Minimization of line overloading and real power loss by optimal placement and sizing of TCSC using genetic algorithm

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Abstract – **In this paper genetic algorithm (GA) based approach has been proposed for optimal placement and sizing of thyristor controlled series compensator (TCSC) for minimization of line overloading and real power loss (PL) in a power system. The TCSC devices are the modern power electronics based devices by which power flow may be controlled and transmission losses can be reduced and hence transfer capability of the transmission line can be enhanced. To implement GA, most severe single line outage contingencies have been selected by calculating overloading index (OLI) for various contingencies and then ranking them in decreasing order of their severity. Thereafter, considering some of the most critical contingencies one-by-one, GA has been implemented for finding the optimal location and size of TCSC for line overloading and real power loss reduction one-by-one. A MATLAB coding is developed for implementing GA. To examine the effectiveness of the GA based approach, it has been implemented on IEEE 30-bus test systems and the results obtained are found to quite satisfactory.**

***Keywords* - Overloading index (OLI), Real power loss (PL), Genetic algorithm (GA), Thyristor controlled series compensator (TCSC).**

I. INTRODUCTION

In the present day development, private power producers are increasing rapidly to meet the increased demand of electricity. In this process power system operation faces new challenges due to restructuring of the electricity industry. For last few decades, load demand is continuously increasing. Due to this, the magnitudes of the power flows in some of the transmission lines sometimes reaches very near to its maximum limits, while in some other lines, it is very low in comparison to their maximum rating. In case of contingencies, some of the lines get overloaded and power system becomes insecure which is the most undesirable state of a power system. With ever increasing load demand, for operating a power system efficiently and maintaining the power system security during contingencies, either existing transmission or generation facilities must be utilized more efficiently or new facilities should be added to the existing power system. Due to the constraints such as lack of investment and difficulties in getting new transmission line, this is not a feasible option, but maximum efficiency with existing system can be attained by using Flexible Alternating Current transmission system (FACTS) devices. FACTS device are the solid state converters having capability of improving power transmission capacity, improving bus voltage profile, enhancing power system stability, minimizing transmission losses etc. In order to optimize and to obtain the maximum benefits from their use, the main issues to be considered are type of FACTS devices, its optimal location and its rating. Commonly used FACTS devices are static var compensator (SVC), thyristor controlled series compensator (TCSC) and unified power flow controller (UPFC) etc. SVC and STATCOM are connected in shunt with the system to improve voltage profile by injecting or absorbing the reactive power, while TCSC is connected in series with the system.

Similar to other FACTS devices, TCSC is also a costly device; therefore it is important to find its optimal location and its size [1], in order to minimize line overloading and system losses in a power system. The complicated problem of optimal location and sizing of FACTS devices has been handled by researchers in various ways by considering different objective functions. To improve the voltage security index of a power system an alternative solution is to locate an appropriate FACTS device [2]. Conventionally, sensitivity analysis is used to decide the optimal placement of TCSC for static security enhancement and for reactive power dispatch. Real power performance index has been used for determining the optimal location of TCSC for congestion management and reduction of total system reactive power losses in deregulated power system, while OPF formulation has been proposed for investment recovery of FACTS devices in the deregulated electricity market [3]. Various methods like sequential quadratic programming, mixed integer programming and line stability index has been proposed for optimal location and sizing of TCSC for voltage stability enhancement. With the advent of evolutionary computational techniques like particle swarm optimization (PSO), differential evolution (DE), simulated annealing (SA), etc, these methods has been applied for the problem of optimal location of FACTS devices [4].

This paper proposes a genetic algorithm (GA) based approach to find out the optimal location and size of TCSC for minimizing line overloading and the real power loss for severe single line outage contingencies. Severity of a single line outage contingency has been determined on the basis of overloading index (OLI) in the power system. The contingency providing the highest value of OLI is considered as the most severe contingency. Optimal location and sizing of TCSC has been determined by applying GA for most critical contingencies one-by-one. Effectiveness of the proposed genetic algorithm (GA) based approach has been tested on IEEE 30-bus system [5]. Genetic Algorithm toolbox of Matlab has been used for finding optimal location and size of TCSC [11-12].

II. OBJECTIVE FUNCTION

A. Overloading Index (OLI)

The severity of a contingency can be evaluated by an overloading index:

$$OLI = \sum_{l \in nl} \frac{W}{2n} \left(\frac{\Delta Sl^{avg}}{Sl^{max}}\right)^{2n} \quad (1)$$

Where n =2, nl is the no. of overloaded lines. Sl^{max} is the rated capacity of line, n is the exponent and W a real non-negative weighing coefficient which may be used to reflect the importance of lines. OLI will be zero when all the lines are within their maximum power flow limits and will reach a high value when there are overloads. Thus, it provides a good measure of severity of the line overloads for a given state of the power system. Most of the works on contingency selection algorithms utilize the second order overloading indices which, in general, suffer from masking effects. The lack of discrimination, in which the overloading index in for a case with many small violations may be comparable in value to the index for a case with one huge violation, is known as masking effect. By most of the operational standards, the system with one huge violation is much more severe than that with many small violations. Masking effect to some extent can be avoided using higher order overloading indices that is n > 1. However, in this study, the value of exponent has been taken as 2 and W = 1.

B. Real power loss (PL)

The second objective of this work is to determine the optimal location and sizing of TCSC in the power system to minimize the real power loss. The real power loss describe as:

$$PL = \sum_{j=1}^{N} g_k \left[V_i^2 + V_j^2 - 2V_iV_j \cos(\delta_i - \delta_j)\right] \quad (2)$$

Subjected to the following equality constraints:

$$P_{gi} - P_{di} - \sum_{j=1}^{N} |V_i||V_j||Y_{ij}| \mathrm{Cos}\,(\delta_{ij} - \theta_{ij}) = 0 \quad (3)$$

$$Q_{gi} - Q_{di} - \sum_{j=1}^{N} |V_i||V_j||Y_{ij}| \mathrm{Sin}\,(\delta_{ij} - \theta_{ij}) = 0 \quad (4)$$

And following inequality constraints:

$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max}$ $\forall_i \in$NG , $Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max}$ $\forall_i \in$ NG

$V_j^{min} \le V_j \le V_i^{max}$ $\forall_i \in$ NG , $\delta_{ij}^{min} \le \delta_{ij} \le \delta_{ij}^{max}$ $\forall_i \in$ NG

$X_{TCSC}^{min} \le X_i \le X_{TCSC}^{max}$

Where PL is the power loss in the k^{th} line, ntl is the number of lines in the system, N is the set of buses, NG is the set of generation buses, Y_{ij} Is the magnitude of ij element in admittance matrix, θ_{ij} phase angle of ij element in admittance matrix, P_{gi} and Q_{gi} are the active and reactive power generation at bus i, P_{di} and Q_{di} are the active and reactive power load at bus i, V_i is the voltage magnitude at bus i, δ_{ij} is the phase angle, X_{TCSC} is the reactance of TCSC.

III. MATHEMATICAL MODEL OF TCSC

The model of a transmission line with a TCSC connected between bus-i and bus-j is shown in Fig. 1. During the steady state, the TCSC can be considered as a static reactance $-jx_c$. The real and reactive power flow from bus-i to bus-j, and from bus-j to bus-i of a line having series impedance and a series reactance can be written as follows [3]:

$$P_{ij}^c = V_i^2 G_{ij}' - V_iV_j\,(G_{ij}' \cos\delta_{ij} + B_{ij}' \sin\delta_{ij}) \quad (5)$$

$$Q_{ij}^c = -V_i^2 (B_{ij}' + B_{sh}) - V_iV_j\,(G_{ij}' \sin\delta_{ij} - B_{ij}' \cos\delta_{ij}) \quad (6)$$

$$P_{ji}^c = V_j^2 G_{ij}' - V_iV_j\,(G_{ij}' \cos\delta_{ij} - B_{ij}' \sin\delta_{ij}) \quad (7)$$

$$Q_{ij}^c = -V_j^2 (B_{ij}' + B_{sh}) + V_iV_j\,(G_{ij}' \sin\delta_{ij} + B_{ij}' \cos\delta_{ij}) \quad (8)$$

The active and reactive power loss in the line having TCSC can be written as,

$$P_L = P_{ij} + P_{ji} = G_{ij}'(V_i^2 + V_j^2) - 2V_iV_jG_{ij}' \cos\delta_{ij} \quad (9)$$

$$Q_L = Q_{ij} + Q_{ji} = -(V_i^2 + V_j^2)(B_{ij}' + B_{sh}) + 2V_iV_jB_{ij}' \cos\delta_{ij} \quad (10)$$

Where $G_{ij}' = \dfrac{r_{ij}}{r_{ij}^2 + (x_{ij} - x_c)^2}$

and $B_{ij}' = \dfrac{-(x_{ij} - x_c)}{r_{ij}^2 + (x_{ij} - x_c)^2}$

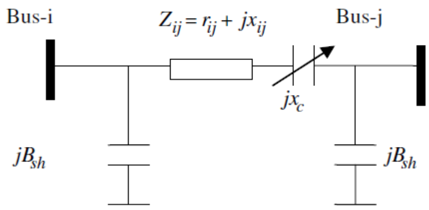

Fig. 1.Model of transmission line with TCSC

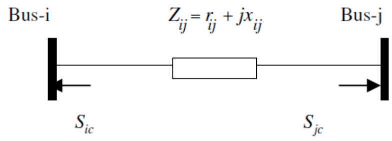

Fig. 2.Injection model of TCSC

The line flow change due to series capacitance can be expressed as a line without series capacitance with power

Injected at the receiving and sending ends of the line as shown in Fig. 2.

The real and reactive power injections at bus-i and bus-j can be expressed as,

$$P_{ic} = V_i^2\,\Delta G_{ij} - V_i V_j\,[\Delta G_{ij}\cos\delta_{ij} + \Delta B_{ij}\sin\delta_{ij}] \quad (11)$$
$$P_{jc} = V_i^2\,\Delta G_{ij} - V_i V_j\,[\Delta G_{ij}\cos\delta_{ij} - \Delta B_{ij}\sin\delta_{ij}] \quad (12)$$
$$Q_{ic} = -V_i^2\,\Delta B_{ij} - V_i V_j\,[\Delta G_{ij}\sin\delta_{ij} - \Delta B_{ij}\cos\delta_{ij}] \quad (13)$$
$$Q_{jc} = -V_i^2\,\Delta B_{ij} + V_i V_j\,[\Delta G_{ij}\sin\delta_{ij} + \Delta B_{ij}\cos\delta_{ij}] \quad (14)$$

where $$\Delta G_{ij} = \frac{x_c r_{ij}\,(x_c - 2x_{ij})}{\left(r_{ij}^2 + x_{ij}^2\right)\,(r_{ij}^2 + (x_{ij} - x_c)^2}$$

and

$$\Delta B_{ij} = \frac{-x_c\,(r_{ij}^2 - x_{ij}^2 + x_c x_{ij})}{\left(r_{ij}^2 + x_{ij}^2\right)\,(r_{ij}^2 + (x_{ij} - x_c)^2}$$

$X_{C,}$ the rating of TCSC depends on reactance x_{ij} of the line *i-j*, to prevent over compensation TCSC reactance is considered between -0.7 x_{ij} to 0.3 x_{ij}.

IV.GENETIC ALGORITHM

The robustness, efficiency and flexibility of biological system encouraged scientists led by john Holland to search for artificial system that would function in the same way as biological systems. Genetic algorithms (GA) were first described by John Holland (1975) [6], who presented them as an abstraction of biological evolution and gave a theoretical mathematical framework for adaptation. The Genetic algorithm has been used to solve difficult engineering problems that are complex and difficult to solve by conventional optimization methods [7-9]. GA maintains and manipulates a population of solutions and executes a survival of the fittest strategy in their search for better solutions. The fittest individuals of any population tend to reproduce and survive to the next generation thus improving successive generations. The inferior individuals can also survive and reproduce.

Modification of GA requires the determination of six fundamental issues: chromosome representation, selection function, the genetic operators, initialization, termination and evaluation function. Brief descriptions about these issues are provided in the following sections [10].

A. Chromosome representation

Chromosome representation scheme determines how the problem is prepared in the GA and also determines the genetic operators that are used. Each individual or chromosome is made up of a sequence of genes. Various types of representations of an individual or chromosome are: binary digits, floating point numbers, integers, real values, matrices, etc. Generally natural representations are more efficient and produce better solutions.

B. Selection function

To produce successive generations, selection of individuals plays a very significant role in a genetic algorithm. The selection function determines which of the individuals will survive and move on to the next generation. A probabilistic selection is performed based upon the individual's fitness such that the superior individuals have more chance of being selected. There are several schemes for the selection process: roulette wheel selection and its extensions, scaling techniques, tournament, normal geometric, elitist models and ranking methods.

The selection approach assigns a probability of selection P_j to each individuals based on its fitness value. In the present study, normalized geometric selection function has been used.

In normalized geometric ranking, the probability of selecting an individual P_i is defined as:

$$P_i = q'(1-q)^{r-1} \quad (15)$$

$$q' = \frac{q}{1-(1-q)^{r-1}} \quad (16)$$

Where,

q = probability of selecting the best individual

r = rank of the individual (with best equals 1)

P = population size

C. Genetic operators

The basic search mechanism of the GA is provided by the genetic operators. There are two basic types of operators: crossover and mutation. These operators are used to produce new solutions based on existing solutions in the population. Crossover takes two individuals to be parents and produces two new individuals while mutation alters one individual to produce a single new solution. The following genetic operators are usually employed: arithmetic crossover, simple crossover and uniform mutation and heuristic crossover as crossover operator, non-uniform mutation, multi-non-uniform mutation, boundary mutation as mutation operator. Arithmetic crossover and non-uniform mutation are employed in the present study as genetic operators. Crossover generates a random number r from a uniform distribution from 1 to m and creates two new individuals by using equations:

$$x_i' = \begin{cases} x_i, & if\ i<r \\ y_i & otherwise \end{cases} \quad (17)$$

$$y_i' = \begin{cases} y_i, & if\ i<r \\ x_i & otherwise \end{cases} \quad (18)$$

Arithmetic crossover produces two complimentary linear combinations of the parents, where r = U (0, 1):

$$\bar{X}' = r\,\bar{X} + (1\text{-r})\,\bar{Y} \quad (19)$$

$$\bar{Y}' = r\,\bar{Y} + (1\text{-r})\,\bar{X} \quad (20)$$

Non-uniform mutation at random selection one variable j and sets it equal to a non-uniform random number.

$$x_i' = \begin{cases} x_i + (x_i - x_i)\,f(G)\ if\ r_1 < 0.5 \\ x_i + (x_i - a_i)\,f(G)\ if\ r_1 < 0.5 \\ x_i, & otherwise \end{cases} \quad (21)$$

Where,

$$f(G) = (r_2\ (1 - \frac{G}{G_{max}}))^b \quad (22)$$

r_1, r_2 = uniform random nos. between 0 to 1.
G = current generation.
G_{max} = maximum no. of generations.
b = shape parameter.

D. Initialization, termination and evaluation function

An initial population is needed to start the genetic algorithm procedure. The initial population can be randomly generated or can be taken from other methods. The GA moves from generation to generation until a stopping criterion is met. The stopping criterion could be highest number of generations, population convergence criteria, lack of improvement in the best solution over a specified number of generations or target value for the objective function.

Evaluation functions or objective functions of many forms can be used in a GA so that the function can map the population into a partially ordered set. The computational flowchart of the GA optimization process employed in the present work is shown in Fig. 3.

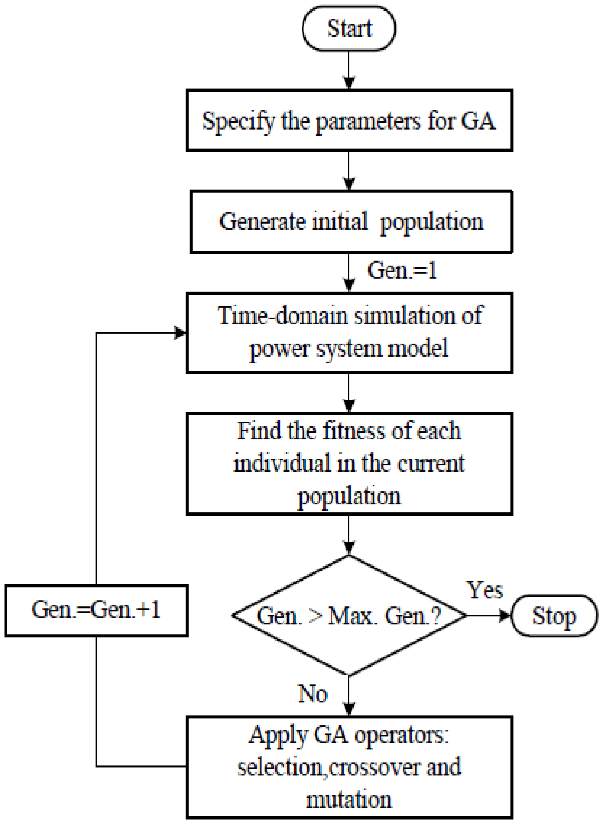

Fig.3 Flowchart of genetic algorithm

V. RESULT AND DISCUSSION

The effectiveness of proposed GA based method is illustrated by applying the approach in IEEE 30-bus system [5]. This test system consists of 6 generation buses, 24 load buses, and 41 transmission lines. In this paper, the optimal placement and size of TCSC has been determined for minimization of overloading index and real power loss in the power system. The largest value of overloading index indicates the most critical line amongst the all lines in a power system. Ranking of four most critical lines is given in Table1.

The four most critical lines are 10, 36, 27 and 15 respectively. As can be observed from Table 1, line no. 10 (connected to buses 6-8) has highest value of overloading index. Therefore, this line is ranked as the most crtical contingency. For these 4 selected most crtical contingencies, GA has been applied for optimal placement and sizing of TCSC in this paper. The optimization parameters are given in Table 2 .

Table 1 OLI Ranking for IEEE 30-Bus System

S. No.	Line outage	Overloading Index	Rank
1	10	4.2460	I
2	36	3.6751	II
3	27	2.8341	III
4	15	1.5015	IV

Table 2 Parameters of GA

Number of variables	1
Population size	16
Number of generation	50
Pareto fraction	0.5
Stall Time Limit	100
TimeLimit	200

A. Optimal placement and sizing of TCSC for overloading reduction

For outage of line nos.10, 36, 27, and 15 one- by- one, GA has been implemented to find out optimal location and size of TCSC so that overloading i.e. OLI were minimized. Table 3 shows the optimal location and sizing of TCSC for these line outage cases for minimizing overlodaing in the system. After implementing GA for installation of TCSC at optimal location for line outage (LO) nos. 10, 36, 27, and 15 one by one, the optimum location of TCSC for overloading reduction were found to be line nos. 13, 33, 29, and 13 respectively. Thus, it can be clearly observed that TCSC optimum location for one contingency may not be optimum for other contingencies and more than one TCSC are required to minimize overloading under various contingencies. The convergence characteristics of GA for overloading reduction are shown in fig.4, fig.5, fig.6 and fig.7 for outage of line nos. 10, 36, 27, and 15 respectively.

Table 3 TCSC Placement for Overloading Reduction

S. No.	Line out	TCSC Optimal Location	TCSC Rating	Overloading Index	
				Without TCSC	With TCSC
1	10	13	-0.1456	4.2460	4.1011
2	36	33	-0.2304	3.6751	3.5321
3	27	29	-0.0165	2.8341	2.8266
4	15	13	-0.1408	1.5015	0.9874

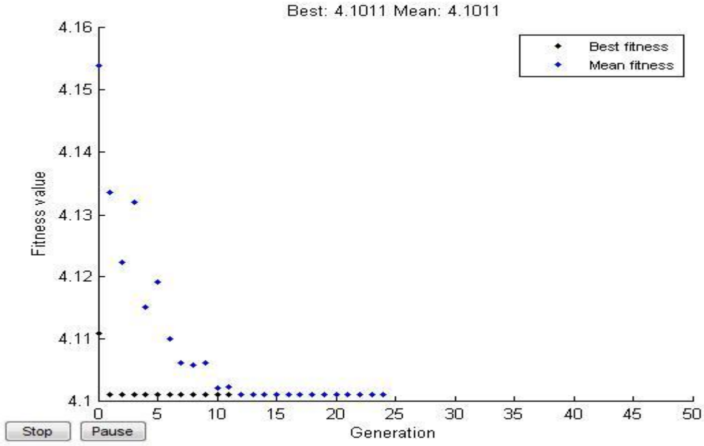

Fig.4. Convergence Characteristic of GA for OLI Reduction (LO 10)

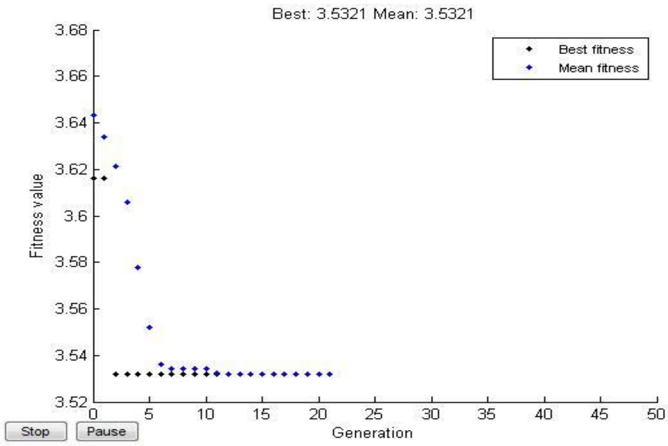

Fig.5. Convergence Characteristic of GA for OLI Reduction (LO 36)

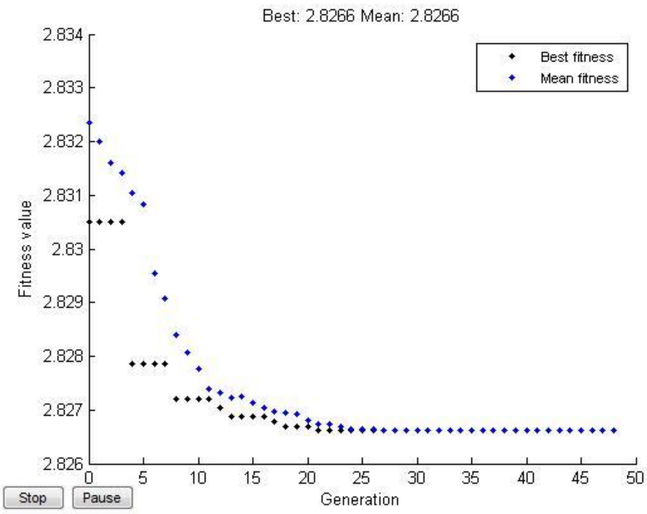

Fig.6. Convergence Characteristic of GA for OLI Reduction (LO 27)

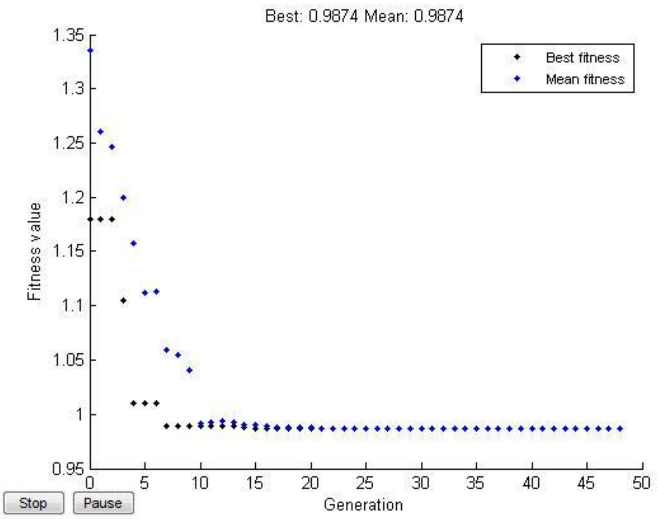

Fig.7. Convergence Characteristic of GA for OLI Reduction (LO 15)

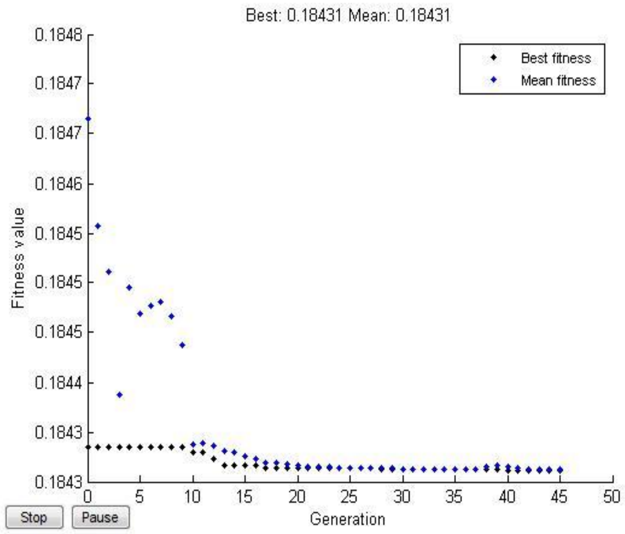

Fig.8. Convergence Characteristic of GA for PL Reduction (LO 10)

B. Optimal placement and sizing of TCSC for real power loss reduction

For outage of line nos.10, 36, 27, and 15 one- by- one, GA has been implemented to find out optimal location and size of TCSC so that the real power losses were minimized. Table 4 shows the optimal location and sizing of TCSC for these line outage cases for real power loss reduction. After installation of TCSC at optimal location for line outage nos. 10, 36, 27, and 15 one by one, the optimum location of TCSC in IEEE 30-bus system for real power loss minimization were found to be line nos. 13, 33, 29, and 13 respectively. Thus, it can be clearly observed that TCSC optimum location for one contingency may not be optimum for other contingencies and more than one TCSC are required to minimize real power loss under various contingencies. The convergence characteristics of GA for real power reduction are shown in fig. 8, fig. 9, fig. 10 and fig. 11for outage of line nos. 10, 36, 27, and 15 respectively.

Table 4 TCSC Placement for Real power loss Reduction

S. No.	Line out	TCSC Optimal location	TCSC Rating	Real power loss	
				Without TCSC	With TCSC
1	10	13	-0.1456	0.1855	0.1843
2	36	33	-0.2304	0.1984	0.1971
3	27	29	-0.0165	0.1799	0.1787
4	15	13	-0.1408	0.2035	0.2016

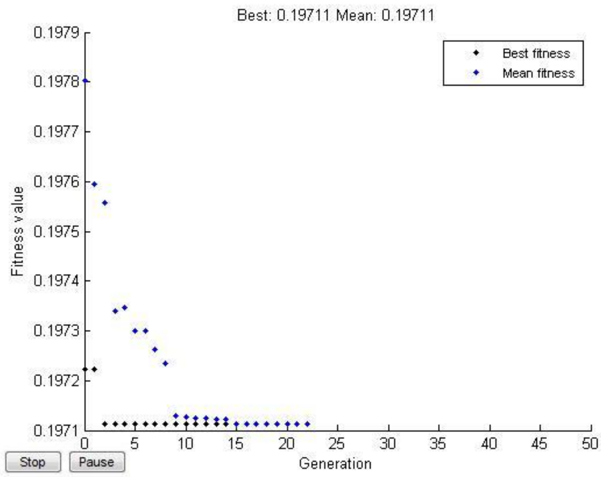

Fig.9. Convergence Characteristic of GA for PL Reduction (LO 36)

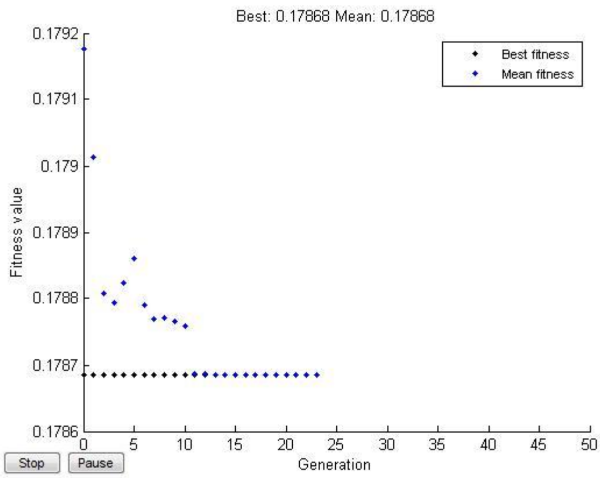

Fig.10. Convergence Characteristic of GA for PL Reduction (LO 27)

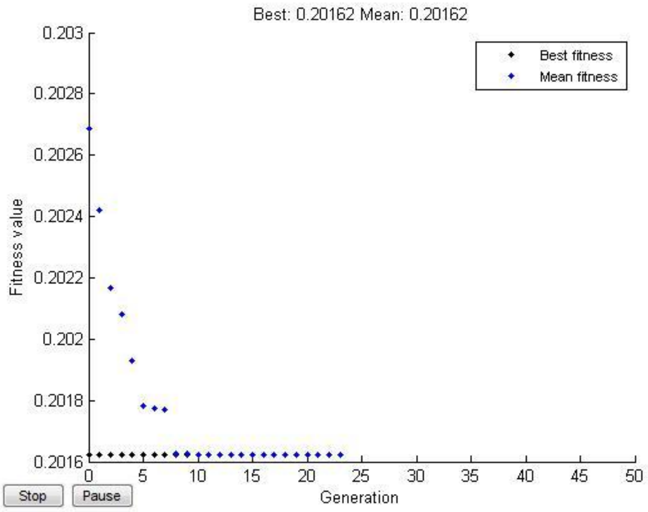

Fig.11. Convergence Characteristic of GA for PL Reduction (LO 15)

VI. CONCLUSIONS

In this paper, genetic algorithm has been proposed for optimal placement and sizing of TCSC for overloading reduction and real power loss minimization under single line outage contingencies of a power system. The effectiveness of this method has been demonstrated on IEEE 30-bus system. It has been observed that TCSC optimum location for one contingency may not be optimum for other contingencies and more than one TCSC are required to minimize overloading and real power losses under various contingencies.

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