Congestion Management by Optimal Choice and Allocation of FACTS Controllers using Genetic Algorithm

D. Venugopal, A. Jayalaxmi

***Abstract**: Congestion management is one of the technical challenges in power system deregulation. This paper presents single objective optimization approach for optimal choice, location and size of Static Var Compensators (SVC) and Thyristor Controlled Series Capacitors (TCSC) in power system to improve branch loading (minimize congestion), improve voltage stability and reduce line losses. Though FACTS controllers offer many advantages, their installation cost is very high. Hence, Independent System Operator (ISO) has to locate them optimally to satisfy a desired objective. Genetic Algorithms (GA) are best suitable for solution of combinatorial optimization and multi-objective optimization problems. This paper presents optimal location of FACTS controllers considering Branch loading (BL), Voltage Stability (VS) and Loss Minimization (LM) as objectives at a time using GA. The developed algorithms are tested on IEEE 30 bus system. Various cases like i) uniform line loading ii) line outage iii) bilateral and multilateral transactions between source and sink nodes have been considered to create congestion in the system. The developed algorithm show effective locations for the cases considered for single objective optimization studies.*

***Index Terms**: FACTS, Single objective optimization,SVC, TCSC, real parameter Genetic algorithms.*

I. INTRODUCTION

Transmission lines are often driven close to or even beyond their thermal limits in order to satisfy the increased electric power consumption and trades due to increase of the unplanned power exchanges. If the exchanges were not controlled, some lines located on particular paths may become overloaded, this phenomenon is called congestion. Political and environmental constraints make the building of new transmission lines difficult and restrict the electrical utilities from better use of existing network. It is attractive for electrical utilities to have a way of permitting more efficient use of the transmission lines by controlling the power flows. FACTS devices have provided strategic benefits for better utilization of existing power systems. The parameter and variables of the transmission line, i.e., line impedance, terminal voltages, and voltage angles can be controlled by FACTS devices in a fast and effective way. FACTS devices are operated in a manner so as to ensure that the contractual requirements are fulfilled as far as possible by minimizing line congestion.

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The objective of this paper is to develop an algorithm to find the optimal location and size of multi-type FACTS devices in power system. The optimizations are performed on three parameters: the location of the devices, their types and rated values. The branch loading, voltage stability and line losses are applied as measures of power system performance. Initially, the problem is formulated as a single objective optimization problem considering maximization of branch loading, voltage stability and minimization of loss independently. At each step, congestion is created in the system by uniform overloading, by line outage, by increasing bilateral and multi-lateral transactions between source and sink nodes [5]. This combinatorial optimization problem is solved using GA. This paper is organized as follows: Static models of FACTS controllers are described in section II. Real parameters of GA are described in section III. Section IV presents objectives of the optimization. Simulation results are discussed in section VI. Finally, brief conclusions are deduced.

II. STATIC MODELING OF FACTS CONTROLLERS

This section focuses on the modeling of two kinds of FACTS devices, namely SVC and TCSC [14]. The power flows of the line connected between bus-i and bus-j having series impedance $r_{ij} + jx_{ij}\left(= 1/(g_{ij} + jb_{ij})\right)$ and without any FACTS controllers [1], can be written as,

$$P_{ij} = V_i^2 g_{ij} - V_i V_j \left(g_{ij} \cos\delta_{ij} + b_{ij} \sin\delta_{ij}\right) \quad (1)$$

$$Q_{ij} = -V_i^2 \left(b_{ij} + B_{sh}\right) - V_i V_j \left(g_{ij} \sin\delta_{ij} - b_{ij} \cos\delta_{ij}\right) \quad (2)$$

where V_i, V_j, δ_{ij} are the voltage magnitudes at bus-i and bus-j and voltage angle difference between bus-i and bus-j is given by

$$g_{ij} = \frac{r_{ij}}{r_{ij}^2 + x_{ij}^2} \quad , \quad b_{ij} = \frac{-x_{ij}}{r_{ij}^2 + x_{ij}^2}$$

Similarly, the real power (P_{ji}) and reactive power (Q_{ji}) flows from bus-j to bus-i in the line can be written as

$$P_{ji} = V_j^2 g_{ij} - V_i V_j \left(g_{ij} \cos\delta_{ij} - b_{ij} \sin\delta_{ij}\right) \quad (3)$$

$$Q_{ji} = -V_j^2 \left(b_{ij} + B_{sh}\right) + V_i V_j \left(g_{ij} \sin\delta_{ij} + b_{ij} \cos\delta_{ij}\right) \quad (4)$$

A. Static Representation of TCSC

The basic idea behind power flow control with TCSC is to decrease or increase the overall lines effective series transmission impedance, by adding a capacitive or inductive reactance correspondingly [14]. The TCSC is modeled as variable impedance, where the equivalent reactance of the line x_{ij} is defined as:

$$x_{ij} = x_{line} + x_{TCSC}$$

where, x_{line} is the transmission line reactance [12]. The level of applied compensation of the TCSC usually varies between 20% inductive and 70% capacitive. Fig 1.shows a controllable reactance $(-jx_{TCSC})$ placed in the transmission line connected between bus-i and bus-j.

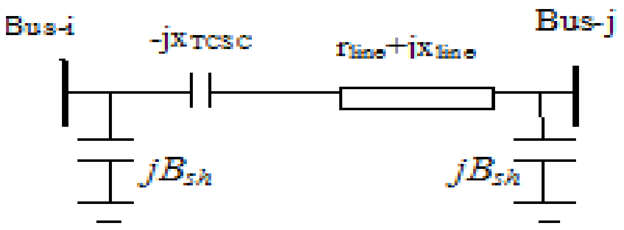

Figure 1. Equivalent Circuit of TCSC

The real and reactive power flows from bus-i to bus-j and bus-j to bus-i in the line can be written with equations (1) to (4) with modified g_{ij} and b_{ij} as given below.

$$g_{ij} = \frac{r_{ij}}{r_{ij}^2 + (x_{ij} - x_{TCSC})^2} \;, \; b_{ij} = \frac{-(x_{ij} - x_{TCSC})}{r_{ij}^2 + (x_{ij} - x_{TCSC})^2}$$

B. Static Representation of SVC

SVC is a shunt connected static Var generator or consumer whose output is adjusted to exchange capacitive or inductive Var so as to maintain or control specific parameters of electrical power system, typically bus voltage [10,11]. Like the TCSC, the SVC combines a series capacitor bank shunted by thyristor controlled reactor. SVC structure is shown in fig.2. Also, shows SVC represented as a continuous variable shunt susceptance.

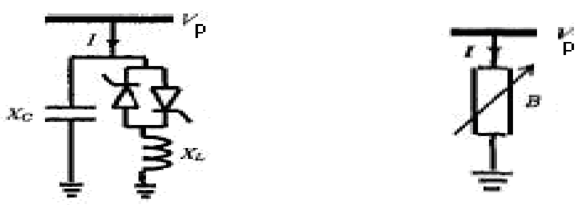

Figure 2. SVC Structure, SVC as Variable Shunt Susceptance

The SVC load flow models can be developed treating SVC susceptance as control variable. Assuming that SVC is connected at node-p to maintain the bus voltage at Vp, the reactive power injected by the controller is given by (5).

$$Q_{pSVC} = -V_p^2 B_{pSVC} \qquad (5)$$

The linearized load flow models make use of eqn. (5) to modify the corresponding Jacobian elements at SVC bus. The SVC load flow model can be developed treating SVC susceptance as control variable (BSVC).

III. GENETIC ALGORITHMS (GA)

GAs are global search algorithms based on mechanisms of natural selection and genetics. GAs start with random generation of initial population and then the selection, crossover and mutation are performed until the best population is found. The goal of the present optimization is to find the best location of a given number of FACTS devices in accordance with a defined objective function within the equality and inequality constraints [13]. The configuration of FACTS devices is encoded by three parameters: the location, type and its rating. Each individual is represented by n_{FACTS} number of strings, where n_{FACTS} is the number of FACTS devices to be optimally located in the power system [3], as shown in fig.3.

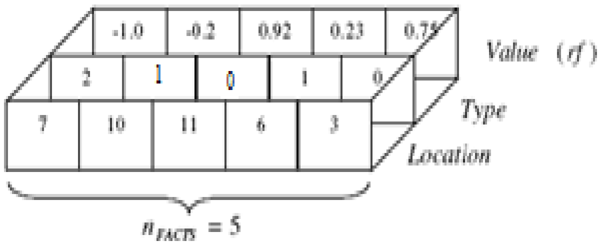

Figure 3. Individual Configuration of FACTS Devices

The first value of each string corresponds to the location information. It must be ensured that on one transmission line there is only one FACTS device.The second value represents the types of FACTS device (n_{type}). The values assigned to FACTS devices are: "1" for SVC located at a bus; "2" for TCSC located in a line, "0" for no FACTS device.The last value rf represents the rating of each FACTS device. This value varies continuously between –1 and +1.If the selected FACTS device is TCSC, then the rated value generated between $-0.7X_{line}$ to $0.2X_{line}$. If it is SVC, the rated value is SVC susceptance (Bsvc) and this value is generated between -0.45p.u to +0.45p.u. To obtain GA population, the above operations are repeated n_{Ind} times, where n_{Ind} is number of individuals of the population. The objective function is computed for every individual of the population and assigned fitness. In our case, the objective functions are defined in order to quantify the impact of the FACTS devices on the state of the power system and are presented in Section IV. Then, the operators of reproduction, crossover and mutation are applied successively to generate the off springs. Reproduction is a process where the individual is selected to move to a new generation according to its fitness. The present work is employed with tournament parent selection technique.

A. Blended (BLX-α) Crossover

The main objective of crossover is to reorganize the information of two different individuals and produce a new one. For two parent solutions $X_i^{(1,t)}$ and $X_i^{(2,t)}$

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(assuming $X_i^{(1,t)} < X_i^{(2,t)}$), the BLX-α randomly picks a solution in the range

$[X_i^{(1,t)} - \alpha(X_i^{(2,t)} - X_i^{(1,t)}), X_i^{(2,t)} + \alpha(X_i^{(2,t)} - X_i^{(1,t)})]$.

If u_i is a random number between 0 and 1, the following (6) is an offspring [6]:

$$X_i^{(1,t+1)} = (1-\gamma_i)X_i^{(1,t)} + \gamma_i X_i^{(2,t)} \quad (6)$$

$where, \gamma_i = (1+2\alpha)u_i - \alpha$. If α is zero, this crossover creates

a random solution in the range $(X_i^{(1,t)}, X_i^{(2,t)})$. It is reported that BLX-0.5(with α=0.5) performs better than BLX operators with any other α value.

B. Non-Uniform Mutation

In Non-uniform Mutation the probability of creating a solution closer to the parent is more than the probability of creating one away from it. However, as the generations (t) proceed, this probability of creating solutions closer to the parent gets higher and higher [6].

For a given parent $X = X_1, X_2, X_3, \ldots\ldots X_K, \ldots\ldots X_l$, if the gene X_K is selected for mutation and the range of X_K is $[U_{min}^K, U_{max}^K]$, then the result (7) X_K' is

$$X_K' = \begin{cases} X_K + \Delta(t, U_{max}^K - X_K) & if\ random\ (0,1) = 0 \\ X_K - \Delta(t, X_K - U_{min}^K) & if\ random\ (0,1) = 1 \end{cases} \quad (7)$$

Where, $\Delta(t,y) = y\left[1 - r^{\left(1-\frac{t}{T}\right)b}\right]$ (8)

$\Delta(t,y)$ (y represents $X_K - U_{min}^K\ and\ U_{min}^K - X_K$) returns a value in the range [*0,y*]. In (8), *r* is a random value in the range of [*0, 1*] and *b* is a parameter determining the degree of non-uniformity. In this simulation, *b*=2 is used.

IV. OBJECTIVES OF THE OPTIMIZATION

The three objectives considered here are branch loading (BL) maximization, voltage stability (VS) maximization and loss minimization (LM).

A. Branch Loading (BL) Maximization

The first objective is related to the branch loading and penalizes overloads in the lines [13]. This term, called BL, is computed for every line of the network. While the branch loading is less than 100%, its value is equal to 1; then it decreases exponentially with the load [6].

$$BL = \prod_{line} J_{line} \quad (9)$$

$$J_{line} = \begin{cases} 1 & ;if\ S_{pq}^{max} \geq S_{pq} \\ e^{\left[\lambda\left(1-\frac{S_{pq}}{S_{pq}^{max}}\right)\right]} & ;if\ S_{pq} > S_{pq}^{max} \end{cases}$$

where, BL is Branch Loading factor, S_{pq} and S_{pq}^{max} are MVA flow and thermal limit of the line between buses p and q. λ is a small positive constant equal to 0.1.

B. Voltage Stability (VS) maximization

The second objective function concerns voltage levels. It favours buses voltages close to 1 p.u. The function is calculated for all buses of the power system. For voltage levels comprised between 0.95 p.u. and 1.05 p.u., the value of the objective function VS is equal to 1. Outside this range, the value decreases exponentially with the voltage deviation [13].

$$VS = \prod_{BUS} J_2 \quad (10)$$

$$J_2 = \begin{cases} 1 & ;if\ 1.05 \geq V_b \geq 0.95 \\ e^{[\mu(1-V_b)]} & ;\quad otherwise \end{cases}$$

where, V_b is Voltage at bus b and μ is a small positive constant equal to 0.1.

C. Loss Minimization (LM) Minimization

For reactive power optimization, system transmission loss minimization is considered as the objective function. The converged load flow solution gives the bus voltage magnitudes and phase angles. Using these, active power flow through the lines can be evaluated. Net system power loss is the sum of power loss in each line.

$$J_3 = \sum_{i=1}^{Nl} LOSS_i = LM \quad (11)$$

where, Nl is the number of transmission lines in a power system.

V. RESULTS AND DISCUSSION

A. Single Objective Optimization

The proposed model is implemented using IEEE 30 bus system. Initially, BL, VS and LM are considered as single objective optimization problems. For case studies, congestion is created in the lines by uniformly loading the system, by line outage and by increasing bilateral and multi-lateral transaction amount. Base case refers to the system normal operating condition, without any optimization objective. GA parameters: Population size: 40, maximum number of generations: 200, Blended (BLX-α) Crossover Probability: 0.95, mutation Probability: 0.001 and elitism index: 0.15. Tournament parent selection technique is used.

Case–i) When the System is Uniformly Loaded:

The system is uniformly loaded by 130%, lines 1 and 10 are loaded by 126.46% and 110.96% respectively. For the BL objective function (9), it is optimized using the real parameter GAs, the obtained objective function values are given in table I and this overloading can be relieved by placing SVC at 11th bus with BSVC of -0.236214p.u and TCSC in 18th line with XTCSC of -0.000501p.u. From Table I it can be further inferred that, when VS is considered as optimization objective, BL is reduced from its base case value and the losses have also increased from its base case value. Considering LM as optimization objective , a reduction in system transmission loss is associated with reduction in BL and VS values.

TABLE I. COMPARISON OF OBJECTVE FUNCTION VALUES AT UNIFORM LOADING OF 130% FOR BASE CASE AND 130% LOADING WITH FACTS DEVICES

Case-ii) When the System is with Line Outage:

When the line 5 is given outage the lines 6 and 8 are loaded by 105.4285% and 117.7534% respectively. For BL objective function (9),it is optimized using the real parameter Gas.The obtained objective function values are given in Table II. This overloading can be relieved by placing SVC at 11th bus with BSVC of -0.375057p.u and three TCSC devices in lines 14,23 and 11 with XTCSC of -0.080656p.u,-0.008245 and -0.024216p.u respectively. Table II also shows the objective function values when VS, LM are considered as independent single objectives. When VS is optimizing objective, the BL show an improvement from base case value, but not as much as is improved in the BL optimization case. The line losses are also increased from base case value. When LM is considered as optimization objective, both BL and VS increase but could not attain the values in BL, VS optimization case. This clearly shows the conflicting nature of the considered objectives. In both these cases congested lines are restricted to thermal limits and system voltage profile has been improved. Table III shows the optimal location of FACTS devices with type of the device ,location of the device and rated value of the device .

TABLE II. COMPARISON OF OBJECTIVE FUNCTION VALUES WHEN OUTAGE IS OCCURS AT LINE 5

	Line 5 is given outage	**Line 5 is given outage with FACTS devices**		
		BL	***VS***	***LM***
BL	25.0162	488.06224	486.1121	483.3938
VS	121.1703	242.7302	314.5073	248.7432
LM	0.1691	0.17025	0.17058	0.167679

TABLE III. OPTIMAL ALLOCATION OF FACTS DEVICES WITH LOCATION TYPE AND RATED VALUES OF THEDEVICE

Rated value of FACTS device	-0.325978	-0.346388	0.244239	0	0
Type of FACTS device	2	2	1	0	0
Location of FACTS device	33	31	28	10	29

Case-iii) When the System is with Bilateral Transaction:

Consider a bilateral transaction between the supplier at node 13 and the consumer at node 5. By increasing the transaction amount to 145% of base case, lines 1 gets loaded by 102.1176% .Objective function is taken as BL from (9). This congestion can be relieved by placing SVCat bus13 with B_{SVC} of -0.037881p.u and TCSC device in lines 24 with X_{TCSC} of 0.3359921p.u respectively.

Figures 4 and 5 present the convergence characteristics of Genetic algorithms for line 5 given outage after placing FACTS devices.

	Base case	**130% loading with FACTS devices**		
		BL	***VS***	***LM***
BL	2537.045	2536.942	2356.242.215	2692.991
VS	1210.617	1210.550	1313.298	1279.618
LM	0.190028	0.1899	0.194517	0.199524

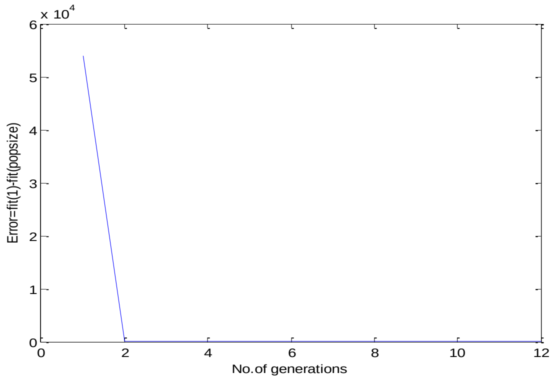

Figure 4 Variation of no. of Generations Vs Error for Branch Loading Objective

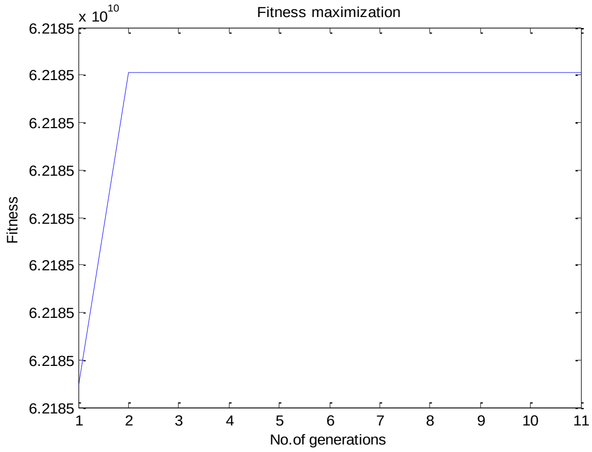

Figure 5 Fitness Maximization for Branch Loading Objective Function

Case-iv) When the system is with Multilateral Transaction

Consider a multi-lateral transaction between the supplier at node 5 and the consumer at nodes 12 and 24. The base case P_{gen} at supplier node 5 is 0.2456p.u., P_{load} at consumer nodes 12 and 24 are 0.112p.u, 0.087p.u respectively. By increasing the transaction amount by 150% at supplier node and drawing the same amount at consumer nodes then lines 14 and 29 get loaded by 122.2383% and 106.2494% respectively. Objective function is taken as BL from (9).

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This overloading can be relieved by placing SVC at bus 30 with B_{SVC} of -0.574376p.u and two TCSC devices in lines 15 and 37 with X_{TCSC} of -0.047801p.u.,-0.274047p.u, respectively.

VI. CONCLUSIONS

In this paper an algorithm is developed for optimal choice and location of FACTS controllers for congestion management in deregulated power systems. Congestion is created in the system using i) uniform loading ii) line outage iii) bilateral transaction and iv) multilateral transactions. Optimal location of FACTS devices to relieve line congestion is treated as a single objective optimization problem considering i) BL ii) VS and iii) TL as objectives. It is observed that the locations which present favorable solution with respect to one of the objectives are not effective with respect to other objectives. The proposed GA with SVC, TCSC models evolves as a good optimization algorithm for single objective optimization studies of optimal location of FACTS controllers' problem.

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