation cost. Power flow equations in the OPF problem incorporating flexible ac transmission system is expressed as follows:

$$\sum_{i=1}^{N_{G}} a_{i} + b_{i} P_{i} + c_{i} P_{i}^{2} + |d_{i} * \sin(e_{i} * (P_{i}^{\text{min}} - P_{i}))| \quad \text{... (3)}$$

Subject to

$$P_{Gi} - P_{Di} - \sum_{j=1}^{N_{B}} V_{i} V_{j} y_{ij} \cos(\theta_{ij} + \delta_{i} - \delta_{j}) = 0 \quad \forall i \in N_{B} \quad \text{... (4)}$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{N_{B}} V_{i} V_{j} y_{ij} \sin(\theta_{ij} + \delta_{i} - \delta_{j}) = 0 \quad \forall i \in N_{B} \quad \text{... (5)}$$

$$\sum_{i=1}^{N_{G}} P_{Gi} - P_{D} - P_{L} \quad \text{... (6)}$$

$$\sum_{i=1}^{N_{Q}} Q_{Gi} - Q_{D} - Q_{L} \quad \text{... (7)}$$

$$P_{Gi}^{\text{min}} \leq P_{Gi} \leq P_{Gi}^{\text{max}} \quad \forall i \in N_{G} \quad \text{... (8)}$$

$$Q_{Gi}^{\text{min}} \leq Q_{Gi} \leq Q_{Gi}^{\text{max}} \quad \forall i \in N_{G} \quad \text{... (9)}$$

$$V_{i}^{\text{min}} \leq V_{i} \leq V_{i}^{\text{max}} \quad \forall i \in N_{B} \quad \text{... (10)}$$

$$x_{ci}^{\text{min}} \leq x_{ci} \leq x_{ci}^{\text{max}} \quad \forall i \in N_{TCSC} \quad \text{... (11)}$$

where, $P_{Gi}$ Real power generation at bus i,

$Q_{Gi}$ Reactive power generation at bus i

$P_{Di}$ Real power demand at bus i

$Q_{Di}$ Reactive power demand at bus i

$y_{ij}$ magnitude of $ij^{th}$ element in bus admittance matrix

$\theta_{ij}$ angle of $ij^{th}$ element in bus admittance matrix

$V_{i}$ voltage magnitude at bus i

$\delta_{i}$ phase angle at bus j

$x_{ci}$ reacance of TCSC i

$N_{G}$ set of generator bus indexes

$N_{D}$ set of bus indexes having reactive power source

$N_{B}$ set of bus indexes

$N_{L}$ set of transmission line indexes

$N_{TCSC}$ set of TCSC

$\alpha_{i}, b_{i}, c_{i}, d_{i}, e_{i}$ cost coefficient of generator i.

### IV. DIFFERENTIAL EVOLUTION

Differential Evolution (DE) is an evolutionary algorithm originally proposed by Price and Storn [6] for optimization problems over a continuous domain. DE is exceptionally simple, significantly faster and robust. The basic idea of DE is to adapt the search during the evolutionary process. Differential Evolution (DE) is a parallel direct search method and selects the optimal solution from D dimension population. The initial vector population is chosen randomly defioned over the parameter space. The perturbation is assumed as large at the start of evolution. At the start of the evolution, the perturbations are large since parent populations are far away from each other. Over the evolution process the population converges to a small region and the perturbations adaptively become small. As a result, the evolutionary algorithm performs a global exploratory search during the early stages of the evolutionary process and local exploitation during the mature stage of the search. In DE the fittest of an offspring competes one-to-one with that of corresponding parent which is different from other evolutionary algorithms. This one-to-one competition gives rise to faster convergence rate. The optimization process in DE is carried out with three basic operations: mutation, crossover and selection. The DE algorithm is described as follows:

1) Initialization

The initial population X with population size of Np is initialized randomly such that $X=[X_1, X_2, X_3, ..., X_{Np}]$. Each solution is given by $X_{n}=[P_{G1}, P_{G2}, P_{G3}, ..., P_{GN}](where n=1, 2, ..., Np,N is the number of real power generations in the problem and Np is the Number of population). The variables shall bound within their upper and lower limits. Let the n<sup>th</sup> component of the m<sup>th</sup> population members may be initialized as

$$x_{mn} = x_{n}^{l} + rand(0,1) * (X_{n}^{u} - X_{n}^{l}) \quad \text{... (10)}$$

Where $X_{n}^{u}$ is the upper bound of the n<sup>th</sup> variable of the problem, $X_{n}^{l}$ is the lower bound of the n<sup>th</sup> variable of the problem, rand(0,1) is a uniformly distributed number within
the limits(0,1), \( x_{mn}^0 \) is the initial \( n^{th} \) variable of the \( m^{th} \) population.

2) Mutation
Mutant population is generated. Among the DE variants used for mutation in DE, the addition of the weighted difference vector between the two population members to the third member is adopted in this approach. Here three different members namely \( X_1 \), \( X_2 \) and \( X_3 \) are chosen from the current population. Then the difference between any two of these members is scaled by a scalar number \( F \), which is then added to the third member. The value of \( F \) is usually in between 0.4 and 1. The Mutation operation using the difference between two randomly selected individuals may cause the mutant individual to escape from the search domain. If an optimized variable for the mutant individual is outside of the domain search, then this variable is replaced by its lower bound or its upper bound so that each individual can be restricted to remain within the search domain. \( m^{th} \) member of the donor vector \( V_d(t) \) is expressed as

\[
V_{mn}^{(t+1)} = x_{r1}m(t) + F * (x_{r2}m(t) - x_{r3}m(t)) \quad \ldots \ldots \ldots \ldots \quad (12)
\]

3) Crossover
A new population is created by suitably combining the parent population and the mutant population. The process of crossover is based on the CR which is in between (0,1). Binomial crossover scheme is used which is performed on all \( D \) variables and can be expressed as:

\[
U_m(t) = V_{mn}(t) \quad \text{if rand (0, 1) < CR}
\]
\[
U_m(t) = X_{mn}(t) \quad \text{else}
\]

where \( U_{mn}(t) \) is the child which is obtained after crossover operation where \( m = 1, 2, \ldots \) \( N_p \), \( n = 1, 2, \ldots \) \( D \). Here, rand ensures that the newly generated vector is different for both \( V_{mn}(t) \) and \( X_{mn}(t) \).

4) Selection
After calculating the objective function \( F(t) \) using \( D \) number of variables for using initial and crossover population, a new population with the least objective function (minimum fuel cost) is formed for the next generation. This is given by

\[
X (t+1) = U_n(t) \quad \text{if } f(U_n(t)) \leq f(X_n(t))
\]
\[
X (t+1) = X_n(t) \quad \text{if } f(U_n(t)) > f(X_n(t))
\]

The process is repeated until the maximum number of generations or no improvement is seen in the real power generation cost after many generations. The global optimum searching capability and the convergence speed of DE are very sensitive to the choice of control parameters \( NP, F \) and \( CR \). The crossover rate \( CR \) is between [0.3, 0.9].

V. PROCEDURAL STEPS
Step 1: initialise the population for decision variables of power system namely: real power generation of the generating units excluding slack bus, voltage magnitude and phase angle of the buses and series capacitors of TCSC. The \( i^{th} \) parent vector is as follows:

\[
p_i = [P_{c1}^i, P_{c2}^i, \ldots, P_{cN_p}^i, V_{1}^i, \ldots, V_{N_b}^i, \delta_{1}^i, \ldots, \delta_{N_b}^i, x_{c1}^i, \ldots, x_{cM}^i, \ldots, x_{TN_{TCSC}}^i]^T.
\]

Step 2: Run Newton–Raphson load flow for each parent vector \( p_i \). The reactive power generations, transmission loss, slack bus generations and line flows are determined. Cost of generation is calculated for each parent vector \( p_i \).

Step 2. Perform mutation for each target vector.
Step 3. Perform crossover for each target vector and create a trial vector.
Step 4. Perform selection for each target vector, by comparing its cost with that of the trial vector. The vector that has lesser cost of the two would survive for the next generation.
Step 5. Stop if the maximum number of generations is reached; otherwise go to Step 2.

VI. RESULTS AND DISCUSSIONS
The effectiveness of the proposed algorithm is tested on IEEE 14-bus system. Two branches, (2, 3), (6, 8) are selected and TCSC are installed. Limits of the series capacitors size are taken in such a manner that the ratio of maximum series capacitors limit to line reactor is equal or more than 50%. The results obtained are tabulated in table 1. The values of TCSC capacitances obtained are presented in table 2.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>162.81</td>
<td>162.30</td>
<td>232.60</td>
</tr>
<tr>
<td>P2</td>
<td>34.95</td>
<td>61.03</td>
<td>40</td>
</tr>
<tr>
<td>P3</td>
<td>26.10</td>
<td>21.56</td>
<td>0</td>
</tr>
<tr>
<td>P4</td>
<td>20.81</td>
<td>13.82</td>
<td>0</td>
</tr>
<tr>
<td>P5</td>
<td>22.58</td>
<td>10.00</td>
<td>0</td>
</tr>
<tr>
<td>Cost($/h)</td>
<td>746.2312</td>
<td>754.7656</td>
<td>801.0287</td>
</tr>
<tr>
<td>Losses(MW)</td>
<td>8.2542</td>
<td>9.711</td>
<td>13.600</td>
</tr>
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</table>

Table 2 Values of TCSC obtained from DE

<table>
<thead>
<tr>
<th>Position of TCSC</th>
<th>Capacitance values in pu</th>
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<tbody>
<tr>
<td>( x_{c2-3} )</td>
<td>0.0826</td>
</tr>
<tr>
<td>( x_{c6-8} )</td>
<td>0.0090</td>
</tr>
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</table>

Table 3 represents the comparison of conventional load flow solution for bus voltages and phase angles of modified IEEE 14 bus system with and without TCSC.
Fig. 2 and Fig. 3 represents the generation cost with and without TCSC respectively.

<table>
<thead>
<tr>
<th>Bus No</th>
<th>Voltages (pu)</th>
<th>Angle Degree</th>
<th>Voltages (pu)</th>
<th>Angle Degree</th>
<th>Voltages (pu)</th>
<th>Angle Degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0000</td>
<td>0</td>
<td>1.0000</td>
<td>0</td>
<td>1.0000</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1.0450</td>
<td>-4.9957</td>
<td>1.0026</td>
<td>-3.9821</td>
<td>0.9874</td>
<td>-3.9624</td>
</tr>
<tr>
<td>3</td>
<td>1.0290</td>
<td>-12.8726</td>
<td>0.9981</td>
<td>-11.0747</td>
<td>0.9876</td>
<td>-8.8393</td>
</tr>
<tr>
<td>4</td>
<td>1.0600</td>
<td>-14.4096</td>
<td>0.9829</td>
<td>-12.0017</td>
<td>1.0249</td>
<td>-10.1571</td>
</tr>
<tr>
<td>5</td>
<td>1.0800</td>
<td>-13.2742</td>
<td>0.9700</td>
<td>-9.8988</td>
<td>1.0343</td>
<td>-6.5195</td>
</tr>
<tr>
<td>6</td>
<td>1.0139</td>
<td>-10.2425</td>
<td>0.9643</td>
<td>-8.6329</td>
<td>0.9727</td>
<td>-7.5957</td>
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<tr>
<td>7</td>
<td>1.0444</td>
<td>-13.2742</td>
<td>0.9636</td>
<td>-10.9786</td>
<td>1.0011</td>
<td>-8.7206</td>
</tr>
<tr>
<td>8</td>
<td>1.0159</td>
<td>-8.7337</td>
<td>0.9649</td>
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<td>0.9742</td>
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<tr>
<td>9</td>
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<td>-14.8829</td>
<td>0.9500</td>
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<td>0.9850</td>
<td>-10.7615</td>
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<tr>
<td>10</td>
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<td>0.9500</td>
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<td>0.9841</td>
<td>-10.9635</td>
</tr>
<tr>
<td>11</td>
<td>1.0390</td>
<td>-14.8713</td>
<td>0.9606</td>
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<td>1.0005</td>
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<tr>
<td>12</td>
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<td>-15.2771</td>
<td>0.9653</td>
<td>-13.0401</td>
<td>1.0075</td>
<td>-11.0981</td>
</tr>
<tr>
<td>13</td>
<td>1.0375</td>
<td>-15.3247</td>
<td>0.9586</td>
<td>-13.1256</td>
<td>1.0006</td>
<td>-11.1509</td>
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<tr>
<td>14</td>
<td>1.0134</td>
<td>-16.1166</td>
<td>0.9500</td>
<td>-14.2504</td>
<td>0.9726</td>
<td>-12.0589</td>
</tr>
</tbody>
</table>

Table 3: bus Voltage magnitudes and Phase angles

In this study, differential evolution is successfully implemented to minimize the generator fuel cost in optimal power flow control with TCSC keeping the equality and inequality constraints in limits. Differential evolution achieves better solution on modified IEEE 14-bus system with TCSC fixed at the given locations. The results has been compared with conventional load flow method and OPF using DE without TCSC and it is concluded that the generator fuel cost reduces significantly and losses are also less when we use TCSC with DE as compared to other two.

REFERENCES


