Enhanced Genetic Algorithm Approach for Security Constrained Optimal Power Flow Including FACTS Devices

R.Narmatha Banu, D.Devaraj

Abstract—This paper presents a genetic algorithm based approach for solving security constrained optimal power flow problem (SCOPF) including FACTS devices. The optimal location of FACTS devices are identified using an index called overload index and the optimal values are obtained using an enhanced genetic algorithm. The optimal allocation by the proposed method optimizes the investment, taking into account its effects on security in terms of the alleviation of line overloads. The proposed approach has been tested on IEEE-30 bus system to show the effectiveness of the proposed algorithm for solving the SCOPF problem.

Keywords—Optimal Power Flow, Genetic Algorithm, Flexible AC transmission system (FACTS) devices, Severity Index (SI), Security Enhancement, Thyristor controlled series capacitor (TCSC).

I. INTRODUCTION

IN any power system, unexpected outages of lines or transformers occur due to faults or other disturbances. These events, referred to as contingencies, may cause significant overloading of transmission lines or transformers, which in turn may lead to a viability crisis of the power system. The principle role of power system control is to maintain a secure system state, i.e., to prevent the power system, moving from secure state into emergency state over the widest range of operating conditions. Optimal Power Flow (OPF) is major tool used to improve the security of the system. The security of the system can be improved either through preventive control or post contingency corrective action. Alsac and Stott [2] extended the penalty function method to security constrained optimal power flow problem in which all the contingency case constraints are augmented to the optimal power flow problem. In this method the functional inequality constraints are handled as soft constraints using penalty function technique. The drawback of this approach is the difficulty involved in choosing proper penalty weights for different systems and different operating conditions which if not properly selected may lead to excessive oscillatory convergence. This combined with prohibitively large computing time makes this method unsuitable for online implementation. Apart from using

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preventive approach for security enhancement, the post contingency state corrective action can also be used for security enhancement. The resulting stage has the same security level as the usual security – constrained optimal power flow case with lower operating cost. The power electronics-based FACTS devices can also be employed for corrective action due to its high speed of response. Thyristor controlled series capacitor (TCSC) is one such device which offers smooth and flexible control of the line impedance, with much faster response compared to the traditional control devices. TCSC can be used effectively in maintaining system security in case of a contingency; by eliminating or alleviating overloads along the selected network branches. It is important to ascertain the location for the placement of these devices due to their considerable costs. In this paper, the location of the TCSC is identified based on the overload index.

The optimal base case control variables and the post contingency TCSC settings are obtained as the solutions to SCOPF problem of minimizing over loaded lines for single line outages. The various formulation aim at either minimizing the total fuel cost or minimizing some defined objective function ie minimizing/alleviating the line overloads with system security constraints [1,2]. A number of mathematical programming based techniques have been proposed to solve the optimal power flow problem. These include the gradient method [2-4], Newton method [5] and linear programming [6].The gradient and Newton methods suffer from the difficulty in handling inequality constraints. To apply linear programming, the input-output function is to be expressed as a set of linear functions which may lead to loss of accuracy. Recently global optimization techniques such as the genetic algorithm have been proposed to solve the optimal power flow problem [8, 9]. A genetic algorithm [10] is a stochastic search technique based on the mechanics of natural genetics and natural selection. In this paper, Genetic Algorithm is used to solve the security constrained optimal power flow problem.

The proposed algorithm solves the SCOPF problem subject to the power balance equality constraints, limits on control variables namely active power generation, controllable voltage magnitude pertaining to the base case, thyristor control series capacitor (TCSC) for contingency case studies. The effectiveness of the proposed approach is demonstrated through preventive and corrective control action for a few harmful contingencies in the IEEE -30 bus system.

II. MODELING AND PLACEMENT OF TCSC

TCSCs are connected in series with the lines. The effect of a TCSC on the network can be seen as a controllable reactance inserted in related transmission line that compensates for the inductive reactance of the line. This reduces the transfer reactance between the buses to which the line is connected. This leads to an increase in the maximum power that can be transferred on that line in addition to reduction in effective reactive power losses. In this study, TCSC acts as the capacitive reactance. Fig. 1 shows a model of a transmission line with TCSC connected between buses 'i' and 'j'. The transmission line is represented by its lumped – equivalent parameters connected between buses.
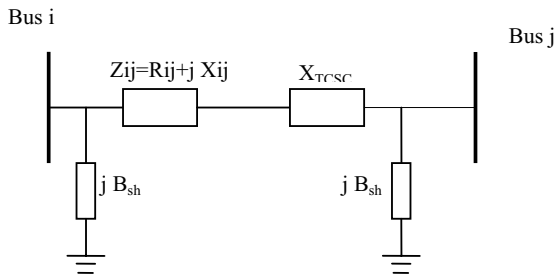

Fig. 1 Model of a TCSC

During the steady state, the TCSC can be considered as a static reactance jx_{TCSC}. This equivalent circuit model represents the thyristor controlled series capacitor as a continuous variable. The controllable reactance x_{TCSC} is directly used as the control variable to be implemented in the power flow equation. The power flow equations of branch can be derived as follows

$$\left.\begin{aligned} P_{ij} &= U_i^2 g_{ij} - U_i U_j (g_{ij} \cos \delta_{ij} + b_{ij} \sin \delta_{ij}) \\ Q_{ij} &= -U_i^2 b_{ij} - U_i U_j (g_{ij} \sin \delta_{ij} - b_{ij} \cos \delta_{ij}) \end{aligned}\right\} \quad (1)$$

where

$$g_{ij} = r_{ij} / (r_{ij}^2 + (x_{ij} - x_c)^2)$$

$$b_{ij} = x_{ij} - x_c / (r_{ij}^2 + (x_{ij} - x_c)^2)$$

The difference between normal line power flow equation and the TCSC line power flow equation is the controllable reactance X_C. In this study, the reactance of the transmission line is adjusted by TCSC directly. The rating of TCSC is depending on the reactance of the transmission line where the TCSC is located.

$$x_{ij} = x_{line} + x_{t \, csc} \quad (2)$$

$$x_{t \, csc} = r_{t \, csc} \, x_{line} \quad (3)$$

where , x_{line} is the reactance of the transmission line and r_{tcsc} is the coefficient which represents the degree of compensation by TCSC.

More than one TCSC may have to be installed in order to achieve the desired performance for a large-scale power system. However, obvious budgetary constraints force the utilities to limit the number of TCSCs to be placed in a given system. Given such a limit on the total number of TCSCs to be installed in a power system, the locations of these TCSCs can be determined according to the ranking of branches and system topology. In this paper, candidate sites for installing TCSC have been pre-examined for the most severe contingencies. The severity of contingency is evaluated in terms of the line overload index. The procedure for selecting the locations to place TCSCs involves the following steps:

1. Identify overloaded lines for each critical contingencies

2. From the overloaded lines , select four common lines to place TCSCs

After selecting common locations, the optimal values of TCSCs are found out using Genetic algorithm

III. PROBLEM FORMULATION

The objective of the SCOPF problem is the minimization of total fuel cost pertaining to base case and alleviation of line over load under contingency case. The adjustable system quantities such as controllable real power generations, controllable voltage magnitudes in the base case and the TCSC setting in the contingency state are taken as control variables. The equality constraint set comprises of power flow equations corresponding to the base case as well as the postulated contingency cases [13].The inequality constraints include control constraints, reactive power generation and load bus voltage magnitude and transmission line flow constraints pertaining to the base case as well as the postulated contingency cases. The mathematical description of objective functions and its associated constraints are presented below

A. Preventive control sub problem or base case operation sub problem

$$Min \ F_T = \sum_{i=1}^{N_g} (a_i P_{gi}^2 + b_i P_{gi} + C_n) \qquad \$/hr \qquad (4)$$

Subject to the constraints

the base case power flow constraints

$$\left.\begin{aligned} P_i - U_i \sum_{\substack{i=1 \\ i=N_b-1}}^{N_g} U_j (G_{ij} \cos \Theta_{ij} + B_{ij} \sin \Theta_{ij}) &= 0 \\ Q_i - U_i \sum_{\substack{i=1 \\ i=N_{PQ}}}^{N_g} U_j (G_{ij} \sin \Theta_{ij} - B_{ij} \cos \Theta_{ij}) &= 0 \end{aligned}\right\} \quad (5)$$

the base-case real and reactive power generation, load bus voltage magnitude and line flow operating constraints

$$\left. \begin{array}{ll} P_{gi}^{\min} \leq P_{gi} \leq P_{gi}^{\max} & ; \ i \in N_B \\ Q_{gi}^{\min} \leq Q_{gi} \leq Q_{gi}^{\max} & ; \ i \in N_B \\ U_i^{\min} \leq U_i \leq U_i^{\max} & ; \ i \in N_B \\ S_l \leq S_l^{\max} & ; \ i \in N_B \end{array} \right\} \quad (6)$$

B. Corrective control sub problem (contingency state)

The objective in the contingency state is to minimize or alleviate the line overloads whose detailed expression is given in equation (8). The problem can be written as

$$Min \ SI_l = \sum_{l=1}^{L_O} \left(\frac{S_l}{S_l^{\max}} \right)^{2m} \quad (7)$$

where,

SI = Severity Index (Overload index)
S_l = MVA flow in line l
$S_l^{\max}$ = MVA rating of the line l.
L_0 = set of overloaded lines.
m = integer exponent.

Subject to

$$\left. \begin{array}{l} P_i^c - U_i^c \sum\limits_{\substack{j=1 \\ i \in N_{PQ}}}^{N_g} U_j^c (G_{ij} \cos \Theta_{ij} + B_{ij} \sin \Theta_{ij}) = 0 \\ \\ Q_i^c - U_i^c \sum\limits_{\substack{j=1 \\ j \in N_{PQ}}}^{N_g} U_j^c (G_{ij} \sin \Theta_{ij} - B_{ij} \cos \Theta_{ij}) = 0 \end{array} \right\} \quad (8)$$

the contingency case line flow security constraints and TCSC reactance constraints

$$\left. \begin{array}{l} S_l^c \leq S_l^{c\,\max} \quad ; \ i \in N_l \\ X_{ci}^{\min} \leq X_{ci} \leq X_{ci}^{\max} , i \in N_{TCSC} \end{array} \right\} \quad (9)$$

where C characterizes the Cth post-contingency state
To avoid overcompensation, the working range of the TCSC is chosen between $-0.5.X_{line}$ and $0.5.X_{line}$. By optimizing the reactance values between these ranges optimal setting of reactance values can be achieved.

C. Overall problem formulation

The overall problem may be stated as

$$Minimize \ F = Min \ (F_T + w * SI_l) \quad (10)$$

where 'w' is the weight factor.
subject to constraints (5-7) & (9-10)

The SCOPF in its general form is a nonlinear, non convex, static, large scale optimization problem with both continuous and discrete variables [2], [3]. The SCOPF has been formulated under two modes "preventive" [2] and "corrective" [3], [11] .In this paper we focus on the preventive as well as corrective control SCOPF problems.

IV. REVIEW OF GENETIC ALGORITHM

Genetic algorithms (GA) [10] are generalized search algorithms based on the mechanics of natural genetics. GA maintains a population of individuals that represent the candidate solutions. Each individual is evaluated to give some measure of its fitness to the problem from the objective function. They combine solution evaluation with stochastic genetic operators to obtain optimality. The details of the genetic operators are given below.

A. Selection Strategy

The selection of parents to produce successive generations plays an important role in the GA. This allows the fitter individuals to be selected more often to reproduce. There are a number of selection methods proposed in the literature [8], fitness proportionate selection, ranking and tournament selection. Tournament selection is used in this work. In this method, n individuals are copied at random from the population and the best of the n is inserted into population for further genetic processing. This procedure is repeated until the mating pool is filled. Tournaments are often held between pairs of individuals although larger tournaments can be held.

B. Crossover

Crossover is an important operator of the GA. It is a structured, yet randomized mechanism of exchanging information between strings. It is usually applied with high probability (0.6-0.9). It promotes the exploration of new regions in search space. In this paper, cross swapping operator is applied on the selected individuals. Here, two different cross sites of parent chromosomes are chosen at random. This will divide the string into three substrings. The cross over operation is completed by exchanging the middle substring between strings

C. Mutation

Mutation is a background operator, which introduces some sort of artificial diversification in the population to avoid premature convergence to local optimum (i.e) it prevents complete loss of genetic material through reproduction and crossover by ensuring that the probability of searching any region in the problem is never zero. Bit wise mutation is used in this work. Bit wise mutation changes a 1 to a 0, and vice versa, with a mutation probability of Pm.

The above mentioned operations of selection, crossover and mutation are repeated until the best individual is found

V. GENETIC ALGORITHM IMPLEMENTATION

When applying GA to solve a particular optimization problem, two main issues must be addressed
(i)   representation of the decision variables and
(ii)   formation of the fitness function

A. Problem Representation

Each individual in the genetic population represents a candidate solution. In the binary coded GA, the solution variables are represented by a string of binary alphabets. The

size of the string depends on the precision of the solution required. For problems with more than one decision variables, each variable is represented by a substring and all the substrings are concatenated to form a bigger string.

In the OPF problem under consideration, generator active-power P_{gi}, generator terminal voltages V_{gi} and the TCSC reactance values X_{TCSC} are the optimization variables. With this representation, a typical chromosome of the OPF problem looks like the following Fig. 2

$$L_{pj} = \begin{cases} K_l(S_l - S_l^{\max}) & if \ S_l > S_l^{\max} \\ 0 & otherwise \end{cases}$$

GA is usually designed to maximize the fitness function which is a measure of the quality of each candidate solution. Therefore a transformation is needed to convert the objective of the OPF problem to an appropriate fitness function to be maximized by GA. Therefore the GA fitness function is formed as follows: $F = k/f$, where, 'k' is a large constant.

97.5	100.8	...	250.70	0.975	1.020	...	0.90	-0.5	.....	0.5
P_{g2}	P_{g3}	...	P_{gn}	U_{g1}	U_{g2}	...	U_{gn}	$TCSC_1$	...	$TCSC_n$

Fig. 2 Chromosome structure

B. Fitness Function

The objective of the SCOPF problem is to minimize fuel cost in the base case and the severity index value under contingency case satisfying the constraints (8)-(9). For each individual, the equality constraints (5) and (8) are satisfied by running Newton Raphson algorithm and the constraints on the state variables are taken into considerations by adding penalty function to the objective function

$$Min \ f = F_T + (w \times SI_l) + SP + \sum_{i=1}^{N_l} UP_j + \sum_{j=1}^{N_g} QP_j + \sum_{j=1}^{N_l} LP_j$$

(11)

where,

F_T represents total fuel cost
SI_l represents the severity index
SP, UPj, QPj and LPj are the penalty terms for the reference bus generator active power limit violation, load bus voltage limit violation; reactive power generation limit violation and the line flow limit violation respectively.
These quantities are defined by the following equations:

$$S_p = \begin{cases} K_S(P_S - P_S^{\max}) & if \ P_S > P_S^{\max} \\ K_S(P_S^{\min} - P_S) & if \ P_S < P_S^{\min} \\ 0 & otherwise \end{cases}$$

$$U_{pj} = \begin{cases} K_U(U_j - U_j^{\max})^2 & if \ U_j > U_j^{\max} \\ K_U(U_j - U_j^{\min})^2 & if \ U_j < U_j^{\min} \\ 0 & otherwise \end{cases}$$

$$Q_{Pj} = \begin{cases} K_q(Q_j - Q_j^{\max})^2 & if \ Q_j > Q_j^{\max} \\ K_q(Q_j - Q_j^{\min})^2 & if \ Q_j < Q_j^{\min} \\ 0 & otherwise \end{cases}$$

VI. NUMERICAL RESULTS

The proposed methodology was applied to solve the SCOPF problem in IEEE -30 bus test systems. IEEE -30 bus system has 6 generators and 41 transmission lines. The generator and transmission line data relevant to the system are taken from [2]. The simulation results of which are presented here. In order to demonstrate the performance of the proposed method, two cases are considered .In case 1, the OPF problem is solved with real power generation and bus voltages as the control variable while in case 2, SCOPF problem is solved with TCSC reactance as the additional control variable. The parameters used for the simulations are $U_{\min}$=0.9 p.u, U_{max}=1.1 p.u and the slack bus bar voltage is 1.06 p.u.

Case 1: Base case OPF Results

Here the contingencies are not considered and the GA based algorithm was applied to find the optimal scheduling of the power system for the base case loading condition given in [2]. The objective function in this case is the minimization of total fuel cost. Generator active power output and the generator bus bar terminal voltages were taken as the optimization variables. The optimal values of control variables obtained are given in table 1. The minimum cost obtained with the proposed algorithm is near to the minimum cost of 802.4 $/h, reported in [2] using gradient method. Corresponding to this control variable, it was found that there are no limit violations in any of the state variables. This fact demonstrates that the proposed algorithm is very robust and reliable in eliminating the limit violations.

TABLE I
BASE CONTROL VARIABLES (CASE 1)

P1	P2	P5	P8	P11	P13	U1	U2	U3	U4	U5	U6	Fuel cost
173.6	50.2	21.8	23.8	10.8	12.3	0.966	0.9987	0.959	0.9688	1.0266	0.950	802..32 $/hr

TABLE II
SUMMARY OF CONTINGENCY ANALYSIS FOR IEEE 30-BUS SYSTEM

Outage Line No.	Over loaded lines	Line flow (MVA)	Line flow limit (MVA)	Severity Index (SI)	Rank
1-2	1-3 3-4 4-6	191.58 174.13 103.37	130 130 90	5.262	1
1-3	1-2 2-6	181.17 66.482	130 65	3.010	2
3-4	1-2 2-6	178.43 65.558	130 65	2.9011	3
2-5	2-6	76.285	65	1.3777	4
28-27	22-24 24-25	19.062 17.781	16 16	2.1979	5
4-6	1-2 2-6	132.63 69.921	130 65	0.6327	6

TABLE III
TCSC LOCATIONS IN IEEE 30 BUS SYSTEMS

Line outage	1-2	1-3	3-4
TCSC Location	2-6 2-5 3-4 6-7	1-2 2-5 6-7 10-21	1-2 2-5 5-7 10-21

TABLE IV
CONTROL VARIABLE SETTINGS FOR SCOPF

Real power settings (Base case)	171.99 (P1)	43.00 (P2)	23.88 (P5)	25.034 (P8)	11.27 (P11)	19.223 (P13)	Fuel Cost : 812.49 $/hr
TCSC settings	Line outage (1-2) -0.3710, 0.2742, -0.0484, 0.0806			Line outage (1-3) 0.4032, -0.1129, -0.4032, 0.2742			Line outage (1-4) 0.2097, -0.4032, -0.4677, 0.0484
Severity index value	0			0			0

Case 2: SCOPF Results

In this case all possible branch contingencies are considered. As a preliminary computation, the contingency analysis was carried out first. According to these results, the most severe contingencies are the outages of lines [(1–2), (1–3), and (3–4)]. Table 2 shows the result of contingency analysis.

In Table 2, the column labeled "SI" is the initial value of severity index. Corresponding to the first three contingencies, the candidate locations for placing the TCSC are identified.

The four locations identified for each contingency are given in table 3.

From this the four locations for placing the TCSC are identified as (2-6), (2-5),(6-7) & (10-27).After selecting the location of the TCSC, the optimal settings of TCSCs were selected within the working range ($-0.5.X_{line}$ and $0.5.X_{line}$.) by applying GA by minimizing (10). GA control parameters are,

Generation: 60
Populationsize: 30
Crossoverprobability: 0.85
Mutation probability: 0.01
String length: 5
Variable size: 8.

After 60 generation it was found that all the individuals have reached almost the same fitness value. This shows that GA has reached the optimal solution. Fig. 3 shows the variation of fitness during the GA run for the best case.
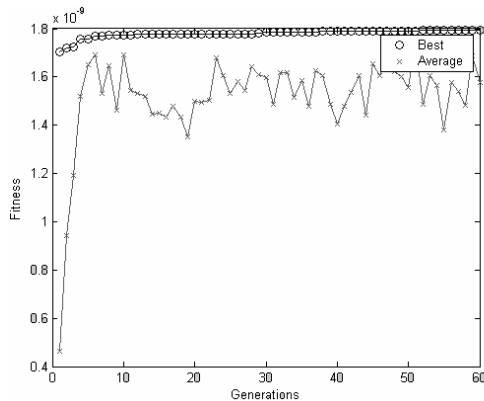

Fig. 3 Convergence of the GA-SCOPF algorithm

Table 4 presents the optimal control variable settings of real power generation and reactance of TCSCs for all three cases along with severity index values. From this table, it is evident that the overloading of the transmission lines has been completely alleviated, in all the three contingencies. Table 5 gives a comparison between the proposed approach and the other algorithms reported in the literature in the case of fuel cost minimization objective. This demonstrates the potential and effectiveness of the proposed approach to solve the OPF problem.

TABLE V
COMPARISON OF SCOPF RESULTS

Method	Total Fuel cost ($/hr)	Total Generation (MW)
Method Proposed in [2]	813.74	290.50
Method proposed in [13]	813.73	290.50
Proposed Algorithm	**812.49**	294.3970

VII. CONCLUSIONS

This paper has presented an effective method for solving SCOPF problem. The objective function is taken as the minimization of the total fuel cost under normal operating condition and minimize/eliminate the line overloads under contingency case. A new procedure has been used to place TCSC along the system branches in an attempt to alleviate overloads during contingencies and a GA based approach is proposed to identify the optimal control variable setting. IEEE-30bus test system is used to evaluate the performance of the proposed approach. Numerical results confirm the effectiveness of the proposed procedure in improving the security of the system.

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