

Security Constrained OPF with TCSC and TCPST

Ch V Ramachandra Rao, N Sri Harish, Ch Rambabu

Abstract— In recent years, power demand has increased substantially while the expansion of power generation and transmission has been severely limited due to limited resources and environmental restrictions. As a consequence, some transmission lines are heavily loaded and the system stability becomes a power transfer-limiting factor. Flexible AC transmission systems (FACTS) controllers have been mainly used for solving various power system steady state control problems. However, recent studies reveal that FACTS controllers could be employed to enhance power system security in addition to their main function of power flow control.

This paper presents a novel approach to solve an optimal power flow problem with embedded security constraints (OPF-SC), represented by a mixture of continuous and discrete control variables, where the major aim is to minimize the total operating cost, taking into account both operating security constraints, and system capacity requirements. The particle swarm optimization (PSO) algorithm has been used as the optimization tool. The effect on security in the presence of Facts device like Thyristor Controlled Series Capacitors (TCSCs) and Thyristor controlled Phase shifting Transformers (TCPSTs) are analyzed. Simulations will be done on IEEE 30 bus system for a few harmful contingencies.

Index Terms— Power System Security, FACTS, TCSC, TCPST.

I. INTRODUCTION

The principle role of power system control is to maintain a secure system state, this is to prevent the power system, moving from secure state into emergency state over the widest range of operating conditions.

Security Constrained Optimal Power Flow (SCOPF) is a valuable tool in obtaining the optimum way of dispatching a load demand while maintaining system security. The SCOPF has the objective to determine a feasible point of operation that minimizes an objective function, guaranteeing that even if a contingency occurs, the post-contingency state will also be feasible, i.e., without limits violations.

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In any power system, line outages or transformers outages occur due to faults or other disturbances. These events may cause transmission line overloading or transformers overloads, which in turn may lead to emergency in power system. Several publication deals with the optimization techniques for corrective control of power system security [5, 15]. The objective is to minimizing the total fuel cost or minimizing /alleviating the line overloads with system security constraints [7-8]. The OPF solution gives the optimal settings of all controllable variables for a static power system loading condition. A number of mathematical programming based techniques [6-8] have been proposed to solve the OPF problem. They have the common weakness of requiring differentiable objective function, convergence to local optima and difficulty in dealing with discrete variables like transformer tap setting and shunt capacitor bank. Also, difficulties are encountered in incorporating directly the discrete variables related to the TCSC and TCPST values. It does not provide a continuous fabric over the solution space. Recently global optimization techniques such as the genetic algorithm have been proposed to solve the optimal power flow problem [10-13]. A genetic algorithm [9] is a stochastic search technique based on the mechanics of natural genetics and natural selection. It works by evolving a population of solutions towards the global optimum through the use of genetic operators: selection, crossover and mutation. The possibility of operating the power system at the minimal cost while satisfying specified transmission constraints and security constraints is one of main current issues in stretching transmission capacity by the use of controllable flexible AC transmission system (FACTS) [1-2, 17-18]. The conventional OPF program must undergo some changes such as inclusion of new control variables belonging to FACTS devices and the corresponding load flow solutions to deal with the above said problem. In applying the FACTS devices, one must address the issue of identifying the proper location, number, type, setting, and installation cost of the FACTS devices.

As a preliminary attempt in solving the SCOPF problem, OPF problem has been solved using Genetic Algorithm and Particle Swarm Optimization Algorithm. The effectiveness of the PSO is tested against the GA in terms of solution quality and computational efficiency using IEEE 30 bus test system.

A contingency is said to be more severe if it leads to more number of limit violations or large violations in small number of variables. A severity index is used to calculate the severity of each contingency. Based on this index, the contingencies are ranked in decreasing order of severity. This is called contingency ranking. Depending upon the computational facilities and the tolerances of the system equipment for contingency, a list of credible contingencies is prepared.

The optimal Power Flow with FACTS devices to eliminate line over loads in the system following single line outages. The Optimization are performed on two parameters .The location of devices, and their values. The FACTS devices are located in the order to enhance the system security. Two

different kinds of FACTS controllers are used for steady state studies, Thyristor Controlled Series Capacitors (TCSCs) and Thyristor Controlled Phase shifting Transformers (TCPSTs). The sensitivity analysis is carried out the location of the FACTS devices. Once location is identified, the problem of determining the optimal TCSC and TCPST parameters is formulated as an optimization problem and a GA and PSO based approach is applied to solve the Optimal Power Flow (OPF) problem. Simulation are done on IEEE 30 bus system for a few harmful contingencies

II. FACTS CONTROLLERS

With the increase in power demand, the operation and planning of large interconnected systems are becoming more and more complex so the operating environment, conventional planning and the operation methods can leave power system exposed to instabilities [9]. Voltage instability is one of the phenomena which have major blackout[7] more over with the fast development of restructuring, the problem of voltage stability become major concern in reregulated power systems.

Several FACTS-devices have been introduced for various applications worldwide. A number of new types of devices are in the stage of being introduced in practice. Even more concepts of configurations of FACTS-devices are discussed in research and literature [2,3].

In this work steady state model of FACTS devices are developed for power flow Studies. So TCSC is modeled simply to just modify the reactance of transmission line. TCPST is the phase shift in the phase-angle relation allows the control of power flow between the transmission lines.

A. Thyristor Controlled Series Capacitor (TCSC)

Thyristor Controlled Series Capacitor (TCSC) consists of a fixed capacitor in parallel with a thyristor controlled reactor. The primary function of the TCSC is to provide variable series compensation to a transmission line [14]. This changes the line flow due to change in series reactance.

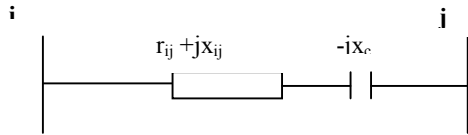


Fig 1 Equivalent Circuit of TCSC

Fig 1 show a model of transmission line with TCSC connected between buses i and j for steady state analysis, the TCSC can be considered as a static reactance -jxc. The controllable reactance xc is directly used as the control variable in the power flow equations. The power flow equations of a transmission line TCSC can be written as

$$\begin{aligned}
 P_{ij} &= V_i^2 g_{ij} - V_i V_j (g_{ij} \cos \delta_{ij} + b_{ij} \sin \delta_{ij}) \\
 Q_{ij} &= -V_i^2 b_{ij} - V_i V_j (g_{ij} \sin \delta_{ij} - b_{ij} \cos \delta_{ij})
 \end{aligned}
 \tag{1}$$

where

$$\begin{aligned}
 g_{ij} &= r_{ij} / (r_{ij}^2 + (x_{ij} - x_c)^2) \\
 b_{ij} &= x_{ij} - x_c / (r_{ij}^2 + (x_{ij} - x_c)^2)
 \end{aligned}$$

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 depends on the reactance of the transmission line where the TCSC is located.

$$X_{ij} = x_{line} + x_{tcsc} \tag{2}$$

$$x_{tcsc} = r_{tcsc} \cdot x_{line}$$

Where, x_{line} is the reactance of the transmission line and r_{tcsc} is the coefficient which represents the degree of compensation by TCSC. 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 settings of reactance values can be achieved.

B. Thyristor Controlled Phase Shifting Transformer (TCPST)

The TCPST consists of three non identical transformer windings with a switch arrangement that can bypass a winding or reverse its polarity. The addition of a quadrature component to the prevailing busbar voltages allows an increase or decrease of the electrical voltages phase-angle relationship of a circuit respectively. The phase shift in the phase-angle relationship allows the control of power flow between the transmission lines.

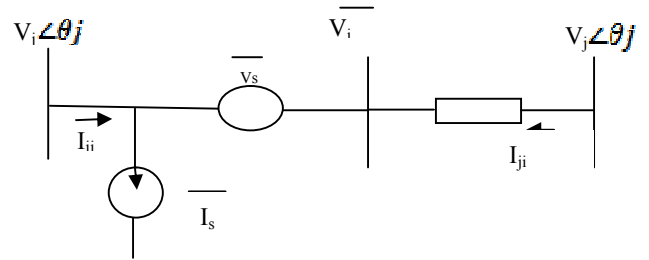


Fig 2 Equivalent circuit diagram of a TCPST

The equivalent circuit of TCPST is shown in Fig 2. The expressions for P_{si} , Q_{si} , P_{sj} and Q_{sj} are given by the following.

$$P_{si} = r \frac{1}{X_s} V_i V_j \sin(\theta_{ij} + \gamma) \tag{3}$$

$$Q_{si} = r^2 \frac{1}{X_s} V_i^2 - r \frac{1}{X_s} V_i V_j \cos(\theta_{ij} + \gamma) \tag{4}$$

$$P_{sj} = -r \frac{1}{X_s} V_i V_j \sin(\theta_{ij} + \gamma) \tag{5}$$

$$Q_{sj} = -r \frac{1}{X_s} V_i V_j \cos(\theta_{ij} + \gamma) \tag{6}$$

P_{si} , P_{sj} are the real power flows at busbar i and j respectively in MW.

Q_{si}, Q_{sj} are the reactive power flows at busbar i and j respectively in MVAR.
 X_{series}, X_{shunt} are the reactance of the series transformer and shunt transformer.
 n is variable phase shift angle, ohms
 r is the ratio between the amplitude of the induced series voltages V_s and the amplitude of the voltage at busbar i, V_i . it is variable in the range $[0, r_{max}]$
 $\gamma = \pm \frac{\pi}{2}$ is the phase shifter control angle, in degrees

III. OPTIMAL POWER FLOW

Optimal Power Flow (OPF) has been widely used in power system operation and planning. 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 with specific constraints. Optimal Power Flow (OPF) is a static nonlinear programming problem which optimizes a certain objective function while satisfying a set of physical and operational constraints imposed by equipment limitations and security requirements. In general, OPF problem is a large dimension nonlinear, non-convex and highly constrained optimization problem.

OPF will perform all the steady-state control functions of the Power System. These functions may include generator control and transmission system control. For generators, the OPF will control generator MW outputs as well as generator voltage. For the transmission system, the OPF may control the tap ratio or phase shift angle for variable transformers, switched shunt control, and all other flexible ac transmission system (FACTS) devices.

A. Problem Formulation

The standard OPF problem can be written in the following form

Minimize $F(x)$ (Objective function)

Subject to:

$h_i(x) = 0, i = 1, 2, \dots, m$ (Equality constraints)

$g_j(x) \leq 0, j = 1, 2, \dots, n$ (Inequality constraints)

There are m - equality constraints and n - inequality constraints and the number of variables is equal to the dimension of the vector x .

1) Objective function

The objective function for the OPF reflects the costs associated with generating power in the system. The quadratic cost model for generation of power will be utilized:

$$F(P_{Gi}) = a_i + b_i P_{Gi} + c_i P_{Gi}^2 \quad (7)$$

Where P_{Gi} is the amount of generation in megawatts at generator i . The objective function for the entire Power System can then be written as the sum of the quadratic cost model at each generator.

This objective function will minimize the total system costs, and does not necessarily minimize the costs for a particular area within the Power System.

2) Equality constraints

The equality constraints of the OPF reflect the physics of the Power System as well as the desired voltage set points throughout the system. The physics of the Power System are

enforced through the power flow equations which require that the net injection of real and reactive power at each bus sum to zero

$$P_{Gi} - P_{Di} - \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) = 0$$

$$Q_{Gi} - Q_{Di} + \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) = 0$$

(8) where P_{Gi} and Q_{Gi} are the real and reactive power outputs injected at bus- i respectively, the load demand at the same bus is represented by P_{Di} and Q_{Di} , and elements of the bus admittance matrix are represented by $|Y_{ij}|$ and θ_{ij} .

3) Inequality constraints

The inequality constraints of the OPF reflect the limits on physical devices in the Power System as well as the limits created to ensure system security. This section will lay out all the necessary inequality constraints needed for the OPF implemented in this thesis.

1 Generators real and reactive power outputs

$$P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max}, i = 1, \dots, N_G$$

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max}, i = 1, \dots, N_G \quad (9)$$

2 Voltage magnitudes at each bus in the network

$$V_i^{\min} \leq V_i \leq V_i^{\max}, i = 1, \dots, NL \quad (10)$$

3 Transmission lines loading

$$S_i \leq S_i^{\max}, i = 1, \dots, nl \quad (11)$$

4 TCSC constraints: Reactance constraint of TCSC

$$X_{TCSCi}^{\min} \leq X_{TCSCi} \leq X_{TCSCi}^{\max}, i = 1, 2, \dots, n_{TCSC} \quad (12)$$

where X_{TCSCi} = Reactance of TCSC at line i

X_{TCSCi}^{\min} = Minimum reactance of TCSC at line i

X_{TCSCi}^{\max} = Maximum reactance of TCSC at line i

n_{TCSC} = number of TCSC's

5 TCPST Constraint

$$\phi_i^{\min} \leq \phi_i \leq \phi_i^{\max}, i = 1, 2, \dots, n_{TCPST} \quad (13)$$

4) Contingency Analysis and Ranking

Contingency selection involves the selection of lines or generators whose outage is more severe. To identify the severity of a transmission line, there is no specific approach by which a unique solution can be obtained. Different methods are suggested for identifying the severity. One such index used in [1] is discussed here

Severity Index:

For a line outage 'k', the severity index is defined as:

$$SI_k = \sum_{l=1}^L \left(\frac{s_l}{s_l^{\max}} \right)^{2m} \quad (14)$$

Where, SI = Severity Index (Overload index)

S_l = MVA flow in line l

S_l^{\max} = MVA rating of line l

L = set of overloaded lines

m = integer exponent

Based on the severity index assigned to each line outage, a list is prepared. This is done by first arranging the lines in the

descending order of their severity and taking the first few lines with the highest severity. For a large power system, 5 to 10% of the lines can be chosen in the contingency list. It is assumed that since these are the more severe outages in the system, handling them in the SCOPF will be fairly enough to improve the security of the system. A value of $m=1$ has been used.

5) 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, controllable transformer taps 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. 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. For each individual, the equality constraints (8) are satisfied both in base case as well as contingency cases by running NR algorithm and the constraints on the state variables are taken into consideration by adding penalty function to the objective function.

$$M \text{ inf} = SI_l + S_p + \sum_{l=1}^{N_l} U_{pj} + \sum_{j=1}^{N_g} Q_{pj} + \sum_{j=1}^{N_l} L_{pj} \quad (15)$$

where, SI_l represents the severity index for outage l ,

S_p, U_{pj}, Q_{pj} and L_{pj} 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:

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

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

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

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

IV. OPTIMIZATION ALGORITHMS

GA and PSO are 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 and PSO. Therefore the GA and PSO fitness function is formed as $F=k/(1+f)$, where, ‘k’ is a large constant.

A. Genetic Algorithm

The Genetic Algorithm cycle has the following steps.

- It begins with a randomly generated population of chromosome encoded “Solutions” to a given problem.
- Calculate the fitness of each chromosome, where fitness is a measure of how well a member of the population performs at solving the problem.
- Retain only the fittest members and discard the least fit members. This process is called selection of fittest strings from existing population.
- Generate a new population of chromosome from the remaining member of the old population by applying the operation reproduction, cross over and mutation.
- Calculate the fitness of these new members of the population, retain the fittest, discard the least fit and re-iterate the process.

The population comprises a group of chromosomes from which candidates can be selected for the solution of a problem. Initially, a population is generated randomly. The fitness values of the all chromosomes are evaluated by calculating the objective function in a decoded form (phenotype). A particular group of chromosomes (parents) is selected from the population to generate the offspring by the defined genetic operations. The fitness of the offspring is evaluated in a similar fashion to their parents. The chromosomes in the current population are then replaced by their offspring, based on a certain replacement strategy.

Such a GA cycle is repeated until a desired termination criterion is reached (for example, a predefined number of generations is produced). If all goes well throughout this process of simulated evolution, the best chromosome in the final population can become a highly evolved solution to the problem. Fig 3 shows the flowchart of Genetic Algorithm.

(3.14)

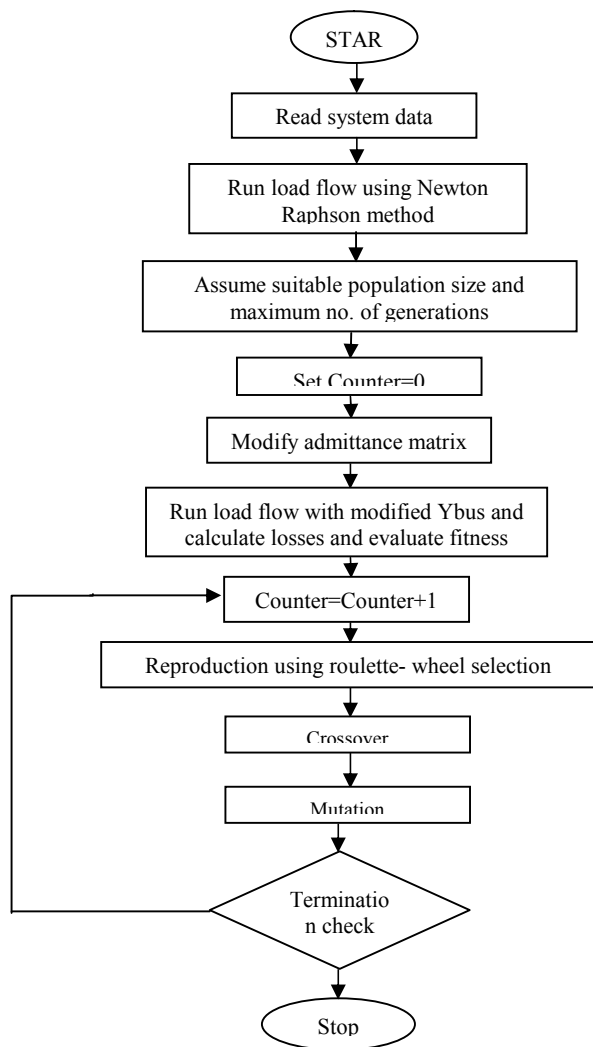


Fig 3: Flowchart of GA

B. Particle Swarm Optimization

Particle swarm optimization (PSO) is a population based stochastic optimization technique developed by Dr. Eberhart and Dr. Kennedy in 1995, inspired by social behavior of bird flocking or fish schooling.

PSO shares many similarities with evolutionary computation techniques such as Genetic Algorithms (GA). The system is initialized with a population of random solutions and searches for optima by updating generations. However, unlike GA, PSO has no evolution operators such as crossover and mutation. In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles.

Compared to GA, the advantages of PSO are that PSO is easy to implement and there are few parameters to adjust. One version, with slight variations, works well in a wide variety of applications. Particle swarm optimization has been used for approaches that can be used across a wide range of applications, as well as for specific applications focused on a specific requirement. PSO has been successfully applied in areas like, function optimization, artificial neural network training, fuzzy system control, and other areas where GA can be applied. Figure 4 shows the flowchart of PSO.

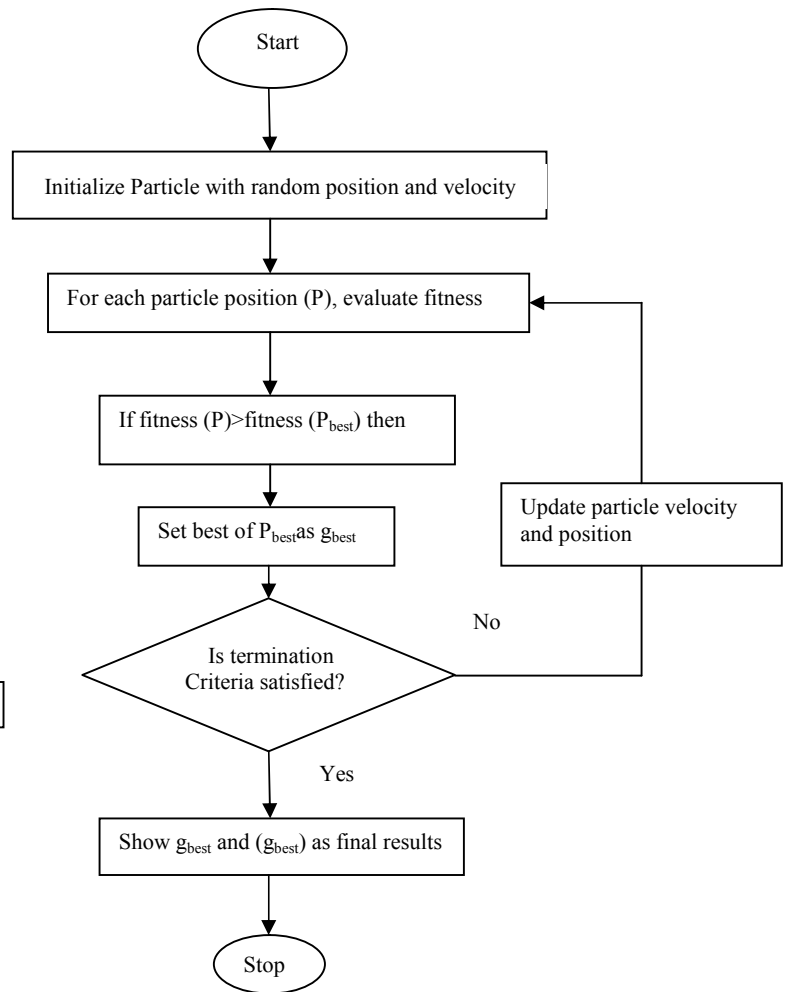


Fig 4: Flowchart for PSO

V. RESULTS AND DISCUSSION

The Optimal Power Flow (OPF) is a highly non-linear, large scale optimization problem due to large number of variables & constraints. It has both continuous and discrete variables as its decision variables. OPF with Fuel cost minimization and over load alleviation through FACTS devices as objective functions are formulated as optimization case.

The SCOPF in its general form is a nonlinear, non-convex, static, large scale optimization problem with both continuous and discrete variables in large number. As an initial attempt in solving SCOPF using genetic algorithm and Particle Swarm Optimization Algorithms, The effectiveness of PSO is compared in solution quality and computational efficiency against GA.

The algorithm is implemented and is tested for its robustness on a standard IEEE 30 bus system. The upper and lower voltage limits at all bus bars except slack were taken as 1.10 p.u and 0.95 p.u respectively. Slack bus bar voltage was fixed to its specified value of 1.06 p.u . It is assumed that the impedance of all TCSCs can be varied within 50% of the corresponding branch impedance and limits of the phase shifting angles of TCPSTs were taken as -20 to +20 degrees. The proposed approach, two different cases have been considered as follows.

Case1: Base case optimal power Flow problem with minimization of fuel cost as objective.

Case 2: Over load alleviation through FACTS devices.

GA Parameters: Population size =45, Uniform Crossover Probability =0.9, String length 155 bits, Mutation Probability=0.01 &Maximum Number of iterations 100. Roulette wheel selection technique is used for parent selection.

PSO Parameters: Population size =45, Maximum Number of iterations=100, Weight coefficients C1=2.05, C2=2.05, Weight vectors W1= 0.9, W2=0.4 and Number of intervals R=10

A. Results for Case 1:

The results obtained for various control variables using GA and PSO are given. If the problem did not converge in maximum number of generations, solution obtained at the last generation can be taken as the optimum value.

TABLE I OPTIMAL SETTINGS OF CONTROL VARIABLES FOR OPF USING GA AND PSO

Variables	GA	PSO
Slack	177.38	176.15
P _{G2}	49.15	48.98
P _{G5}	21.38	21.76
P _{G8}	20.12	21.44
P _{G11}	12.56	12.45
P _{G13}	12.42	12.01
Q _{G1}	-11.12	-10.72
Q _{G2}	9.42	9.34
Q _{G5}	23.58	22.89
Q _{G8}	41.17	41.09
Q _{G11}	30.83	30.87
Q _{G13}	40.25	40.69
V _{G1}	1.0646	1.0673
V _{G2}	1.0451	1.0377
V _{G5}	1.0219	1.0180
V _{G8}	1.0282	1.1000
V _{G11}	1.0250	1.0102
V _{G13}	1.0869	1.0834
Tap 6-9	1.0375	1.0024
Tap 6-10	0.9000	0.9365
Tap 4-12	1.0625	1.0055
Tap 28-27	0.9875	0.9602
Optimal fuel cost(\$/hr)	802.73	801.66

It is observed that the results obtained by PSO are more optimal than the one obtained using GA. Also, the result obtained using mathematical technique reported in [1] i.e., 801.4 \$/hr, is nearer to the one obtained using GA. This shows that PSO works better than the mathematical techniques in finding the optimal solution for the OPF problem. Convergence characteristics for GA and PSO are shown in below.

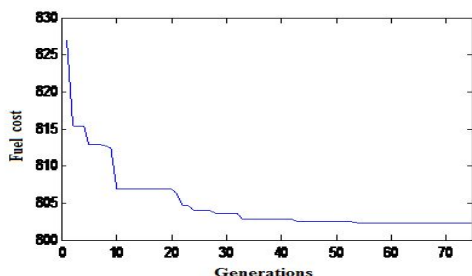


Fig 5 Convergence characteristic of GA for OPF

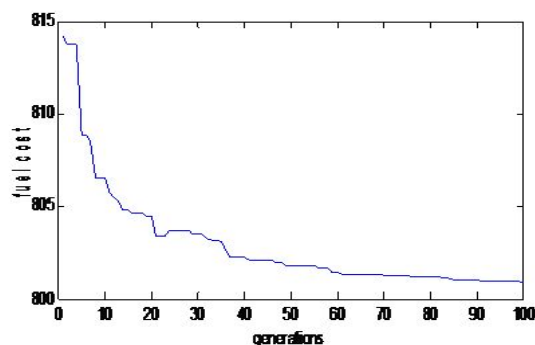


Fig 6 Convergence characteristic of PSO for OPF

B. Results for Case 2:

1) Contingency Analysis and Ranking

In this case, the GA and PSO algorithms are used for corrective control of contingency state. Contingency analysis was conducted under the base load conditions to identify the harmful contingencies. From the contingency analysis, it was found that the line outages 1-2, 1-3, 2-5 and 3-4 have resulted in overload on other lines. The power flow on the overload lines and the calculated value of severity index for each contingency are given in Table II and Table III.

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

Outage Line No	Over loaded lines	Line flow (MVA)	Line flow limit(MVA)	Severity Index (SI)	Rank
1-2	1-3	195.09688	130	5.73341	1
	3-4	178.21908	130		
	4-6	107.48931	90		
1-3	1-2	184.64821	130	2.91164	2
	2-6	65.92880	65		
2-5	2-6	76.67529	65	2.84321	3
	5-7	75.80836	70		
3-4	1-2	181.90032	130	2.04372	4

TABLE III SUMMARY OF CONTINGENCY ANALYSIS FOR IEEE 30-BUS SYSTEM BY USING PSO

Outage Line No	Over loaded lines	Line flow (MVA)	Line flow limit(MVA)	Severity Index (SI)	Rank
1-2	1-3	159.071	130	4.1318	1
	3-4	150.516	130		
	4-6	94.137	90		
1-3	1-2	176.547	130	2.8719	2
	2-6	65.852	65		
2-5	2-6	70.885	65	2.1927	3
	5-7	70.80836	70		
3-4	1-2	168.014	130	1.6704	4

2) Location of FACTS devices in IEEE 30-bus system

From the Tables II and III, the line outage 1-2 is the most severe one and result in overloading on three other lines. The Sensitivity analysis was carried out to identify the suitable locations of the TCSCs and TCPSTs to alleviate the line overload. The four locations identified for each contingency are given in Table IV.

TABLE IV
TCSCS & TCPSTS LOCATIONS IN IEEE 30-BUS SYSTEM

Line outage	1-2	1-3	2-5	3-4
TCSC & TCPST Locations	24-25	3-4	21-22	1-3
	21-22	21-22	14-15	14-15
	8-28	23-24	8-28	21-22
	2-6	5-7	23-24	23-24

In This case, two types controller simultaneously have been implemented to improve power system security and reduce the Severity Index. This results show that Control variable settings of the combined TCSC and TCPST, and combined 2 TCSCs and 2 TCPSTs are given in Table V.

CONCLUSIONS

In this paper, OPF problem is attempted using Genetic Algorithm and Particle Swarm Optimization Algorithms.

TABLE V
CONTROL VARIABLE SETTINGS WITH FACTS

Line outage	GA				PSO			
	1-2	1-3	2-5	3-4	1-2	1-3	2-5	3-4
P1	126.45	128.88	138.69	140.56	124.45	126.48	137.32	138.72
P2	63.16	64.77	68.08	58.34	61.66	63.21	66.38	58.34
P5	47.57	40.98	32.35	42.69	45.57	41.58	33.46	42.69
P8	28.58	32.54	26.88	31.61	27.48	31.34	25.27	31.61
P11	22.58	26.64	22.85	22.72	22.33	24.64	21.29	22.72
P13	21.71	24.48	28.88	27.30	20.71	22.28	27.15	25.47
TCSC 1	0.1176	0.0072	0.0051	0.0030	0.1076	0.010	0.0069	0.028
TCSC 2	0.0626	0.0059	-0.093	-0.037	0.0624	0.0017	-0.091	-0.043
TCPST 1	11.75	14.96	3.127	8.6618	9.752	15.96	9.127	-8.6618
TCPST 2	-10.52	-13.472	-10.182	3.094	-15.52	-17.472	-13.182	-11.094
SI without FACTS	5.7331	2.9117	2.8431	2.0434	4.1318	2.8719	2.1927	1.6704
SI with FACTS	0	0	0	0	0	0	0	0

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