

Optimization of Transmission System Security Margin under (N-1) Line Contingency Using Improved PSO Algorithm

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Abstract: The abnormalities like (N-1) line contingencies are unavoidable and consequently can cause for either transmission system security margin decrement or power loss increment. Both the issues are primary objectives of the modern power system operation due to their significant effect on generation capacity and economics. This paper proposes Generalized Unified Power Flow Controller (GUPFC) for maintaining adequate security margin and performance improvement under (n-1) contingencies. At first stage, the optimal location of GUPFC device is proposed to determine based on (N-1) line contingency severity index. In second stage, the rating of the GUPFC device is optimized towards minimization of multi-objective function, which formulated using real power loss and security margin index. The parameters involved in the power injection modeling (PIM) of GUPFC and various system operational parameters are optimized using Particle Swarm Optimization (PSO) and Improved Particle Swarm Optimization (IPSO) algorithms towards minimization of multi-objective function. The case studies on IEEE 14-bus and IEEE 30-bus test system are validating the capability GUPFC device to minimize transmission loss and improve security margin significantly even under (n-1) line contingency and need of FACTS devices for real-time.

Keywords: GUPFC; transmission losses; security margin; (N-1) line contingency; PSO; IPSO

1. Introduction

One of the critical concerns in Indian power sector operation is the uninterrupted power supply, and the issue is still attracting by various researchers for sustainable solutions. In the present days, the overall energy deficit significantly decreased to less than 1% with an ambitious rural electrification program, but the aggregated transmission and distribution (T&D) losses are still a considerable concern with more than 20% of total electricity generation [1]. As reported in [2], inadequate reactive compensation has one of the basic reasons for having high technical losses. Apart from the reactive power compensation at distribution side with shunt capacitors and regulating transformers, the integration of modern technologies like Flexible AC Transmission System (FACTS) devices at transmission side is also become an essential requirement in Indian power sector after being subjected to historical blackouts in 2012 which have been initiated by one line contingency [3]. From the invention to till date, the development and concepts of different FACTS devices have changed the overall power system operation and control dramatically across the world. Among these, Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC) can control the power system attributes by working as an individual mode of operation either in series or in shunt type or a combined mode of operation [4]. Due to these features, the operating problems associated with voltage stability, transient stability, transmission system loadability and transmission losses efficiently addressed in the literature. Also, one of the significant issues, transmission system congestion in deregulation environment highly discussed with FACTS devices [5]. The research is still progressing towards the development of hybrid as well as versatile FACTS devices recently. Some of such inventions are Generalized Unified Power Flow Controller (GUPFC) [6] and Optimal Unified Power Flow Controller (OUPFC) [7]. These devices are

getting high attention by the researchers in recent years due to their multi-line power flow controlling capability with improved voltage profile. Some of such works are addressed here.

In [8], the Nigerian power system is analyzed by integrating GUPFC. The GUPFC controls are optimized have better voltage profile and minimum transmission losses via controlling the active and reactive power flows effectively in the network. In [9], loadability index (LBI) is proposed for overall system and sub areas are evaluated for static and dynamic loads under normal and contingency cases. The formulated LBI objective is optimized while satisfying equality, inequality constraints and device limits. In [10], an improve bat algorithm is proposed to optimize the generation cost, emissions, and total power loss objectives under various practical constraints including GUPFC device limits. In [11], novel nonlinear dynamic simulation of the GUPFC consisting of one shunt converter and two series converters based on voltage source converter (VSCs) and DC link capacitor installed in a substation in a multi-machine power system is presented. The effect of UPFC and GUPFC to maximize the Available Transfer Capability (ATC) is presented [12]. In [13], various FACTS devices such as STATCOM, SSSC, UPFC, IPFC and GUPFC devices are used to enhance the transfer capability of the power system. The dynamic nature of multi-machine power system is analyzed and improved stability using Power System Stabilizers (PSS) and GUPFC Power Oscillation Damping (POD) controllers [14]. In [15], the GUPFC impact has been analyzed for both open loop and close loop configuration in Single Machine Infinite Bus (SMIB) system. All these works have shown the adoptability of GUPFC to solve various operational and controlling issues in modern power system. In [30], UPFC and GUPFC and in [32], GUPFC have been proposed to enhance system security margin in terms of ATC. In [31], the impact of GUPFC on reactive power flow control in the transmission system is analyzed. In [33], the effectiveness of UPFC and GUPFC are compared w.r.t. economic operation of power system. The results have shown the 2-series converter configured GUPFC has shown the better result than 3-series converter GUPFC and UPFC. In this paper, 2-series converter GUPFC device is proposed for transmission loss minimization as well as transmission system security margin enhancement under (n-1) contingency conditions.

2. Modeling of GUPFC Device

A. Basic Configuration of GUPFC

Basically, GUPFC has similar configuration to Interline Power Flow Controller (IPFC) except shunt converter. The basic configuration of GUPFC can formulate by considering three converters, one as shunt converter and the remaining two as series converters in the transmission lines. Preferably, GUPFC shunt converter can be placed at a substation and the series converters can be kept in the multiple lines associated to that sub-station. The common DC link between shunt converter and series converter is responsible for active power exchange between the converters. The shunt converter can able to regulate bus voltage for the desired value by compensating reactive power and it is also responsible to supply required active power for the series converter associated it, so that can be able to control both active and reactive power flows in the transmission lines. The comprehensive explanation of GUPFC working principle can found in [16, 17]. Also, the reader can find GUPFC design mode with one shunt converter coupled IPFC is explained with mathematical modeling suitable for nonlinear predictor-corrector primal-dual interior-point OPF algorithm [18].

B. Power Injection Modeling of GUPFC

The Power Injection Modeling of FACTS devices are employed widely in literature due to simple form and easy to implement in load flow study without modifying Jacobian matrix. In [9, 18], power injection model of GUPFC with its incorporation procedure in conventional NR load flow is presented. In [19], a power injection model is presented for the GUPFC, which can suit to implement in power flow and optimal power flow programs. In [20], a developed model of GUPFC controller in NR load flow algorithm is presented. The model is based on power injection approach. The series converters of GUPFC are represented by injected loads as a

function of specified active and reactive power flows, while the shunt converters are represented as a synchronous condenser. An optimal power flow incorporating GUPFC static power injection modeling is analyzed for economic operation under wheeling environment [21]. The modeling presented in [18] is briefed here.

By considering shunt converter at bus- i and series converters in the lines i - j and i - k , then the power injections at all the incident buses are as follows:

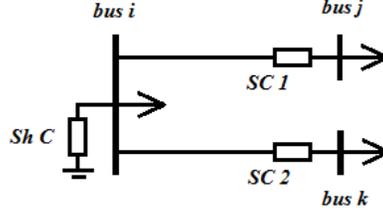


Figure 1. Single line diagram of GUPFC connected lines

The power injections at shunt converter bus- i are:

$$P_{inj,i} = \sum_n r_{i-n} b_{s,i-n} V_i V_n \sin(\theta_{i-n} + \gamma_{se,i-n}), \quad n = j, k \quad (1)$$

$$Q_{inj,i} = \sum_n r_{i-n} b_{s,i-n} V_i^2 \cos(\gamma_{se,i-n}) + Q_{sh,i}, \quad n = j, k \quad (2)$$

The power injections at series converter bus- j are:

$$P_{inj,j} = -r_{i-j} b_{s,i-j} V_i V_j \sin(\theta_{i-j} + \gamma_{se,i-j}) \quad (3)$$

$$Q_{inj,j} = -r_{i-j} b_{s,i-j} V_i V_j \cos(\theta_{i-j} + \gamma_{se,i-j}) \quad (4)$$

The power injections at series converter bus- k are:

$$P_{inj,k} = -r_{i-k} b_{s,i-k} V_i V_k \sin(\theta_{i-k} + \gamma_{se,i-k}) \quad (5)$$

$$Q_{inj,k} = -r_{i-k} b_{s,i-k} V_i V_k \cos(\theta_{i-k} + \gamma_{se,i-k}) \quad (6)$$

At any operating condition, the amount of rear power imparted to the DC link is shared to the series converters and hence the GUPFC operating constraint is:

$$P_{inj,i} - \sum_n P_{inj,n} = 0, \quad n = j, k \quad (7)$$

where, V_i , V_j and V_k are the magnitude bus voltages at buses i , j and k respectively, θ_{i-j} and θ_{i-k} are the voltage angle difference between buses i , j and buses i , k respectively, $b_{s,i-j}$ and $b_{s,i-k}$ are the series branch admittances, r_{i-k} and r_{i-j} are the magnitudes of controllable series injected voltage sources, $\gamma_{se,i-k}$ and $\gamma_{se,i-j}$ are their respective phase angles.

3. Optimal Location and Rating of GUPFC Device

A. Location

In this paper, the optimal location of GUPFC device is determined based on (N-1) line contingency severity. For a specific line contingency, the power flows in the remaining lines of the network may change significantly. The power flow of a line may increase or decrease under contingency. The increased power flows can be considered as dominant flows and decreased power flows can be considered as counter flows. By having net dominant flow greater than net counter flow, the network can be subjected to transmission loss increment otherwise, it can have decrement transmission loss as compared to pre-contingency case. Hence, the (N-1) line contingencies are ranked according to total transmission losses for identifying the location for GUPFC device.

B. Rating

Similarly, rating of the GUPFC device is also a key factor for efficient operation of the network. According to the PIM of GUPFC devices, the net power injections at the GUPFC incident buses can vary by controlling their bus voltages as well as its associated series voltage sources magnitudes and angles. Basically the FACTS devices are passive in nature and can be able to generate or consume reactive power and consequently the bus voltages will regulate to desire values. Hence in this work, all the load bus voltages are mainly considered to control by regulating the generator bus voltages and consequently GUPFC power injections. By performing load flow with these power injections, the entire system variables and its performance can be obtained. The rating of the GUPFC device is optimized towards minimization of real power loss and enhancement of security margin using proposed optimization algorithm.

4. Power System Security Assessment

By having increased power flows, the loadability margin of the remaining lines may also decrease considerably. Hence the deviation of average loadability of the network from base case is considered to identify the severity of the line contingency as well as the role of that line in the network for security management. Since the power flow from both the directions is not same hence the average loadability deviation is computed for a line contingency by considering MVA flow from both the directions for every line as follows:

$$\Delta S_{l,avg} = \frac{1}{2(nl-1)} \sum_{l=1}^{(nl-1)} (S_{l,ij}^c + S_{l,ji}^c) - \frac{1}{2nl} \sum_{l=1}^{nl} (S_{l,ij}^b + S_{l,ji}^b) \quad (8)$$

where $S_{l,ij}^c$ and $S_{l,ij}^b$ are the MVA flow from bus- i to bus- j after and before contingency respectively; $S_{l,ji}^c$ and $S_{l,ji}^b$ are the MVA flow from bus- j to bus- i after and before contingency respectively; nl is the number of transmission lines. The Eq. (8) is modified as for with GUPFC device under contingencies as follows:

$$\Delta S_{l,avg} = \frac{1}{2(nl-1)} \sum_{l=1}^{(nl-1)} (S_{l,ij}^{ef} + S_{l,ji}^{ef}) - \frac{1}{2(nl-1)} \sum_{l=1}^{(nl-1)} (S_{l,ij}^c + S_{l,ji}^c) \quad (9)$$

Where $S_{l,ij}^{ef}$ is the MVA flow from bus- i to bus- j and $S_{l,ji}^{ef}$ is the MVA flow from bus- j to bus- i with GUPFC device under contingency respectively.

The positive value of $\Delta S_{l,avg}$ is the indication of decreased security margin of the network under contingency where as negative value indicates the increase of network security margin even under contingency.

5. Problem Formulation

A. Mathematical Formulation

The objective function of the problem is considered as minimization of loss and $\Delta S_{l,avg}$. The decreased $\Delta S_{l,avg}$ value is an indication of improvement in security margin also. The decreased real power loss indicates an improvement in system performance.

$$f(x) = \min(\Delta S_{l,avg} + P_{loss}) \quad (10)$$

Subjected to:

$$\begin{aligned} r_{\min} &\leq r \leq r_{\max} \\ \gamma_{se,\min} &\leq \gamma_{se} \leq \gamma_{se,\max} \\ V_{\min} &\leq V \leq V_{\max} \end{aligned} \quad (11)$$

By adjusting these variables, the controllable parameters $x = [P_{inj} \ Q_{inj}]$ at the GUPFC device associated buses.

The residual powers in terms of power injections and withdrawals can be related by using static load flow equations of NR load flow method as follows:

$$\Delta P_p = P_{p,cal} - P_{sp,p} = \sum_{q=1}^{Nb} V_p V_q Y_{pq} \cos(\theta_{pq} - \delta_p + \delta_q) - (P_{g,p} - P_{d,p}); \quad p = 2, \dots, N_b \quad (12)$$

$$\Delta Q_p = Q_{p,cal} - Q_{sp,p} = -\sum_{q=1}^{Nb} V_p V_q Y_{pq} \sin(\theta_{pq} - \delta_p + \delta_q) - (Q_{g,p} - Q_{d,p}); \quad p = 2, \dots, N_b \quad (13)$$

By the injection of real and reactive powers of GUPFC device at its associated buses, the modifications in residual power equations are as follows:

$$\Delta P_{p,new} = \Delta P_{p,old} + P_{inj,p}, \quad p = i, j, k \quad (14)$$

$$\Delta Q_{p,new} = \Delta Q_{p,old} + Q_{inj,p}, \quad p = i, j, k \quad (15)$$

The bus voltages magnitudes and phase angles in a power system can be obtained by an iterative approach NR load flow method as given by:

$$\begin{bmatrix} \Delta \delta_p \\ \Delta V_p \end{bmatrix} = \begin{bmatrix} \frac{\partial P_p}{\partial \delta_p} & \frac{\partial P_p}{\partial V_p} \\ \frac{\partial Q_p}{\partial \delta_p} & \frac{\partial Q_p}{\partial V_p} \end{bmatrix}^{-1} \begin{bmatrix} \Delta P_p \\ \Delta Q_p \end{bmatrix}, \quad p = 2, \dots, N_b \quad (16)$$

By assuming initial bus voltages magnitudes and phase angles, the residual power will be updated in Eq. (14) and the new updates for bus voltages magnitudes and phase angles are computed as follows:

$$\delta_{p,new} = \delta_{p,old} + \Delta \delta_p, \quad p = 2, \dots, N_b \quad (17)$$

$$V_{p,new} = V_{p,old} + \Delta V_p, \quad p = 2, \dots, N_b \quad (18)$$

The bus voltages magnitudes and phase angles will be updated up to convergence criterion in NR load flow by satisfy all the operational constraints in power system. This process will be repeated up to maximum iterations in the optimization problem to determine optimal ratings of the FACTS device.

B. Particle Swarm Optimization

The targeted benefits from any FACTS device are highly dependent on its location as well as rating. Many works have been focused on these issues in literature. The location is based on the targeted benefit like power system stability enhancement, ATC enhancement, loss minimization, operational cost minimization etc. [22, 23]. These approaches can be classified as strategic, sensitivity analysis based and heuristic approaches. To avoid the computational effort involved in strategic and sensitivity based approaches, the heuristic algorithms have been adopted in many power system optimization problems. For a change in operating condition, the solution of optimal location of FACTS device may change in sensitivity based as well as heuristic approaches. Hence the strategic approach is better as a long-term solution since the location of FACTS is not possible to change for every operating condition. On the other side, the rating or parameters tuning as per the system operating condition is required to optimize and is a complex problem. To handle this complexity, the need for heuristic algorithms has arrived and addressed by many heuristic algorithms in the literature. Among many heuristic approaches, the Particle Swarm Optimization (PSO) algorithm is highly adopted due to its simplicity as well as effectiveness. PSO technique has proven to be very efficient for solving unconstrained or inequality constrained optimization problems [24]. A good literature survey on PSO applications in electrical engineering can be found in [25]. Since the introduction of the PSO method in 1995, a considerable amount of work has been done in modifying the

original version of PSO. In [26], various advancements for basic PSO and their applications in power system are discussed. The basic motivation behind this invention is social behavior simulation of fish schooling or bird flocking. The detailed explanation of PSO is given in [24]. Here we have presented the fundamental equations involved in PSO and Improved PSO algorithms.

- Basic PSO

Basically it works based on two major equations i.e., velocity and position which updates for each iteration towards global solution. The velocity equation is formulated with three important parameters (i) inertia weight (ii) cognitive coefficient (iii) social coefficient and given in Eq. (19). According to the velocity, the position updates as per Eq. (20).

$$\underbrace{V_i^{k+1}}_{\text{Velocity}} = \underbrace{\omega^k V_i^k}_{\text{Inertia term}} + \underbrace{c_1^k \cdot \text{rand}_1 \otimes (P_{lbest,i}^k - X_i^k)}_{\text{Cognitive component}} + \underbrace{c_2^k \cdot \text{rand}_2 \otimes (P_{gbest,i}^k - X_i^k)}_{\text{Social component}} \quad (19)$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \quad (20)$$

where X_i^k and $V_i^k \in \mathfrak{R}^n$ denote the position and velocity of the i th particle at time k , respectively. ω^k is an initial factor, c_1^k is an individual confidence factor or cognitive parameter, c_2^k is a swarm confidence factor or social parameter, $\text{rand}_1, \text{rand}_2 \in \mathfrak{R}^n$ are random vectors each component of which is uniformly distributed in $[0,1]$, and \otimes is an element-by-element operator for vector multiplication. $P_{lbest,i}^k = \arg(\max_{k=1,2,\dots} \{g(X_i^k)\})$, where $g(X_i^k)$ is the fitness value of the i th particle at time k is the best position of the i th particle, lbest up to now, and $P_{gbest,i}^k = \arg(\max_{k=1,2,\dots} \{g(X_i^k)\})$ is the global best position of swarm of particles, gbest, respectively.

In addition to position and velocity, every particle has memory of best position which is called as personal best or lbest and among the members of all the particles, there is a common best memory called global best or gbest; After each iteration, the position and velocity of each particles lbest value and gbest values are updated. The new position is found out from personal best and global best and the previous velocity.

- Improved PSO

Since the introduction of the PSO method in 1995, a considerable amount of work has been done in modifying the original version of PSO. Generally, in population-based search optimization methods, considerably high diversity is necessary during the early part of the search to allow the use of the full range of the search space. On the other hand, during the latter part of the search, when the algorithm is converging to the optimal solution, fine-tuning of the solutions is important to find the global optima efficiently. Considering these concerns, Shi and Eberhart have found a significant improvement in the performance of the PSO method with a linearly varying inertia weight over the generations by balancing the local and global search during the optimization process [27].

The improved evaluation model with linear diminishing inertial weight can be obtained as follows:

$$\omega^k = \omega_{\max} - (\omega_{\max} - \omega_{\min}) \frac{k}{k_{\max}} \quad (21)$$

6. Results and Discussions

The proposed methodology is applied in IEEE 14-bus and 30-bus test systems. The details of test system can be found in [28]. The case studies are performed for base case condition as well as under (N-1) contingency conditions. The total load is allocated to all the generators as per their capacity.

The parameter settings for the PSO algorithms are taken as follows. In two algorithms, the population size and maximum iteration are taken as 50, C1 and C2 are taken as 2. The inertia weight is fixed to 0.9 in BPSO and where as in IPSO, it is controlled with $W_{\min} = 0.4$ and $W_{\max} = 0.9$. In addition, all bus voltages are constrained by the range of 0.90 p.u to 1.10 p.u [29].

A. IEEE 14-bus Test System

The test system has 5 generator (PV) buses and 9 load (PQ) buses with 20 interconnected transmission lines. It has 259 MW real power load and 73.5 MVar reactive power load. The generation schedule for the base case and for the generator contingency cases are given in Table 1.

Table 1. Generation schedule according to their maximum limit

Gen #	1	2	3	4	5
Pmax (MW)	332.4	140	100	100	100
Schedule	111.46	46.95	33.53	33.53	33.53

The system is suffered with 4.645 MW for the base case. The (N-1) contingencies are imposed in to test system and the corresponding losses are given in Table 2. The line 7-8 is not considered due to network configuration or bus-8 isolates under this contingency. As per the incurred losses, the line contingencies are ranked. The lines which are incident to generator buses (i.e., 1, 2, 3, 6 and 8) as well as with tap-changing transformers (4-7, 4-9 and 5-6) are excluded from the priority list and indicated as NA in Table 2. The remaining lines are ranked. The line contingencies 7-9 and 9-14 are ranked top and these two lines are considered for the GUPFC integration.

Since the basic GUPFC configuration required minimum two transmission lines with a common incident bus. As per the GUPFC configuration, the common bus of these two lines is bus-9 and considered for the shunt converter location. The GUPFC parameters i.e., minimum and maximum phase angles of the two converters are taken as 0^0 to 360^0 and series injected voltage magnitudes considered as 0 p.u to 0.2 p.u. The case studies are divided as base case and line contingency case. The effectiveness of GUPFC is observed on system transmission losses in all the case studies.

Since PSO algorithm is a stochastic search algorithm and hence the optimized solution may not be same for every simulation. We have simulated each case ten times and among those, the best and worst cases are only given Table 3. By comparing basic PSO, the IPSO has given better results in terms of minimum losses. An example of convergence characteristics for both the algorithms are given only for line (13-14) contingency in Fig. 2 and the remaining line contingencies are not provided due to space limitation.

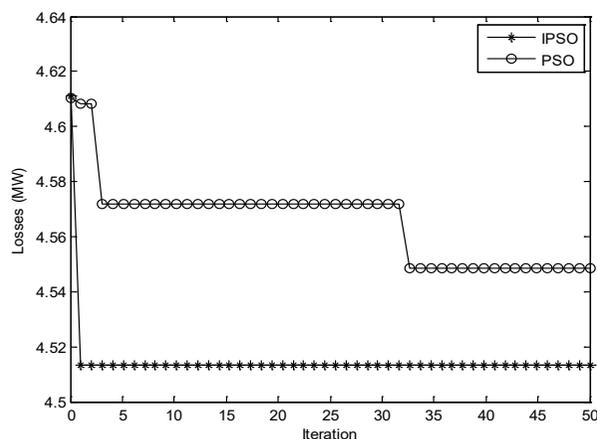


Figure 2. Convergence characteristics of the algorithms under line (13-14) outage

Table 2. (N-1) Line contingency ranking in IEEE 14-bus system

Line	Loss (MW)	Rank	Line	Loss (MW)	Rank
7-9	5.791	1	12-13	4.653	5
9-14	5.068	2	10-11	4.689	6
9-10	4.718	3	4-5	5.755	7
13-14	4.803	4			

Table 3. Optimized performance of IEEE 14-bus test system with GUPFC device

Line	Loss (MW)			$\Delta S_{l,avg}$		
	Without GUPFC	With GUPFC		Without GUPFC	With GUPFC	
		PSO	IPSO		PSO	IPSO
1-2	10.075	9.395	9.304	2.4390	-0.6301	-0.7435
1-5	6.575	6.209	6.112	2.2701	-0.4360	-0.5109
2-3	8.438	7.914	7.840	4.9191	-0.7835	-0.8411
2-4	5.350	5.074	5.009	1.6059	-0.4344	-0.3968
2-5	4.962	4.702	4.657	-0.1227	-0.5298	-0.6133
3-4	4.746	4.549	4.501	-0.1167	-0.1823	-0.5049
4-5	5.755	5.456	5.391	0.1748	-0.2444	-0.2608
4-7	4.633	4.411	4.355	0.3980	-0.4163	-0.3703
4-9	4.754	4.493	4.450	1.0674	-0.7312	-0.5908
5-6	4.641	4.323	4.175	1.0260	-0.5652	-1.2532
6-11	4.823	4.566	4.525	1.6142	-0.4913	-0.6619
6-12	4.887	4.660	4.572	1.4741	-1.0696	-0.8445
6-13	5.714	5.382	5.343	2.0323	-0.4823	-0.5254
9-10	4.718	4.516	4.447	1.2378	-0.7688	-0.8875
10-11	4.689	4.453	4.398	1.0944	-0.3868	-0.5974
12-13	4.653	4.430	4.348	1.1098	-0.9585	-0.7638
13-14	4.803	4.548	4.513	1.1178	-0.5987	-0.6789

B. IEEE 30-bus Test System

The test system has 6 generator (PV) buses and 24 load (PQ) buses with 41 interconnected transmission lines. It has 283.40 MW real power load and 126.20 MVar reactive power load. The generation schedule for the base case and for the generator contingency cases are given in Table 4.

Table 4. Generation schedule according to their maximum limit

Gen #	1	2	3	4	5	6
Pmax(MW)	360.2	140	100	100	100	100
Schedule (MW)	113.4	44.07	31.48	31.48	31.48	31.48

The system is suffered with 5.658 MW for the base case. The (N-1) contingencies are imposed in to test system and the corresponding losses are given in Table 5. The lines 9-11, 12-13, 25-26 are not considered due to network configuration or bus-11, 13 and 26 can isolate under these contingency respectively. As per the incurred losses, the line contingencies are ranked. The lines which are incident to generator buses (i.e., 1, 2, 5, 8, 11 and 13) as well as with tap-changing transformers (6-9, 6-10, 4-12, 28-27) are excluded from the priority list and the remaining lines are only listed in Table 5. The remaining lines are ranked. The line

contingency 3-4 and 10-21 are ranked top but these is no common bus for these two lines. Hence, the next two lines i.e., lines 6-7 and 4-6 are considered for the GUPFC integration.

Table 5. (N-1) Line contingency ranking in IEEE 30-bus system

Line Contingency	Loss	Rank	Line Contingency	Loss	Rank
6-7	7.19	1	15-18	5.797	14
3-4	7.164	2	10-17	5.790	15
10-21	6.516	3	29-30	5.790	16
4-6	6.393	4	10-22	5.764	17
12-15	6.272	5	22-24	5.764	18
9-10	6.255	6	25-27	5.757	19
27-30	6.162	7	16-17	5.696	20
27-29	6.038	8	15-23	5.690	21
10-20	6.030	9	18-19	5.684	22
12-14	5.883	10	23-24	5.679	23
19-20	5.871	11	14-15	5.661	24
6-28	5.864	12	21-22	5.661	25
12-16	5.815	13	24-25	5.615	26

As per the GUPFC configuration, the common bus of these two lines is bus-6 and considered for the shunt converter location. The GUPFC operating constraints are same as considered in the IEEE 14-bus test system simulation. The generator contingencies are possible line contingencies are simulated with GUPFC in the network. The effectiveness of GUPFC is observed on the transmission losses in all the case studies. The best results among ten simulations are only given in Table 6. By comparing basic PSO, the IPSO has given better results in terms of global optima or minimum losses. The convergence characteristics of both the algorithms are given for line 6-9 only due to space limits in Fig. 3, but the similar type of characteristics have been observed for remaining cases also. Similarly by observing transmission security margin for 14-bus test system in Table 3 and for 30-bus test systems, the increased insecurity margin is decreased significantly even under contingency cases. As compared to basic PSO, the IPSO is able to redistribute the power flows from heavily loaded lines to under loaded lines by optimizing the power injections of GUPFC device at its incident buses.

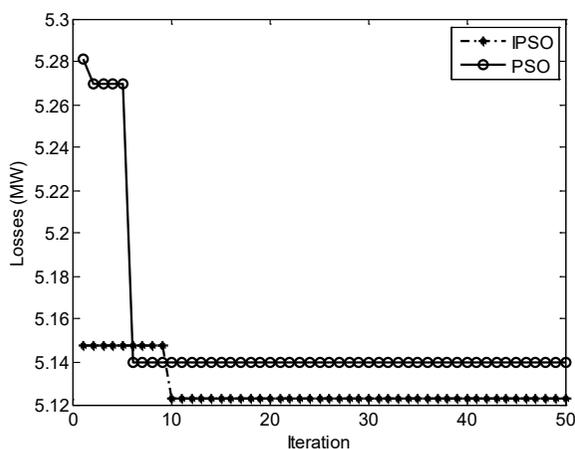


Figure 3. Convergence characteristics of the algorithms under line (6-9) outage

Table 6. Optimized performance of IEEE 30-bus test system with GUPFC device

Line	Loss (MW)			$\Delta S_{l,avg}$		
	Without GUPFC	With GUPFC		Without GUPFC	With GUPFC	
		PSO	IPSO		PSO	IPSO
1-2	12.127	11.097	11.042	3.3966	-0.7577	-0.5543
1-3	7.364	6.835	6.805	-0.3803	-0.3702	-0.2334
2-4	5.872	5.393	5.365	-0.1752	-0.5266	-0.4331
3-4	7.164	6.626	6.582	-0.4542	-0.4015	-0.2452
2-5	10.575	9.638	9.56	3.6826	-0.4689	-0.4557
2-6	6.119	5.583	5.583	0.3771	-0.4052	-0.4342
4-6	6.393	5.973	5.893	-0.4222	-0.4308	-0.3705
5-7	5.727	5.193	5.152	-0.4235	-0.6614	-0.7438
6-7	7.190	6.467	6.381	-0.3486	-1.0901	-1.1361
6-8	5.552	5.154	5.111	-0.0848	-0.3028	-0.1822
6-9	5.671	5.140	5.123	-0.0634	-0.6219	-0.5281
6-10	5.695	5.163	5.137	0.4191	-0.8325	-0.6085
9-10	6.255	5.619	5.579	1.3303	-0.4010	-0.4696
4-12	5.591	5.002	5.002	0.4993	-0.9010	-0.9010
12-14	5.883	5.328	5.319	0.5728	-0.6194	-0.8300
12-15	6.272	5.682	5.67	0.9914	-0.8475	-0.5982
12-16	5.815	5.309	5.241	0.6725	-0.6713	-0.6220
14-15	5.661	5.120	5.08	0.3814	-0.8706	-0.6892
16-17	5.696	5.126	5.118	0.4364	-0.7410	-0.7487
15-18	5.797	5.234	5.23	0.6406	-0.7753	-0.8164
18-19	5.684	5.092	5.072	0.4299	-0.7178	-0.8381
19-20	5.871	5.308	5.275	0.5562	-0.8340	-0.6152
10-20	6.03	5.478	5.449	0.7265	-0.7198	-0.8540
10-17	5.79	5.251	5.223	0.5342	-0.9285	-0.7858
10-21	6.516	5.911	5.876	1.4250	-0.6365	-0.5512
10-22	5.764	5.221	5.215	0.5017	-0.8562	-0.5390
21-22	5.661	5.103	5.081	0.4102	-0.8026	-0.6738
15-23	5.69	5.143	5.097	0.5259	-0.7150	-0.7352
22-24	5.764	5.203	5.184	0.5017	-0.6494	-0.7469
23-24	5.679	5.119	5.111	0.4365	-0.7323	-0.7828
24-25	5.615	5.076	5.06	0.3433	-0.7571	-0.6844
25-27	5.757	5.229	5.195	0.5555	-0.8664	-0.5796
28-27	7.695	6.934	6.912	2.2105	-0.5377	-0.6484
27-29	6.038	5.455	5.431	0.4400	-0.7593	-0.8180
27-30	6.162	5.550	5.523	0.6694	-0.6562	-0.7443
29-30	5.79	5.249	5.223	0.3481	-0.9047	-0.6714
8-28	5.664	5.137	5.12	0.4154	-0.6492	-0.7232
6-28	5.864	5.362	5.331	0.5280	-0.5767	-0.5611

The effectiveness of the proposed approach is compared for 30-bus test system with the results given in [33], in which the system parameters and GUPFC parameters are optimized using Uniformly Distributed Two Stage Particle Swarm Optimization (UDT PSO) based optimal power flow (OPF) approach. The generation schedule and GUPFC parameters provided in [33] (Ref. Table 9: Case 3 with 2 series converters-GUPFC configurations) are considered and the system performance is determined for base case and contingency cases. For commonality, the system security index (SI) is determined using the index proposed in [33, 34]. By observing the results, the impact of GUPFC is less with the methodology proposed in [33] as compared with the current authors' methodology. The results for base case, line 5 and line 36 cases are given without and with GUPFC in Table 7. The active power loss comparison without and with GUPFC are given in Figure 4 and Figure 5 respectively. The security index (SI) without and with GUPFC are given in Figure 6 and Figure 7 respectively. In comparison, the active power loss and SI are decreased with GUPFC, where as it is more significant in the current work than [33].

Table 7. Comparison of GUPFC impact in 30-bus system

Methodology	Case	Without GUPFC				With GUPFC			
		Ploss	Qloss	Vmin	SI	Ploss	Qloss	Vmin	SI
Ref [33]	Base	10.520	-27.903	0.915	4.794	10.517	-28.287	0.916	4.509
	Line 5 Contingency	17.768	-4.527	0.912	11.097	17.747	-4.961	0.913	10.646
	Line 36 Contingency	13.081	-20.005	0.782	11.342	13.042	-20.577	0.786	10.971
Proposed Methodology	Base	5.782	-29.506	0.931	1.126	6.284	-28.389	0.950	2.013
	Line 5 Contingency	11.089	-10.820	0.929	3.125	11.296	-11.250	0.945	3.556
	Line 36 Contingency	8.491	-22.182	0.776	8.594	8.416	-24.179	0.824	8.183

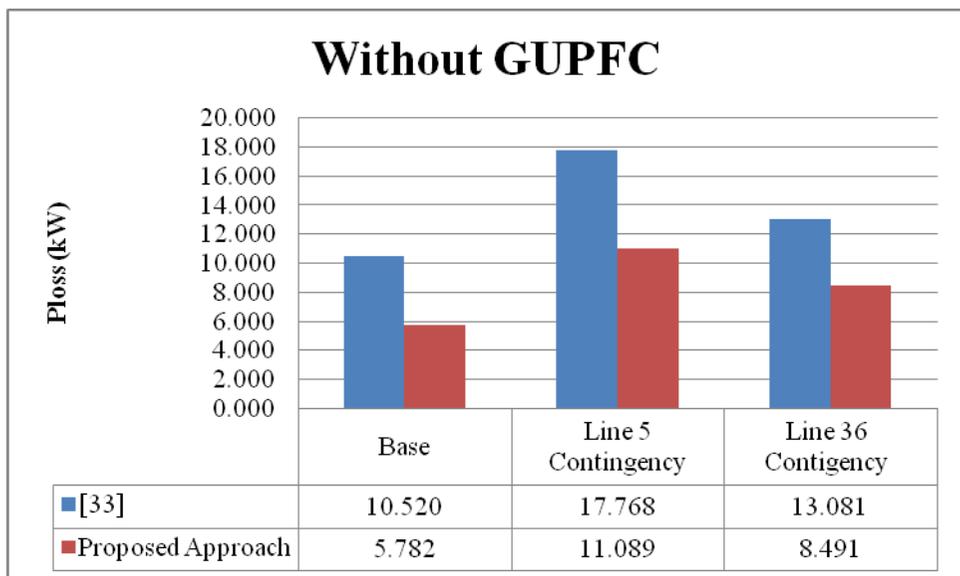


Figure 4. Active power loss comparison without GUPFC in 30-bus test system

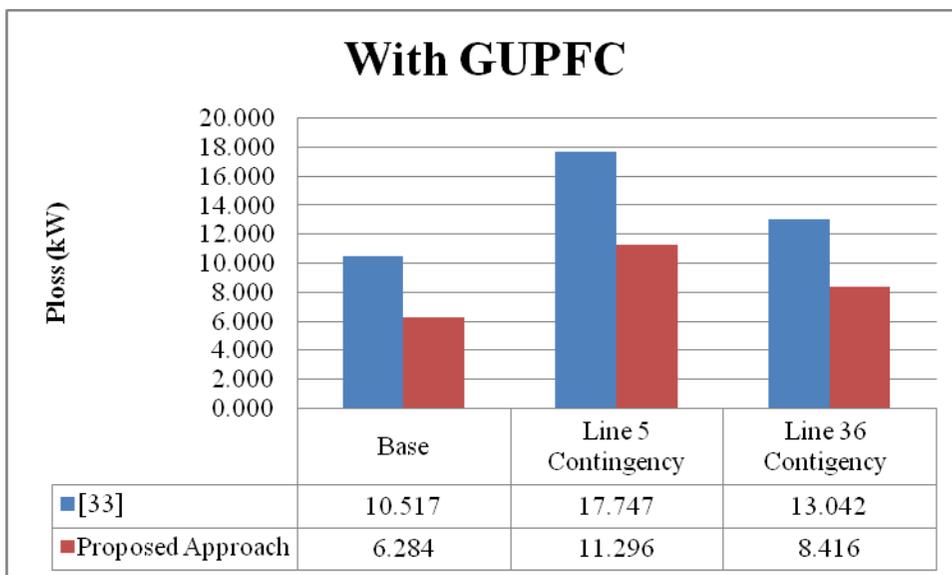


Figure 5. Active power loss comparison with GUPFC in 30-bus test system

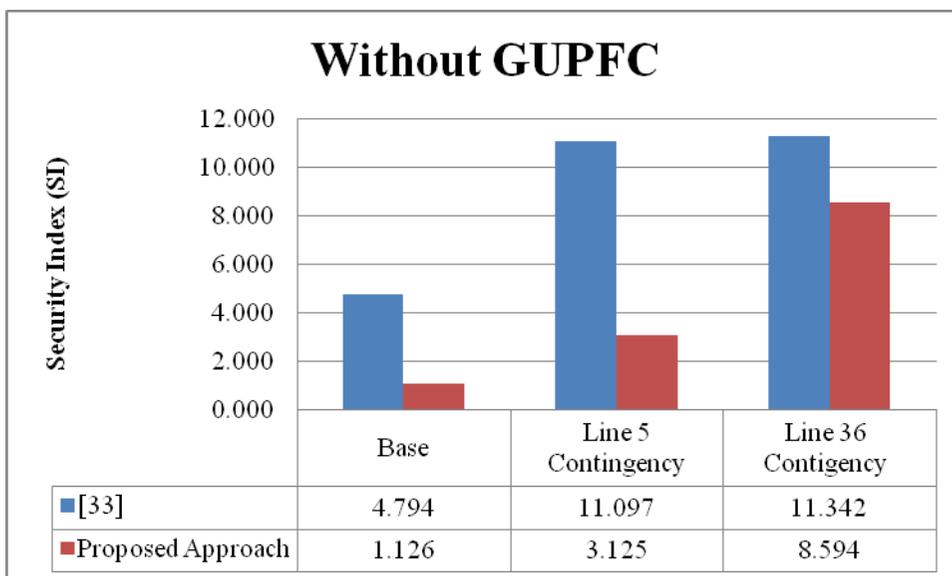


Figure 6. Comparison of Security Index (SI) [33, 34] without GUPFC in 30-bus test system

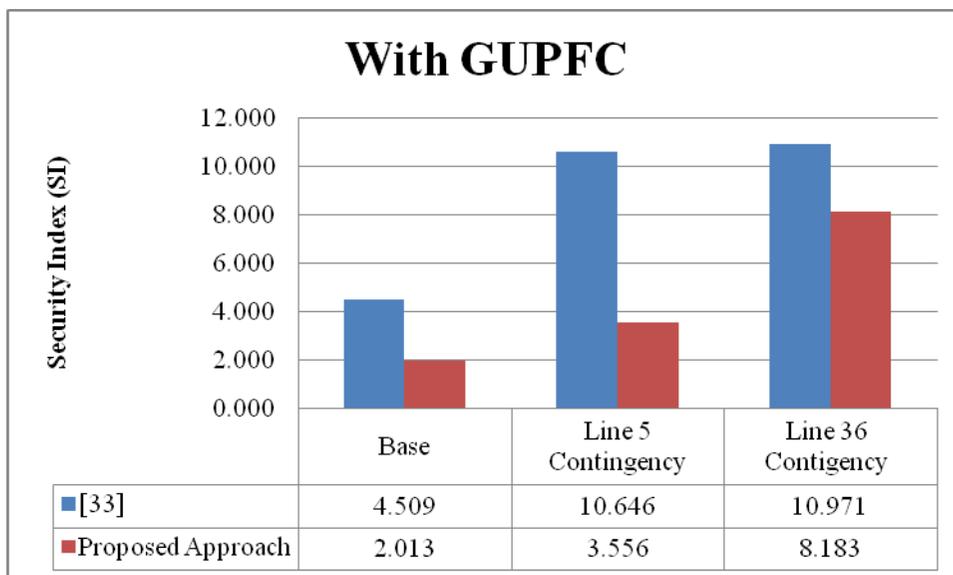


Figure 6. Comparison of Security Index (SI) [33, 34] with GUPFC in 30-bus test system

7. Conclusion

Transmission system security and loss minimization is an important issue in modern power system operation and control. Since both are dependent on contingencies as well as power flows of the transmission lines and can be optimized by redistributing the power flows effectively. Among the FACTS devices, GUPFC is an efficient device which can control multiple lines simultaneously or consecutively. In general, the location and parameters of GUPFC device would play a key role in better operation. This paper presented GUPFC effectiveness on transmission system performance. A simple strategic approach is presented for the GUPFC device location based on (N-1) line contingency severity by considering transmission losses. The optimization problem is solved using basic PSO (BPSO) and Improved PSO (IPSO) algorithms. Both the algorithms are effectively optimized the transmission losses by injecting powers as per the PIM of GUPFC but as compared to BPSO, IPSO has resulted better solution in terms of minimized transmission losses and improved security margin. The case studies are performed on the IEEE 14-bus and 30-bus test systems and the results are validating the GUPFC application for the real-time towards transmission losses minimization and security margin improvement.

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