OVERLOADED LINE MINIMISATION INCORPORATING FACTS DEVICES

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Abstract: This paper deals with power system network contingency due to branch overloading and voltage violation. It leads to insecure conditions like block outs in power system. In order to provide proper security in power system by alleviate overloads Flexible AC Transmission system (FACTS) is widely used. The location is then identified using single real power flow performance index. The identification of the optimal location of FACTS devices like TCSC and TCPAR are obtained using an enhanced genetic algorithm. The effectiveness of FACTS devises for overloaded line minimization is verified using IEEE 30 bus system.

Keywords: Severity index (SI), real power flow performance index (PI), Thyristor Controlled Series Capacitor (TCSC), Thyristor Controlled Phase Angle Regulator (TCPAR), Enhanced OPF based Genetic Algorithm

1. 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 feasibility crisis of the power system FACTS controllers such as thyristor controlled series compensators (TCSC), Thyristor to controlled phase angle regulators (TCPAR) can enhance the power system security by effectively controlling the line flows.

Controlling the power flows in the network helps in reducing the flows in heavily loaded lines, resulting increased system loadability, less system loss and improved security of the system [1].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 [2]. Contingency analysis of a power system is a major action in power system development and process. Contingency analysis is used to evaluate violation [3]. To improve security analysis of power system [4]. It is necessary to find overloaded lines. The line outage allocation factors are utilized to present contingency analysis in power system. The single line contingency sensitivity index which is used to rank the system branches is proposed in this paper. According to the result the most severity line is identified. Real power flow performance index is applied in each branch to determine the branches which are suitable for FACTS placement [5]. The different types of FACTS devices have been chosen and placed optimally in order to control the power flows in the power system network [6]. Then it is crucial factor to find the optimal location of FACTS device.

The OPF solution gives the optimal settings of all controllable variables for a static power system loading condition. A number of mathematical approaches have been proposed to solve the OPF problem. In this paper, Enhanced Genetic algorithm is used to search the optimal setting of TCSC &TCPAR parameters. Performance of this method is analyzed in relation with several GA operators' type of crossover, selection and mutation [7].

This paper mainly focuses the overloaded line minimization by using TCSC and TCPAR device. Section 2 describes the contingency ranking based on severity index. FACTS device location based on real power flow performance index is given in section 3.Section 4 briefly describes the Genetic algorithm Simulation results are given in section 5 and references are listed out in section 6.

2. CONTINGENCY ANALYSIS

Contingency analysis is a major activity in the power system planning and operation [8]. Single line contingency analysis is carried out using severity index is mentioned below and based on that contingency ranking result is listed in section 6.

Severity Index (SI)

$$SI_l = \sum_{l=1}^{Lo} \left(\frac{S_l}{S_l^{\max}} \right)^{2m} \qquad (1)$$

Where,

S_l =MVA flow in line 1

$S_l^{\max}$ =MVA rating of the line 1

L_o =set of overloaded lines.

m =integer exponent

The power flow in transmission lines (1) are obtained from Newton-Rapson load flow calculation. The difference of maximum rating of transmission line $(S_l^{\max})$ and actual flow (S_l) identifies the over loaded line. In order to avoid masking effect the value of m is taken as 1.

3. FACTS DEVICES

In 1988, Hingorani defined the FACTS concept [9]. FACTS devices can able to control the various electrical parameters such as the voltage magnitude at chosen buses, the phase angle and line impedances of transmission line. They will provide advantages such as control of power flow, avoiding blackouts, improving voltage stability, limiting short circuit currents, etc; the four categories of FACTS namely series, shunt, series-series and combined series shunt controllers. In this paper two FACTS controllers such as Thyristor controlled series compensator (TCSC) and Thyristor Controlled Phase Angle Regulator (TCPAR) have been considered.

3.1 Thyristor Controlled Series Capacitor (TCSC)

Thyristor controlled series capacitor (TCSC) is a one of the main component FACTS device and connected in series with the transmission line [10]. TCSC is a capacitive reactance compensator, which is used to control the effective line reactance by connecting a TCR combination with mechanically switched capacitor section in series. These are the three combination thyristor controlled reactors (TCR) thyristor controlled capacitors (TSC) and fixed capacitors (FC). TSR is based on thyristor without the gate turn off capability. TCSC can be used effectively in maintaining system security. The model of a transmission line with series impedance $Z_{ij} = r_{ij} + jx_{ij}$ and a TCSC connected between bus-i and bus-j is shown in Figure1. Consider that the complex voltages at bus-i and bus-j are $V_i \angle \delta_i$ and $V_j \angle \delta_{j,}$ respectively. During the steady state, the TCSC can be considered as a static reactance offering an impedance of $-jx_c$

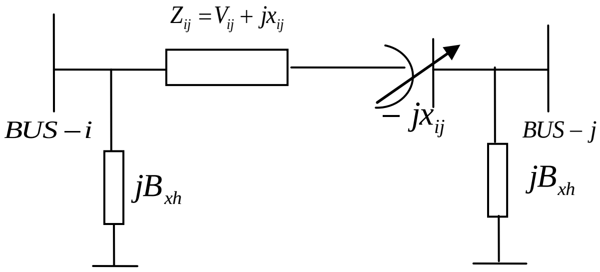


Figure1. Equivalent circuit of TCSC Model

The controllable reactance x_c is directly used as the control variable to in the power flow equation The power flow equations of a transmission line with TCSC can be written as

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

$$Q_{ij} = -V_i^2 b_{ij} - V_i V_j (g_{ij} \sin\delta_{ij} - b_{ij} \cos\delta_{ij}) \qquad (2)$$

Where,

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

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

Here, the only difference between normal line power flow equation and the TCSC line power flow equation is the controllable reactance x_c where TCSC acts as the capacitive or inductive compensation respectively. 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

$$x_{ij} = x_{line} + x_{t\,\mathrm{csc}} \qquad (3)$$

$$x_{t\,\mathrm{csc}} = r_{t\,\mathrm{csc}} x_{line} \qquad (4)$$

Where, X_{line} is the reactance of the transmission line and $r_{t\,\mathrm{csc}}$ is the coefficient which represents the degree of compensation, by TCSC. To evade overcompensation, the working range of 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 location of reactance values can be achieved.

3.2 Thyristor Controlled Phase Angle Regulator (TCPAR)

TCPAR is the series compensation devices. TCPAR is also a thyristor based compensator which makes it possible to increase or decrease the power forward in the line [11, 12]. A phase shifter model can be represented by an equivalent circuit, which is equation (5) it consists of admittance in series with an ideal transformer having a complex turn's ratio $K\angle\phi$. The static model of a TCPAR in transmission line between bus-i and bus-j is shown in Figure 2. From the basic circuit theory; the injected equivalent circuit of figure can be obtained

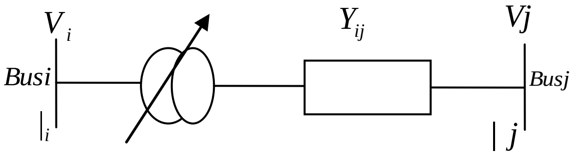


Figure2. Equivalent circuit of TCPAR

The injected active power at bus-'i' (P_{is}) and bus-j (P_{js}) of a line having a phase shifter can be written as,

$$P_{is} = -V_i^2 K G_{ij} - V_i V_j K[G_{ij} \sin\delta_{ij} - B_{ij} \cos\delta_{ij}] \tag{5}$$

$$P_{js} = -V_i V_j K[G_{ij} \sin\delta_{ij} + B_{ij} \cos\delta_{ij}] \tag{6}$$

Where

K=tanϕ

The mathematical model of phase shifter can be derived as follows

$$\begin{bmatrix} \vec{I}_i \\ \hline \bar{I}_j \end{bmatrix} = \begin{bmatrix} Y_{ij}'+Y & -Y_{ij}' \\ -Y_{ij}' & Y_{ij}'+Y_i \end{bmatrix} \begin{bmatrix} \bar{V}_i \\ \hline \bar{V}_j \end{bmatrix} \tag{7}$$

Where

$$Y_i = Y'_{ij}\left[\frac{1}{K^2} - 1 + \left(1 - \frac{1}{K\angle -\phi}\right)\frac{V_i}{V_j}\right] \tag{8}$$

$$Y_j = Y_{ij}'\left[\left(1 - \frac{1}{K\angle\phi}\right)\frac{V_i}{V_j}\right] \tag{9}$$

In TCPAR to nullify overcompensation [13] quadrature component is added to the prevailing bus voltage to increase or decrease its angle range between $-20^0 \le \phi_{TCPAR} \le +20^0$ .The optimal locations of TCPAR is then achieved by optimizing the angle values between these ranges.

3.3 Problem Formulation

The conventional formulation of OPF problem [14] determines the optimal settings of control variables such as real power generations, generator terminal voltages, transformer tap setting and reactance values of TCSCs while minimizing an objective function as fuel cost given in (10)

$$F_T = \Sigma(a_i p_{gi}^2 + b_i p_{gi} + c_i) \tag{10}$$

During security control, the prime task of the power system operator would be to remove the line overload. Hence the minimum severity index is taken as the objective function in this paper. The minimization problem is subjected to the constraints.

(i) Load flow constraints:

$$\left.\begin{aligned} P_i - V\sum_{\substack{j=1 \\ i=N_{PQ}}}^{N_B} V_j\left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) = 0 \\ Q_i - V_i\sum_{\substack{j=1 \\ i\in N_{PQ}}}^{N_b} V_j\left(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}\right) = 0 \end{aligned}\right\} \tag{11}$$

(ii) Voltage constraint

$$V_i^{\min} \le V_i \le V_i^{\max} ; i \in N_B \qquad (12)$$

(iii) Unit constraints

$$\left.\begin{array}{l} P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} ; i \in N_B \\ Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} ; i \in N_B \end{array}\right\} \qquad (13)$$

(iv)Transmission line flow constraint

$$S_l \le S_l^{\max} ; i \in N_l \qquad (14)$$

(v) TCSC reactance constraint

$$X_{ci}^{\min} \le X_{ci} \le X_{ci}^{\max} ; i \in N_{TCSC} \qquad (15)$$

The power flow equations are used as equality constraints and the inequality constraints are the limit on active and reactive power generations, TCSC reactance settings, bus bar voltage magnitudes and apparent power flows.

4. PLACEMENT OF TCSC AND TCPAR

The location of TCSC is identified using real power flow performance index (PI) [15, 16] as given below.

$$PI = \sum_{m=1}^{N_l} \frac{w_m}{2n} \left(\frac{P_{lm}}{P_{lm}^{\max}} \right)^{2n} \qquad (16)$$

Where,

P_{lm} = is the real power flow

$P_{lm}^{\max}$ = is the rated capacity of the line-‘m’

n = is the exponenent

w_m = A real non negative weighting coefficient

This may be used to reflect the relative importance of the lines. N_l is the total number of lines in the network. In this study, the value of exponent has been taken as 2 and $w_m = 1$

The control parameters considered for TCSC is the effective line reactance X_{ij} the real power flow PI sensitivity factors with respect to the parameters of TCSC can be defined as,

$$c^k = \frac{\partial PI}{\partial X_{i,j}} / = PI \quad \text{Sensitivity with respect to } X_{ij} \qquad (17)$$

Where x_{ij} is the value of the reactance, as provided by the TCSC installed on line K the sensitivity of PI with respect to TCSC parameter connected between bus-i and bus-j can be written as,

$$\frac{\partial PI}{\partial x_{ij}} = \sum_{m=1}^{N_l} w_m P_{lm}^3 \left(\frac{1}{P_{lm}^{\max}} \right)^4 \frac{\partial P_{lm}}{\partial x_{ij}} \qquad (18)$$

The location of TCPAR is identified using real power flow performance index. A sensitivity approach has been used to see the suitability of the FACTS devices in the line. The real power flow PI sensitivity factors with respect to the parameters of TCPAR can be defined as,

$a_k^c = \frac{\partial PI}{\partial \phi_k} /_{\phi_k = 0}$ =PI sensitivity with respect to line 'K' (19)

$$\frac{\partial PI}{\partial X_k} = \sum_{m=1}^{N_l} w_m P_{lm}^3 \left[\frac{1}{P_{lm}^{\max}} \right]^4 \frac{\partial P_{lm}}{\partial X_k} \qquad (20)$$

Equations (20) were calculated for TCPAR placed in every line one at a time for the same operating conditions. The TCPAR should be placed in a line (k) having largest absolute value of sensitivity factor.

5. REVIEW OF GENETIC ALGORITHM

Genetic algorithms (GA) are essentially search algorithms based on the mechanics of nature (e.g. natural selection, survival of the fittest) and natural genetics. It combines solution evaluation with randomized, structured exchanges of information between solutions to obtain optimality. Genetic algorithms are considered to be robust methods because solution for given system.

Calculate no restrictions on the solution space are made during the process. The power of this algorithm comes from its ability to exploit historical information structures from previous solution guesses in an attempt to increase performance of future solution structures.

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. In each generation, a new population is formed by selecting the more fit individuals based on particular selection strategy. Some members of new population undergo genetic operations to form new solutions. Two commonly used genetic operators are crossover and mutation. Crossover is a mixing operator that combines genetic material from selected parents. Mutation acts as a background operator and is used to search the unexplored search space by randomly changing the values at one or more positions of the selected chromosome. The detailed various components of proposed algorithm are presented in the following subsection

5.1 Genetic Algorithm Implementation

When applying GAs to solve a particular optimization problem, two main issues have to be there 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 [17]. In the binary coded GA, the solution variables are represented by a string of double 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 usually represented by a substring. All substring are concatenated together to form a bigger string. In OPF problem under consideration, variables need to be determined by the optimization algorithm are generator active-power $P_{gi,}$ generator terminal voltages V_{gi} and the TCSC reactance values X_{TCSC}.These variables are represented in their natural form, $i.e\ P_{gi}, V_{gi}$ and the X_{TCSC} values are represented as real numbers. With this representation, a typical chromosome of the OPF problem looks like the following Figure3. The use of floating point numbers in the GA representation has a number of advantages over binary encoding. The efficiency of the GA is increased as there is no need to convert the solution variable to binary type. Moreover, less memory is required and there is no loss in precision by discretization to binary or other values. Also, there is greater freedom to use different genetic operator

Figure3. Chromosome structure

97.5	100.8	...	250.70	0.975	1.020	...	0.90	-0.5	...	0.5
Pg2	Pg3	....	Pgn	Vg1	Vg2	....	Vgn	TCSC1	....	TCSCn

B. Fitness function

The objective is to minimize the severity index value under contingency case satisfying the constraints (11)-(15). For each individual, the equality constraints (11) are satisfied by running Newton Raphson algorithm and the constraints on

The state variables are taken in to considerations by adding penalty function to the objective function. Thus the new objective function becomes,

$$\text{Min f=} SI + SP + \sum_{j=1}^{N_i} VP_J + \sum_{i=1}^{N_g} OP_j + \sum_{j=1}^{N_L} LP_j \qquad (21)$$

Here, **SP, Vpj, QPj** and **LPj** are the penalty terms for the reference bus generator active power generation 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:

$$SP = \begin{cases} K_S(P_S - P_S^{\max}) & if \quad P_S \rangle P_S^{\max} \\ K_S(P_S - P_S^{\min}) & if \quad P_S \langle P_S^{\min} \\ 0 & \text{otherwise} \end{cases}$$

$$VP_j = \begin{cases} K_V(V_j - V_j^{\max})^2 & if \quad V_j \rangle V_j^{\max} \\ K_V(V_j - V_j^{\min})^2 & if \quad V_j \langle V_j^{\min} \\ 0 & \text{otherwise} \end{cases}$$

$$QP_j = \begin{cases} K_q(Q_j - Q_j^{\max})^2 & if \quad Q_j \rangle Q_j^{\max} \\ K_q(Q_j - Q_j^{\min})^2 & if \quad Q_j \langle Q_j^{\min} \\ 0 & \text{otherwise} \end{cases}$$

$$LP_j = \begin{cases} K_l(S_l - S_{\max})^2 \\ 0 & \text{otherwise} \end{cases}$$

GA is usually designed to maximize the fitness function, which is a measure of the quality of each candidate solution. In the OPF under consideration, the objective is to minimize

The severity in the post contingency state satisfying the equality and inequality constraints (11, 15) 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 produced as follows

$$F = K/(1+f)$$

Where, k=a large constant. In the denominator a value of 1 is added with f in order to avoid division by zero in case of complete overload alleviation.

C. Selection Strategy

The selection of parents to produce successive generations plays an important role in the GA. The goal allows the fittest individuals to be selected more often to reproduce. There are a number of selection methods proposed in the literature [10] fitness proportionate selection, ranking and tournament selection. Fitness proportionate selection is used in this work. In this selection, individual strings are copied according to their objective function values (fitness function values). Copying strings according to their fitness values means that strings with a higher value have a higher probability of contributing one or more offspring in the next generation. This operator is an artificial version of natural selection, as Darwinian survival of the fittest among string creatures.

D. Crossover

Crossover is an important operator of the GA. It is responsible for the structure recombination (information exchange between mating chromosomes) and the convergence speed of the GA and it is usually applied with high probability (0.6-0.9).After selection operation, simple crossover proceeds. It is the primary genetic operator, which promotes the exploration of new regions in search space. Crossover is a structured, yet randomized mechanism of exchanging information between strings.

E. Mutation

Mutation is a background operator, which produces spontaneous changes in various chromosomes. In artificial genetic systems the mutation operator protects against some irrecoverable loss. It is the occasional random alteration of the value in the string position. Mutation is needed because even though reproduction and crossover effectively search and recombine extent notions, occasionally they may become overzealous and lose some potentially useful genetic material.

6. SIMULATION RESULTS

The proposed method has been tested on IEEE 30 bus system, which consists of six generators and 41 transmission lines. The generator and transmission-line data applicable to the system are taken from [17]. The upper and lower voltage limits at all the bus bars expect slack were taken as 1.10p.u and 0.95p.u respectively. The slack bus bar voltage was fixed to its particular value of 1.06p.u. It is assumed that the impedance of all TCSCs can be varied within 50% of the related branch impedance and the limits of the phase shifting angles of TCPAR were taken as $\pm 20^0$ and the limits of TCSC were taken as ± 0.5 .

In this system each and every single possible branch contingencies be present measured. As a first calculation, the contingency analysis was carried out first. According towards these results, the for the most part severe contingences were the outage of lines [(1-2), (1-3), and (4-6)] in table 1 and 4, the column labelled "**SI**" is the initial calculation of severity index. Calculation of **PI** was carried exposed to make out the proper locations of the TCSCs and TCPAR to alleviate the line overload. In common the larger PI value a branch have, the more sensitive it will be present. The four locations were identified for every contingency in table 2and 5.

The GA based OPF algorithm was practical to improve the line overload in all four severe contingency cases. Generator active power and the reactance values of TCSCs are taken as the control variable. The limits of the TCSCs were taken as ± 0.5 . And TCPAR limit range $\pm 20^0$ .The lowest severity index is unavailable as the aim purpose of GA. The algorithm was run for a maximum of 100 generation. The best results of the GA were obtained with the following control parameters: Number of Generations-100The population size -30, Crossover probability-0.85 and Mutation Probability-0.01

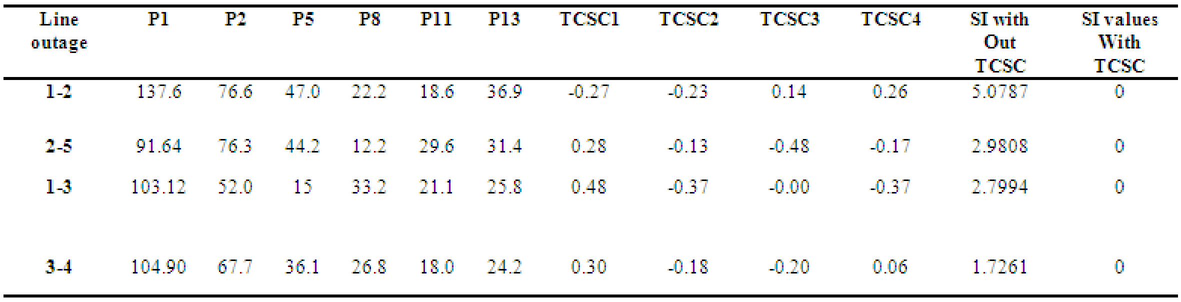
TABLE 1. Line outage ranking using severity index

Outage Line No	Over Loaded lines	Line Flow (MVA)	Line Flow Limit (MVA)	Severity Index (SI)	rank
1-2	1-3	183.02	130	5.0787	1
	3-4	172.93	130		
	4-6	103.68	90		
2-5	2-6	77.39	65	2.9808	2
	5-7	87.52	70		
1-3	1-2	173.80	130	2.7994	3
	2-6	65.39	65		
3-4	1-2	170.80	130	1.7261	4
4-6	2-6	68.07	65	1.1000	5

TABLE 2. TCSC Location in IEEE-30 Bus system

Line outage	1-2	2-5	1-3	3-4
TCSC location	1-3	1-2	1-2	1-2
	3-4	2-6	2-5	2-5
	4-6	4-6	4-6	4-6
	10-20	22-24	22-24	22-27

TABLE 3. Control variable setting for corrective action in IEEE-30Bus system



Line outage	P1	P2	P5	P8	P11	P13	TCSC1	TCSC2	TCSC3	TCSC4	SI with Out TCSC	SI values With TCSC
1-2	137.6	76.6	47.0	22.2	18.6	36.9	-0.27	-0.23	0.14	0.26	5.0787	0
2-5	91.64	76.3	44.2	12.2	29.6	31.4	0.28	-0.13	-0.48	-0.17	2.9808	0
1-3	103.12	52.0	15	33.2	21.1	25.8	0.48	-0.37	-0.00	-0.37	2.7994	0
3-4	104.90	67.7	36.1	26.8	18.0	24.2	0.30	-0.18	-0.20	0.06	1.7261	0

TABLE 4. Line outage ranking using severity index

Outage Line No	Over Loaded lines	Line Flow (MVA)	Line Flow Limit (MVA)	Severity Index (SI)	rank
1-2	1-3	192.03.	130	5.6770	1
	3-4	182.87	130		
	4-6	110	90		
1-3	2-6	183.23	130	3.0757	2
	5-7	67.83	65		
3-4	1-2	173.80	130	2.9859	3
	2-6	65.39	65		
4-6	1-2	170.80	130	1.4242	4

TABLE 5. TCPAR Location in IEEE-30Bus System

Line outage	**1-2**	**2-5**	**1-3**	**3-4**
TCSC location	1-3	1-2	1-2	1-2
	2-5	2-4	2-5	2-5
	4-6	3-4	2-6	2-6
	5-7	4-6	3-4	3-4

TABLE 6. Control variable setting for corrective action in IEEE-30Bus System

Line outage	**P1**	**P2**	**P5**	**P8**	**P11**	**P13**	**TCPAR 1**	**TCPAR 2**	**TCPAR 3**	**TCPAR 4**	**SI with Out TCSC**	**SI values With TCSC**
1-2	97.54	79.06	49.35	34.60	30.01	39.63	17.41	5.80	-4.51	13.54	5.0787	0
1-3	199.89	79.97	49.90	34.68	28.20	38.07	-8.38	9.67	5.80	-3.22	2.9808	0
3-4	118.49	79.92	49.63	34.90	29.03	37.23	8.38	-20.00	-10.96	-5.80	2.7994	0
4-6	166.44	79.94	49.94	34.95	30.15	12.05	9.67	9.67	-18.70	-5.80	1.7261	0

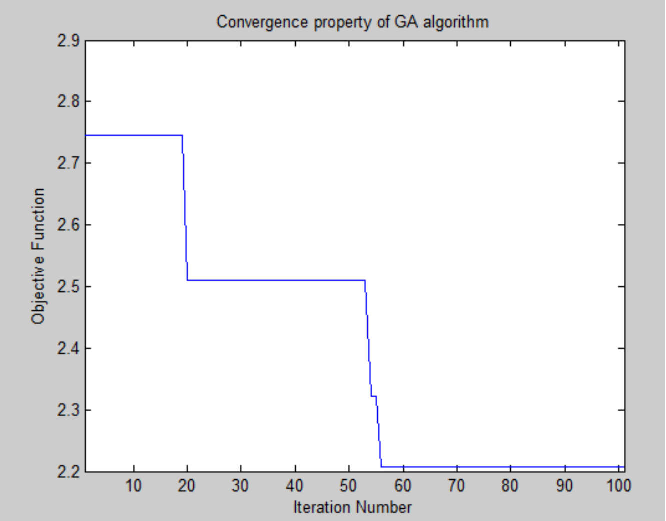


Figure 4. Convergence of the GA-OPF algorithm

After 100 generation it was found that all the individuals have reached almost the same objective function value. This shows that GA has reached the optimal solution. Figure4.

Shows the variation of fitness during the GA run for the best case. Table 3and6 presents the optimal control variable settings for all four cases, along with the final values of severity index. Corresponding to these control variables, it was found that all the state variables satisfy the lower and upper limits. This shows the effectiveness of the proposed algorithm for line over load elevation.

7. CONCLUSIONS

This paper discuses contingency analysis of overloaded line using FACTS devices. The severity index result index result gives the most severity line which is to be protected during contingency condition. The location of FACTS devices are identified using real power flow performance index. The FACTS device parameters are optimized using enhanced genetic algorithm (GA) to find optimum location of FACTS devices. The result shows enhanced genetic algorithm produces better result compared to other optimization method.

8. SCOPE FOR FURTHER RESEARCH

In this work Genetic algorithm is applied only for a small system like IEEE 30 bus system. In future it may be extended to larger system using IEEE 118 bus system and also this work will be compared with Particle swarm optimization method (PSO).

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