Basic Concept on Power Flow Optimization with TCSC and TCPS using Differential Evolution Method

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Abstract: **The main objective of power System is to meet the load demands. During power flow there is losses in the transmission lines. So the system has to generate power equal to the sum of load demand and losses. If the loss increases, the generation increases and hence the cost also increases. So our aim is to optimize the flow so that the losses will be minimized therefore we use TCSC and TCPS in the line to improve power flow in the line. Here, we are using IEEE 30 bus and installed Thyristors – controlled Series Capacitor and Thyristor controlled phase shifter. Using Newton- Raphson load flow solution method we calculated the power flow, losses, voltages and phase angles of buses. Then we calculated the cost of generation for different iterations.. Then the differential evolution is applied to the system to find out the optimal generation cost, generator value and TCPS and TCSC values.**

Keyword: Power flow optimization, TCSC, TCPS, Differential evolution method.

I. INTRODUCTION

The rapid growth in electrical energy use, combined with the demand for low cost energy, has gradually led to the development of generation sites remotely located from the load centres. In particular, the remote generating stations include hydroelectric Stations, fossil fuel stations, geothermal stations, tidal power plants and nuclear plants Purposely built away from urban centres. The generation of bulk power at remote Locations necessitates the use of transmission lines to connect generation sites to load Centres. Furthermore, to enhance system reliability, multiple lines that connect load Centres to several sources, interlink neighbouring utilities and build the needed levels of redundancy that have gradually led to the evolution of complex interconnected Electrical transmission networks.

In general if a power delivery system was made up of radial lines from individual local generators ,many more generations resources would be needed to serve the load with the same reliability and the cost of electricity would be much higher. With that perspective transmission is always an alternative to a new generation resource. Less transmission capability means that more generation resources would be required regardless of the whether the system is made up of large or small power plants .In fact small distributed generation becomes economically viable only if there is a backbone of transmission grid.

II. OPTIMAL POWER FLOW (OPF)

The Optimal Power flow module is an intelligent load flow that employs techniques to automatically adjust the power system control settings while simultaneously solving the load flows and optimizing operating conditions within specific constraints. Optimal Power Flow use state-of-art techniques including an interior point method with barrier functions and infeasibility handling to achieve ultimate accuracy and flexibility in solving systems of any size. Asses generation interconnection impacts on the grid and the associated costs of transmission upgrades. Optimal Power Flow problem is a static constrained nonlinear optimization problem ,the solution of which determines the optimal setting for control variables in a power network respecting various constraints .OPF has been widely used in power system operation and planning .Many techniques such as linear programming ,nonlinear programming and quadratic programming have been applied to the solution of OPF problem .These methods rely on convexity to obtain the global optimum solution and as such are forced to simplify the relationships to ensure convexity.

III. FACTS DEVICES

The main idea behind FACTS is to use network parameters as controls to direct flow, thus eliminating problems caused by unwanted loop or parallel flows. The potential benefits brought by the new technologies include reduction of operation and transmission investment cost, increase of system security and reliability and increase of transfer capabilities.

Among FACTS devices series controllers such as TCSC (Thyristor controlled series capacitor), TCPS (Thyristor controlled phase shifter), UPFC (Unified power flow controller), SSSC (Static synchronous series capacitor) are capable of controlling loop power flows or parallel path flows dynamically. Expected effects of these controllers are the reduction of power transmission losses, mitigation of power flow congestion, enhancement of voltage stability, power swing stability and so on. This flexibility, however connects with a price. As the controls influence each other, a good co-ordination is required in order to bring all devices to work together not interfering with each other. Setting these controls may be a difficult task, and the planner or operator will need assistance of computational tools to analyze the effects of the new devices on the system performance.

A. *Thyristor Controlled Series Compensator*

The effect of TCSC on the network can be seen as a controllable reactance inserted in the related transmission line. The model of the network with TCSC is shown in Fig 1. The controllable reactance, xc, is directly used as the control variable to be implemented in the power flow equation. The power flow equations of the branch can be derived as follows:

$$\begin{aligned} P_{mn} &= V_m^2 g_{mn} - V_m V_n g_{mn} \cos(\delta_m - \delta_n) \\ &\quad - V_m V_n b_{mn} \sin(\delta_m - \delta_n) \end{aligned} \tag{1}$$

$$\begin{aligned} Q_{mn} &= -V_m^2 b_{mn} - V_m V_n g_{mn} \sin(\delta_m - \delta_n) \\ &\quad + V_m V_n b_{mn} \cos(\delta_m - \delta_n) \end{aligned} \tag{2}$$

$$\begin{aligned} P_{nm} &= V_n^2 g_{mn} - V_m V_n g_{mn} \cos(\delta_m - \delta_n) \\ &\quad + V_m V_n b_{mn} \sin(\delta_m - \delta_n) \end{aligned} \tag{3}$$

$$\begin{aligned} Q_{nm} &= -V_n^2 b_{mn} + V_m V_n g_{mn} \sin(\delta_m - \delta_n) \\ &\quad + V_m V_n b_{mn} \cos(\delta_m - \delta_n) \end{aligned} \tag{4}$$

where $g_{mn} = \frac{r_{mn}}{r_{mn}^2 + (x_{mn} - x_c)^2}$, $b_{mn} = -\frac{x_{mn} - x_c}{r_{mn}^2 + (x_{mn} - x_c)^2}$

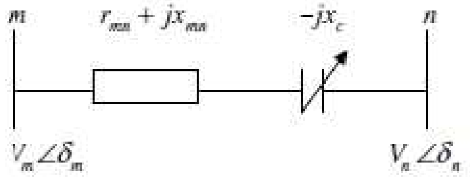

Fig.1. Model of network with TCSC

The TCSC can be operated in bypass –thyristor mode, blocked-thyristor mode and vernier mode. In bypass-thyristor mode, the thyristors are made to fully conduct with a conduction angle of 1800.Gate pulses are applied as soon as the voltage across the thyristors reaches zero and becomes positive, resulting in a continuous flow of current through the thyristor valves. The TCSC module behaves like a parallel capacitor inductor combination. In blocked-thyristor mode, the firing pulses to the thyristor valves are blocked. If the thyristors are conducting and a blocking command is given, the thyristors turn off as soon as the current through them reaches a zero crossing. The net TCSC reactance is capacitive. The vernier mode allows the TCSC to behave either as a continuously controllable capacitive reactance or as a continuously controllable inductive reactance. It is achieved by varying the thyristor-pair firing angle in an appropriate range.

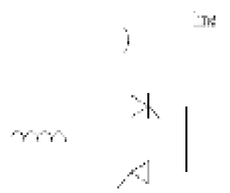

Fig.2. Schematic Diagram of TCSC

An actual TCSC system usually comprises a cascaded combination of many such TCSC modules ,together with a fixed series capacitor. The fixed series capacitor is provide primarily to minimize costs. The equivalent impedance Z_{eq} of this LC combination is expressed as :-

$$Z_{eq} = (j\ 1/wC)\ \|\ (jwL) = -j/(wC-1/wL)$$

The impedance of the fixed capacitor C alone, however is given by –j(1/wC).If wC-1/wL>0 or in the other word wL>1/wC, the reactance of the fixed capacitor C is less than that of the parallel-connected variable reactor and that this combination provides a variable-capacitive reactance.

B. *TCPS (Thyristor controlled Phase Shifter)*

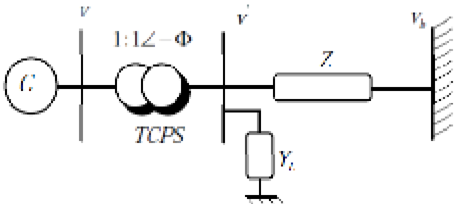

Fig-3, Model of TCPS

Thyristor controlled phase shifting transformer is a phase shifting transformer adjusted by thyristor switches to provide a rapidly variable phase angle. In general, phase shifting is obtained by adding a perpendicular voltage vector in series with a phase as shown in Fig, the perpendicular series voltage is made variable with a variety of power electronic topologies.

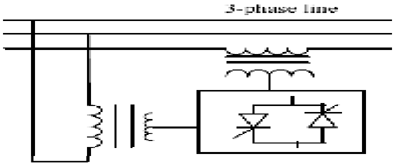

Fig-4, Schematic Diagram of TCPS

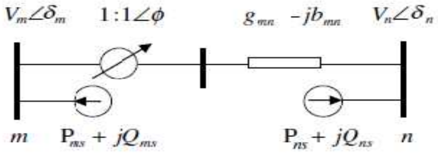

Fig-5, Circuit diagram of TCPS

The power flow equations of the line can be derived as follows:

$$\begin{aligned}
P_{mn} &= \frac{V_m^2 g_{mn}}{\cos^2\phi} - \frac{V_m V_n}{\cos\phi}[g_{mn}\cos(\delta_m - \delta_n + \phi) \\
&\quad + b_{mn}\sin(\delta_m - \delta_n + \phi)] \\
Q_{mn} &= -\frac{V_m^2 b_{mn}}{\cos^2\phi} - \frac{V_m V_n}{\cos\phi}[g_{mn}\sin(\delta_m - \delta_n + \phi) \\
&\quad - b_{mn}\cos(\delta_m - \delta_n + \phi)] \\
P_{nm} &= V_n^2 g_{mn} - \frac{V_m V_n}{\cos\phi}[g_{mn}\cos(\delta_m - \delta_n + \phi) \\
&\quad - b_{mn}\sin(\delta_m - \delta_n + \varphi)] \\
Q_{nm} &= -V_n^2 b_{mn} + \frac{V_m V_n}{\cos\phi}[g_{mn}\sin(\delta_m - \delta_n + \phi) \\
&\quad + b_{mn}\cos(\delta_m - \delta_n + \varphi)]
\end{aligned}$$

The injected real and reactive power of TCPS at bus m and bus n are as follows;

IV. OPTIMAL POWER FLOW PROBLEM FORMULATION

$$P_{ms} = -g_{mn} V_m^2 \tan^2\phi - V_m V_n \tan\phi [g_{mn} \sin(\delta_m - \delta_n) \\ - b_{mn} \cos(\delta_m - \delta_n)]$$

$$Q_{ms} = b_{mn} V_m^2 \tan^2\phi + V_m V_n \tan\phi [g_{mn} \cos(\delta_m - \delta_n) \\ + b_{mn} \sin(\delta_m - \delta_n)]$$

$$P_{ns} = -V_m V_n \tan\phi [g_{mn} \sin(\delta_m - \delta_n) + b_{mn} \cos(\delta_m - \delta_n)]$$

$$Q_{ns} = -V_m V_n \tan\phi [g_{mn} \cos(\delta_m - \delta_n) - b_{mn} \sin(\delta_m - \delta_n)]$$

The optimal power flow problem is a nonlinear optimization problem with nonlinear objective function and nonlinear constraints. The various methods of solving optimal power flow using conventional methods that are being widely used are Newton method, Gradient method and interior point methods. Successful applications of evolutionary programming methods like Genetic algorithm, Evolutionary computations, PSO, Differential evolution etc. Have reduced the limitations of the conventional methods to a great extent. The OPF problem requires the solution of non-linear equations, describing optimal and/or secure operation of a power system. The general OPF problem can be expressed as:

Minimize F(x,u)
Subject to g(x,u) =0
h(x,u)≤0

where $X^T=[\delta V^T_L]$
$U^T = [P_G^T \; V_G^T \; t^T \; Q_{SH}^T]$

The load flow equations are:
P_i-$V_i \sum_{j=1}^{NB} V_j(G_{ij}cos\theta_{ij}$+$B_{ij}sin\theta_{ij}$)=0 i
Q_i-$V_i \sum_{j=1}^{NB} V_j(G_{ij}cos\theta_{ij}$+$B_{ij}sin\theta_{ij}$)=0
Where N_B is the number of buses.
The fuel cost function is given as:

$$\sum_{J=1}^{NB}(a_i \, P_{Gi}^2 + b_i P_{Gi} + c)$$

Where, g(x,u) is a set of nonlinear equality constraints (power flow equations) and h(x,u) a set of nonlinear inequality constraints of a vector argument x and u. The generator fuel cost curve is quadratic ($F=(aP^2+bP+c)$).In fact, it is a polynomial of higher order with some sine or exponential (e) term ,but is reduced to quadratic .The incremental fuel cost is linear and this helps is determining the optimal solution (IFC=dF/dP=λ).In the Indian power scenario, there is an important need to reduce the power losses at the distribution level due to different voltage profile. APDRP (accelerated power development reforms program) is one such effort made by the Indian power sector to reduce power losses by raising the distribution –level voltage from 440 volts to 11kv.Real power loss minimization is different from real power optimization, but strongly related to the context of reactive power optimization. Vector x consists of dependent variables and vector u of control variables. The variables h(x,u) constitute a set of a system operating constraints that include

The state variable vector x consists of the following:
(a) Branch flow $|S_K| \le S_K^{max}$ k=1..........n1
(b) voltage at load buses $V_{LK}^{min} \le V_{LK} \le V_{LK}^{max}$
k=1.......N_L
(c) Generator MVAR $Q_{GK}^{min} \le Q_{GK} \le Q_{GK}^{max}$ k=1.......N_G
(d) Slack bus MW $P_G^{min} \le P_G \le P_G^{max}$

The control variable vector u consist of the following:
(e) Generator MW(except slack bus) $P_{GK}^{min}\le P_{GK} \le P_{GK}^{max}$
(f) Generator bus voltage $V_{LK}^{min}\le V_{LK} \le V_{LK}^{max}$ k=1........N_G
(g) Transformer tap setting $t_{K}^{min}\le t_{K} \le t_{K}^{max}$
The transformer taps are discrete witha change step of 0.0125pu.
(h) Bus shunt capacitor $b_{shK}^{min}\le b_{shK} \le b_{shK}^{max}$ k=1.......NC

V. DIFFERENTIAL EVOLUTION

Differential Evolution (DE) is a type of evolutionary algorithm originally proposed by Price and Storn 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 .. In DE the fittest of an offspring competes one-to-one with that of corresponding parent which is different from other evolutionary algorithm. This one-to-one competition gives rise to faster convergence rate. Price and Storn gave the working principle of DE with simple strategy. The algorithm of a general DE method are given below.

DE computational flow

The main features of the DE algorithm can be stated as follow:

1. Like any other evolutionary algorithm, DE starts with a population size of NP individuals where the individuals are D-dimensional variable vectors.
2. The subsequent generations will be represented by discrete time steps like t=0, 1, 2, . . ., t, t + 1, etc.
3. Since the vectors are likely to be changed over different generations, the following notation may be adopted for representing the ith vector of the population at the current generation (i.e. at time t): Xi(t) = [xi,1(t), xi,2(t), . . . , xi,D(t)]

VI. BLOCK DIAGRAM OF DE

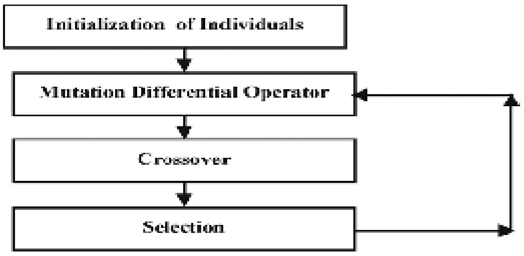

Fig-7, Block Diagram of Differential Evolution

The major stages of DE algorithm can be described as follow

A. Initialization:

At the early stage of DE search, i.e., t = 0, the problem independent variables are initialized somewhere in their feasible numerical range. Therefore, if the jth variable has its lower and upper bounds X_J^L as and X_J^U, respectively, then the jth component of the ith population member may be initialized as:

$$Xi,j(0) = X_J^L + \mathrm{rand}(0,1).X_J^U X_J^L$$

where rand (0,1) is a uniformly distributed random number between 0 and 1.

B. Mutation:

In each generation, a donor vector _*v*i(t) is created in order to change the population member vector _Xi(t). Generally, the method of creating this donor vector demarcates between various DE schemes. In this paper, DE/rand/1 mutation strategy is selected and implemented. In this mutation strategy, creation of the donor vector _*v*i(t) for the ith member x_i passes through the following steps:

1. Three different members x_{r1}, x_{r2} and x_{r3}, are chosen randomly from the current population and not coinciding with the current member x_i.
2. Next, a scalar number F scales the difference between any two of the chosen members and this scaled difference is added to the third one. Therefore, the jth component of _*v*i(t) can be expressed as:
   $v_{ij}(t+1)=x_{r1,j}+F(x_{r2,j}(t)-x_{r3,j}(t))$

C. Crossover:

To increase the diversity of the population, crossover operator is carried out in which the donor vector exchanges its components with those of the current member _Xi(t).

D. Selection:

The selection process can be expressed as,

$$\vec{X}_i(t+1)=\begin{cases}\vec{U}_i(t) & \text{if} \quad f(\vec{U}_i(t))\le f(\vec{X}_i(t))\\ \vec{X}_i(t) & \text{if} \quad f(\vec{X}_i(t))<f(\vec{U}(t))\end{cases}$$

where f() is the function to be minimized. So, if the child yields a better value of the fitness function, it replaces its parent in the next generation; otherwise, the parent is retained in the population.

VII. DE FOR OPF WITH FACTS DEVICES

ALGORITHM

1. Iteration ITER is set to 1
2. Voltage magnitude limits of generator buses are set to 0.95 p.u≤V≤1.1 p.u and load buses are set to 0.95 p.u≤V≤1.05 p.u.
3. Similarly voltage angles limit are taken -14≤δ≤0
4. Now random sets of voltages are selected , Similarly random sets of angles are selected.
   Vg1(q,j)=(rand-(1/2))*(Vmax(j) - Vmin(j))+(1/2) * (Vmax(j) + Vmin(j))
   Vg1(q,j)=(rand-(1/2))*(Vmax(j) - Vmin(j))+(1/2) * (Vmax(j) + Vmin(j))
5. Then line data for IEEE 30 bus system is taken.
6. From line data Table bus admittance matrix is calculated.
7. The bus data is taken consisting of bus number, bus code, and load and generator data.
8. Random values of generator between their maximum and minimum range i.e P_G^{min} and P_G^{max} is taken and assigned to bus data table.
9. Using Newton-Raphson method voltage magnitude, phase angle, flow between the buses and losses are calculated
10. Random generator values are obtained from the bus data table. Then cost is calculated by using parameters a, b, c .e and f of the generators.
11. Generator values and cost for this iteration is stored in matrix.
12. Now TCPS installed between the buses mentioned and phase shift angle taken between -5^0<⍰<5^0
13. TCSC installed between buses and the capacitance limit is taken as such a manner that ratio of maximum series capacitor limit to line capacitor is equal to more than 50%.
14. Random values of capacitance and shifting angles are inserted in line data of a bus data Table respectively.
15. Now the step from i to xi is performed again and again.
16. Results of different iterations are stored in a matrix.

VIII. CONCLUSION

This topic presents a methodology for the representation of FACTS devices such as phase shifter and series compensation in OPF models. The DE method has proven to be very adaptable at solving the OPF problem. The OPF performs generator control and transmission system control while taking into account system limits. The marginal cost data from the OPF were shown to aid in the available transfer capability (ATC) calculation, real and reactive power pricing, and transmission system pricing and transmission system component valuation. At present, the OPF works very well for small systems (less than 50 buses)

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