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Sensitivity Based Congestion Management in a Deregulated Power System by Optimal Allocation & Parameter Setting of TCSC using Grey Wolf Optimization

Anubha Gautam[1], Parsh Ram Sharma[2], and Yogendra Kumar[3]

[1]Assistant Professor, Department of Electrical Engineering,
YMCA University of Science & Technology, Faridabad, India
[2]Professor, Department of Electrical Engineering,
YMCA University of Science & Technology, Faridabad, India,
[3]Professor, Department of Electrical Engineering,
Maulana Azad National Institute of Technology, Bhopal, India,
tanyashroti@gmail.com, prsharma1966@gmail.com, ykmact@yahoo.co.in

Abstract: In a deregulated power system as the power demand is increasing rapidly, with a limited power system framework, it is very difficult to transmit bulk power. This limitation is due to the thermal constraints of the transmission line. There is a need to increase the loadability of the line without hitting the thermal limits of the system. Thyristor Controlled Series Compensator (TCSC) is used in this paper to reduce congestion in the system by reducing losses and increasing the loadability of the lines. The sensitivity factor applied to optimally allocate TCSC is Disparity Line Utilization Factor (DLUF) and parameter setting is optimized using Grey Wolf Optimisation (GWO). The lines are sorted in terms of the degree of congestion with the help of LUF and then optimal location of TCSC is obtained using DLUF to minimize congestion. TCSC parameters are optimally calculated by the multivariable objective function applying GWO. The method is validated on IEEE 30 bus system. The congestion is reduced and the loadability of a line is increased by the algorithm used in this paper. Effects of congestion alleviation by proposed method are suitably demonstrated in this paper for reduced real and reactive power loss, reduced voltage deviation and incremented security margin of the test system. Results obtained by the proposed algorithm is establishing an upper hand over other state of art algorithms in terms of solution of problem formulated for congestion alleviation

Keywords: Deregulation; congestion Alleviation, FACTS; TCSC; DLUF; LUF; Grey Wolf Optimisation.

1. Introduction

With the increasing power demand and privatization in the deregulated power system, the transmission lines are strained and the thermal limits are approached to make the line congested [1]. Congestion in the power system not only is a menace to the physical network security but makes the system uneconomical due to hike in power prices [2]. To reduce the congestion and to have a limitation on price hike FACTS devices can play an effective and influential role in the deregulated environment. FACTS devices can be used most efficiently and economically by optimal placement and parameter setting [3]. For optimized placement and parameter setting different techniques like Reactive power spot price based index (QSPI) has been applied by J G Singh et al. [4] for the incorporation of Static VAR compensators in a congested power system. One of the versatile FACTS device is TCSC. TCSC due to its effectiveness in swiftly and efficiently changing reactance property is used widely in the congested power system. Hadi Besharat et al. [5] applied real power performance index for optimal placement and tuning of TCSC in standard two 5 bus power system for N-1 contingency condition. These methods successfully searched the economical size and optimized location of TCSC. Siddhartha Panda et al [6], developed a program to compare the methods of Genetic Algorithm (GA) & newly developed Particle Swarm Optimization (PSO) for tuning of TCSC. The controller of TCSC was tuned with GA as well as PSO for reducing power system oscillations created to improve the stability of the power system. PSO was found to give better results as compared to GA. A R

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Jordehi et al [7] compared various heuristic methods such as GA, ES, EP, DE, SA, TS, etc. for optimization of FACTS and discussed the benefits and limitations of the methods to be considered in future for better results. A further method of ATC enhancement for congestion management was suggested by K Rani et al [8].The location of TCSC has been calculated by Genetic algorithm (GA) for alleviating congestion problem [9]. Application of real coded Genetic algorithm for optimizing the size & location of TCSC & SVC for ATC maximization was detailed. The location and sizing of TCSC for power system optimization can also be obtained by considering different sensitivity factors as performance index sensitivity factor suggested by Ya-Chin Chang [10], Chang used fitness sharing multi-objective PSO and real power flow PI sensitivity factors given by Mandala et al. [11]and applied modified PSO (MPSO) to minimize the generation & TCSC cost.

Esmaili et al [12] worked upon the indices of voltage stability margin (VSM) and corrected transient stability margin (CTEM) as deciding factors for determination of most congested line and placement of TCSC for congestion management.K. Pandiarajan et al [13] used overload factor (OLF) for estimating the overloaded line or congested lines by reducing the severity index following the generation and voltage limit constraints. DEPSO was used for achieving the objective of minimizing rescheduling cost while removing overload on the line. Naik et al. [14] proposed PSO algorithm based on Constriction Factor (CFBPSO), assuring convergence of algorithm for suitable results from OPF. Omid Ziaee et al [15] applied the congestion rent factor for determining the most congested line and hence the location for placement of TCSC. Siddiqui et al. [16] proposed a method to implement multiple FACTS devices of same category and studied their effect on HV transmission lines with an aim to mitigate congestion. I N Trivedi et al. [17] proposed a novel meta-heuristic optimization algorithm Ant Lion Optimizer (ALO) to optimize the power flow problem with an aim to enhance voltage stability and reduce system losses. Anwar Shahzad Siddiqui et al [18] used a loss sensitivity index for determining the location for placement of TCSC & STATCOM to reduce congestion. Here sensitivity indices were calculated by applying the reactive power loss reduction approach. Akansha Mishra et al [19] worked on a disparity line utilization factor which in turn was used for deciding the suitable location of IPFC using Gravitational Search Algorithm with an aim of congestion management.

TCSC is a variable reactance FACTS device which is connected in series with the line and hence can control the power flow in the line by varying the reactance of the line for achieving the objective of reducing system losses and enhancing voltage stability.

In this paper DLUF and LUF, being very versatile sensitivity indices, used to calculate the most suitable location of TCSC while control parameters of TCSC are being optimized by using Grey Wolf Optimisation. Among several state of art methods available, the Grey wolf algorithm is one of the most versatile methods used to optimize the objective function taken into consideration. This is a nature-based algorithm in which the hunting behavior and process of Grey Wolf are considered to find the solution of non-linear power system equations to reduce congestion in the system. This algorithm was originally proposed by Mirjalili, Seyedali et al. [20]. In literature a number of optimization algorithms has been applied to enhance the security margin of a power system to mitigate congestion.

In this research paper, GWO has been applied for enhancing the security margin of the power system together with TCSC, which has not been found in literature as far as my survey is concerned. GWO being applied on the test system to alleviate congestion by reducing voltage deviation and system power losses. The security margin has been improved to make system more stable TCSC parameter being optimized by GWO such that the minimum size of the device may achieve congestion management at a lower cost while suitably placing the device by using sensitivity indices.

2. Sensitivity Index Analysis

In the current demonopolized power system under deregulation, different FACTS devices plays a vital role in congestion management. But for achieving the goal of reducing congestion with the economy, it is necessary that FACTS devices must be placed at a very reasonable

position and must be of an optimized control parameter. Choudekar et al. [21] proposed a method utilizing Line voltage stability index sensitivity factors to demonstrate its effectiveness for system analysis and got the results suitable to justify the superiority of method over other diagnostic intelligence methods. Chakraborty S. et al. [22] presented a research based on DG placement in congested node of distribution system with the help of forward backward sweep method and Sensitivity factor (LSg). Here LSg has been used to get the congested line to place DG to get rid of critical congestion condition
Line Utilisation Factor (LUF), can be mathematically explained as the percentage ratio of MVA flow of line to its capacity. LUF has been one of the promising sensitivity factor to be applied for FACTS allocation in power system. The difference of LUF between two lines which are connected to same bus is calculated to determine optimised location of TCSC.

$$LUF_{mn} = \frac{MVA\ flow\ in\ line\ mn}{Max\ capacity\ of\ MVA\ flow\ in\ line\ mn} \tag{1}$$

Now Disparity line utilization factor (DLUF), is calculated by the difference of LUF for the concerned pair of lines. Minimum value of DLUF suggests the line for optimal location of TCSC. The reactance parameter of TCSC is manipulated by applying GWO

$$DLUF_{(ij-iq)} = \left|LUF_{ij} - LUF_{iq}\right| \tag{2}$$

Where,

$DLUF_{(ij-iq)}$is the DLUF of line pair ij & iq connected to a common bus m.

3. Modelling of TCSC

M Nafar et al. [23], explained TCSC as a device which automatically manipulates its reactance to change the power flowing through the line where it is located. The power flow model is shown in Figure (1).

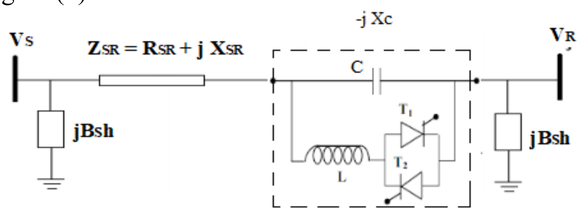
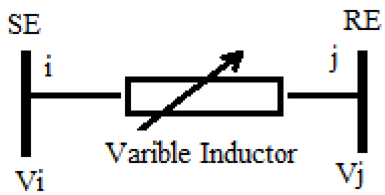
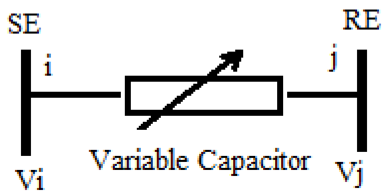


Figure 1. Power flow model of TCSC [25]



(a).



(b).

Figure 2(a). Adjustable Inductive mode of TCSC
(b). Adjustable Capacitive mode of TCSC

TCSC regulates the power flow by operating either in capacitive mode or inductive mode as per the load connected to the line Figure 2a shows the inductive mode while capacitive mode of operation in illustrated by Figure 2b.

Now we know that:

$$I_{Bus} = Y_{bus} * V_{bus} \tag{3}$$

And also

$$Y_{mn} = G_{mn} + jB_{mn} \tag{4}$$

Where

G_{mn}- Conductance of line mn and B_{mn}- Susceptance of line mn

The impedance of TCSC can be calculated as:

$$Z_{TCSC} = \frac{V_{TCSC}}{I_L} \tag{5}$$

The change of admittance of line after placing TCSC:

$$\Delta Y_{RS} = y'_{RS} - y_{RS}$$

$$so,\ \Delta Y_{RS} = (G'_{RS} + B'_{RS}) - (G_{RS} + B_{RS}) \tag{6}$$

Where,

$$G_{RS} = \frac{R_{RS}}{\sqrt{R_{RS}^2 + X_{RS}^2}} \& B_{RS} = \frac{-X_{RS}}{\sqrt{R_{RS}^2 + X_{RS}^2}} \tag{7}$$

$$G'_{RS} = \frac{R_{RS}}{\sqrt{R_{RS}^2 + (X_{RS} + X_{TCSC})^2}} \tag{8}$$

$$\& B'_{RS} = \frac{-(X_{RS} + X_{TCSC})}{\sqrt{R_{RS}^2 + (X_{RS} + X_{TCSC})^2}} \tag{9}$$

When X_{TCSC} is modified it changes admittance (Ymn) of the targeted line in which it is connected. This modification further manipulates the Y_{bus} matrix which then modifies Jacobian Matrix of the system in NR load flow.

Multi-Objective function:

Equation (10) represents the objective function

$$f = w_1 \times SM + w_2 \times PL + w_3 \times VD + w_4 \times X_{TCSCS} \tag{10}$$

Where,

w_1, w_2, w_3 & w_4 are weight factors considered for each variable. It is valued to 0.25 each.

SM in equation (10) is a security margin which can be mathematically represented as:

$$SM = \frac{\sum_{k \in kload}(S_k cons) - \sum_{k \in kload}(S_{kin})}{\sum_{k \in kload}(S_k cons)} \tag{11}$$

K_{load} in (11) represents a set of all load buses

For normal operating conditions of power system, the value of SM must lie between 0 & 1, thus for achieving the goal of minimization of the objective function in (10), equation (11) can be rewritten as:

$$1 - SM = \frac{\sum_{k \in kload} S_{kin}}{\sum_{k \in kload} S_k cons} \tag{12}$$

Real power loss can be represented mathematically as:

$$PL = \left(|V_p^2|G_{pq} - |V_p||V_q|[G_{pq}\cos\theta_{pq} + B_{pq}sin\theta_{pq}] - |V_p||V_{snpq}|[G_{pq}\cos\theta_{snpq} + B_{pq}sin\theta_{snpq}]\right)\left(|V_q^2|G_{pq} - |V_p||V_q|[G_{pq}\cos\theta_{qp} + B_{pq}sin\theta_{qp}] - |V_q||V_{snpq}|[G_{pq}\cos\theta_{snpq} + B_{pq}sin\theta_{snpq}]\right) \tag{13}$$

Voltage deviation can be expressed as:

$$VD = \sum_m^{NB} |V_m - V_{mref}|^2 \tag{14}$$

where V_m *and* V_{mref} are the actual and reference value of voltage at bus m respectively
TCSC reactance:
The limits of reactance of TCSC can be given as:

$$-0.8X_L \leq X_{tcsc} \leq 0.2X_L$$

for economics point of view (15)

4. Constraints

Table 1. Equality and Inequality constraints

Limitations	
True Power	$P_{gn} - P_{dn} - P_n(V_n, \theta_n) = 0$
Reactive Power	$Q_{gn} - Q_{dn} - Q_n(V_n, \theta_n) = 0$
Generator True Power	$P_{gn}^{min} \leq P_{gn} \leq P_{gn}^{max}$
Generator Reactive Power	$Q_{gn}^{min} \leq Q_{gn} \leq Q_{gn}^{max}$
Bus Voltage	$V_{nmin} \leq V_n \leq V_{nmax}$
Xtcsc	$X_{tcsc}^{min} \leq X_{tcsc}^{n} \leq X_{tcsc}^{max}$

Where Pgn&Qgn are active & reactive power generations at n_{th} bus, Pdn & Qdn are active & reactive power demand at the n_{th}bus. Here Vn&θ_n are the voltage and its corresponding angle at n_{th} bus.

5. Grey Wolf Optimiser

GWO is based on the social pecking order of a pack of Grey Wolves. It imitates the hunting behavior of the pack of wolf which is integral part and specialty of their social hierarchy. The wolf hunting a prey can be divided into three categories as encircling, hunting and attacking the prey. The pack is led by Alpha wolf which finally attacks the prey. Next hierarchy is of beta wolfs which supports alpha wolf in hunting. Third category of wolfs are the gamma wolfs again supporting the wolfs in hunting. Base on this alpha(α) is considered as best fitness value while beta (β) and gamma (γ) are considered as second and third best fitness. Searching of prey is done by all wolves. After positioning the prey, it is encircled and harassed. Once get tired becomes stationary and then it is attacked.

Mathematically different steps can be represented as below [24]

$$D^{\rightarrow} = |C^{\rightarrow} * X^{\rightarrow}_{\_prey}(t) - X^{\rightarrow}\_GW(t)| \quad (16)$$

$$X^{\rightarrow}_{\_GW}(t+1) = X^{\rightarrow}_{\_prey}(t) - A^{\rightarrow} * D^{\rightarrow} \quad (17)$$

Where t indicates the current position of grey wolf, $X^{\rightarrow}$is the position vector of the prey, $X^{\rightarrow}$_GW represents a position vector of the grey wolf, A & C are coefficient vectors and calculated as follows.

$$\left.\begin{aligned} \vec{A} &= 2\vec{a} * \vec{r}_1 - \vec{a} \\ \vec{C} &= 2 * \vec{r}_2 \end{aligned}\right\} \quad (18)$$

Here a is reduced from 2 to 0 through the span of emphases and $\vec{r}_1$ *and* $\vec{r}_2$ are random values between 0 and 1.

The error introduced by this factor 'a' manipulates the result so the algorithm never stuck to local minima but iterations are carried out till global minima is obtained.

Power system when modelled, converted into very complex non-linear mathematical expressions. These equations cannot be realized by traditional methods. Thus, iterative methods like GWO here is implemented to locate (calculate) the location of prey (solution). Best fitness values are those given by Alpha, Beta & gamma. At each iteration the positions of remaining wolves are compared with these three wolves to get any update in first three positions. This process can mathematically be represented as:

$$\left.\begin{aligned}\vec{X}_1 &= \vec{X}_{-\alpha}(t) - \vec{A}_1 * \vec{D}\_\alpha \\ \vec{X}_2 &= \vec{X}_{-\beta}(t) - \vec{A}_1 * \vec{D}\_\beta \\ \vec{X}_3 &= \vec{X}_{-\gamma}(t) - \vec{A}_1 * \vec{D}\_\gamma\end{aligned}\right\} \tag{19}$$

Where $\vec{D}\_\alpha, \vec{D}\_\beta\ and\ \vec{D}\_\gamma$ are defined as

$$\left.\begin{aligned}\vec{D}\_\alpha &= |C * \vec{X}_{-\alpha}(t) - \vec{X}_{GW}(t)| \\ \vec{D}\_\beta &= |C * \vec{X}_{-\beta}(t) - \vec{X}_{GW}(t)| \\ \vec{D}\_\gamma &= |C * \vec{X}_{-\gamma}(t) - \vec{X}_{GW}(t)|\end{aligned}\right\} \tag{20}$$

The average of the algebraic sum of three positions of wolves gives us the best position of the grey wolf

$$X_{GW}(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \tag{21}$$

Grey Wolf optimizer Algorithm:
Step1: Initialize a, A and C {GWO Parameters} and Read input
Step2: Adjust grey wolf population (n=100)
Step 3: Initialize iteration counter, iter=0
Step 4: After evaluating the fitness, update three best solutions as $\alpha, \beta\ and\ \gamma$.
Step 5: Change the value of 'a' from 2 to 0 using equation below:

$$\text{a(iteration)} = 2 \times \text{iteration}_{\text{count}} \times \left(\frac{2}{\text{Maximum Iteration}}\right)$$

Step6: Update position vectors $\vec{D}\_\alpha, \vec{D}\_\beta\ and\ \vec{D}\_\gamma$ after getting the new values of A and C
Step 7: Apprise position of all solutions
Step 8: if the solution value is same end iteration, else increment iteration counter to t=t+1and move to Step 4.

Steps followed to solve the objective of research:

- *OPF with NR load flow is applied to calculate line losses without TCSC.*
- *Calculate LUF for each line by using equation (1). The lines having high LUF values are congested.*
- *Calculate DLUF from equation (2) and get its minimum value.*
- *Find optimal location of TCSC at the line where DLUF is minimum.*
- *Once located, TCSC is optimized for its size by applying PSO algorithm.*
- *OPF with NR and TCSC is again carried out to compare the results with base case.*
- *The same steps are followed with GWO.*

6. Result analysis and Discussion

For verification of proposed algorithm three different cases are considered. First case is the base case where normal operating conditions of IEEE 30 bus system are being considered. In second case contingency condition of line outage in IEEE 30 bus system is considered and in third case 125% overloading on all the load buses is done. In all the three cases GWO has proven the better algorithm for reduction of congestion, loss minimization, reducing voltage deviation and enhancement of security margin.

Case-A: Normal Operating Condition:
LUF values for all lines are calculated in normal conditions without implementing TCSC and with TCSC located at suitable location given by DLUF. The parameter being optimized by PSO and GWO. These values are represented in Table no 2. Table shows that maximum value of LUF obtained is 0.699 at line 18 between bus 12-15 in base case when TCSC is not connected

Table 2. LUF for all lines with & without TCSC for normal operation

Line No	From	To	LUF		
			Base Case	PSO	GWO
			Without TCSC	With TCSC	With TCSC
1	1	2	0.616	0.485	0.461
2	1	3	0.349	0.277	0.263
3	2	4	0.384	0.304	0.291
4	3	4	0.321	0.242	0.242
5	2	5	0.454	0.427	0.422
6	2	6	0.537	0.416	0.406
7	4	6	0.486	0.361	0.363
8	5	7	0.266	0.317	0.322
9	6	7	0.299	0.329	0.327
10	6	8	0.236	0.264	0.268
11	6	9	0.215	0.154	0.138
12	6	10	0.3	0.0242	0.0657
13	9	11	0.453	0.452	0.458
14	9	10	0.485	0.289	0.301
15	4	12	0.252	0.187	0.263
16	12	13	0.671	0.23	0.04
17	12	14	0.28	0.187	0.073
18	12	15	0.699(max)	0.538	0.3
19	12	16	0.341	0.381	0.243
20	14	15	0.154	0.19	0.282
21	16	17	0.442	0.476	0.0927
22	15	18	0.487	0.251	0.177
23	18	19	0.278	0.382	0.113
24	19	20	0.189	0.192	0.17
25	10	20	0.264	0.223	0.21
26	10	17	0.188	0.37	0.169
27	10	21	0.665	0.592	0.587(max)
28	10	22	0.239	0.239	0.235
29	21	23	0.0303	0.118	0.0141
30	15	23	0.504	0.65(max)	0.167
31	22	24	0.473	0.475	0.467
32	23	24	0.243	0.436	0.285
33	24	25	0.161	0.361	0.27
34	25	26	0.267	0.262	0.256

35	25	27	0.118	0.202	0.157
36	28	27	0.244	0.196	0.19
37	27	29	0.401	0.395	0.387
38	27	30	0.456	0.449	0.439
39	29	30	0.235	0.231	0.225
40	8	28	0.0877	0.0815	0.0825
41	6	28	0.439	0.378	0.379

This can be observed from table 2 that line 16 (bus 12-13), line 17(bus 12-14) and line 19 (between bus 12-bus16) are linked to mutual bus 12. Thus, here DLUF is evaluated for lines 16, 17 and 19 with respect to line 18. The line with least value of DLUF is the optimized position to locate TCSC.

The results obtained for DLUF values for line number 16, 17 and 19 with respect to line between bus 12-15 are shown in Table no.3

Table 3. DLUF values for lines linked to bus 12 with respect to line 18

S.B.	R.B.	DLUF
12	13	0.0279 (min)
12	14	0.42
12	16	0.359

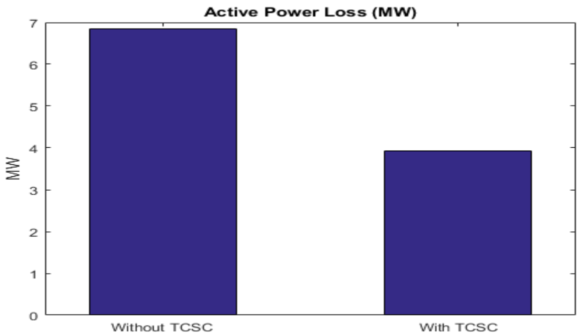
As shown by the table no 3 line no 16 (connected between the bus 12 to bus 13) is with least value of DLUF. Thus, it is the best site to place TCSC for alleviating congestion. Once TCSC located, it is optimized for its parameter by applying GWO and PSO.

From table 2 it can be seen that after implementation of TCSC and its optimization for parameter the LUF of line 1 is decreased to 0.485 from a high value 0.616 when optimized with PSO. This value is further reduced to 0.461 when TCSC is optimized for parameter. Line number 17, 27 and 30 also relieved from congestion. Thus, we can see that after the TCSC being optimized with PSO and GWO, the line utilization is good under safe limits. While on the other side the lines which were underloaded i.e. line number 8, 9 and 10, were suitably loaded. We can depict from table 2, the LUF value of line number 8 is improved to 0.317 (by applying PSO) and to 0.322 (by applying GWO) from a small value of 0.266. Similarly, for line number 9 and 10 same LUF variations are obtained. GWO algorithm produced better results for the optimized location of TCSC for enhancing the loadability of line, loss reduction, reduced voltage deviation and enhanced security margin.

Results with GWO

Figure 3(a),3(b), 3(c) & 3(d) displays the results for enhanced security margin, reduction in active power loss and voltage deviation and variation of LUF with the application of TCSC and without it.

TCSC is optimized to a value -0.305pu and located at line 16 (bus 12-13). Figure 3(a), 3(b), 3(c) and 3(d) it can be depicted that while TCSC is employed and optimised with GWO gives better results as compared to the base case. In this case the implementation of TCSC has reduced active power loss to 4.79 MW from 6.85 MW., a markable reduction in voltage deviation. The system stability has improved as 1- security margin has reduced to 0.808 after deploying TCSC optimized with GWO



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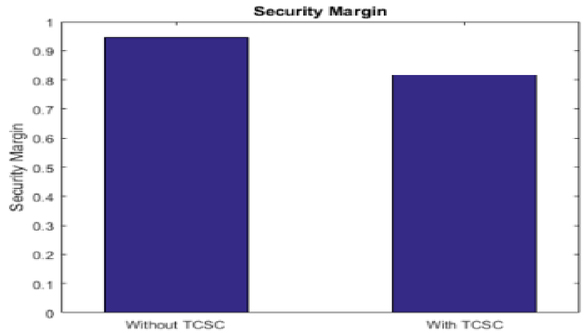

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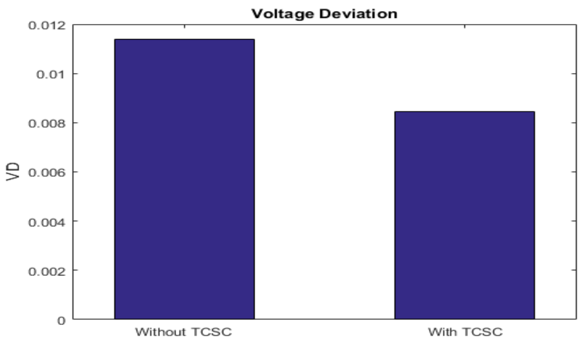

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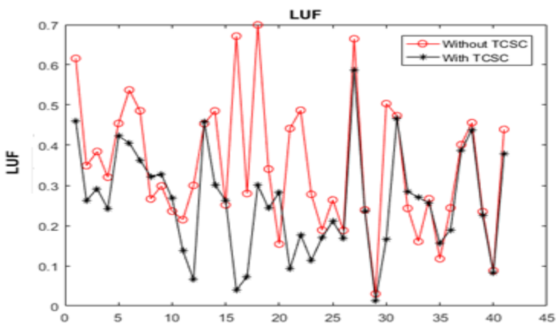
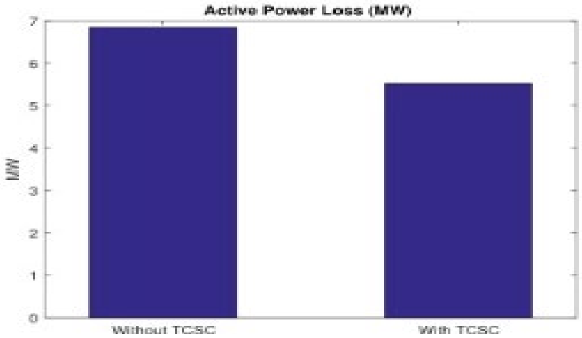


(d).

Figure 3(a). True power loss (b). 1-SM Reductio (c). Voltage deviation d. LUF Redistribution

Results with PSO



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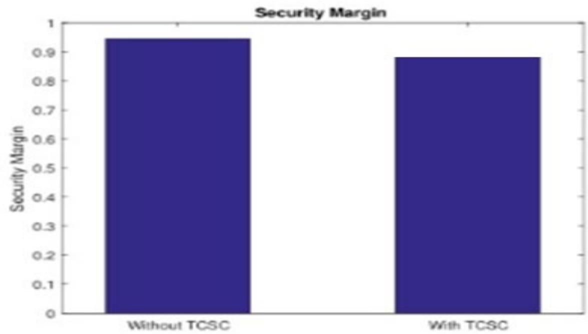

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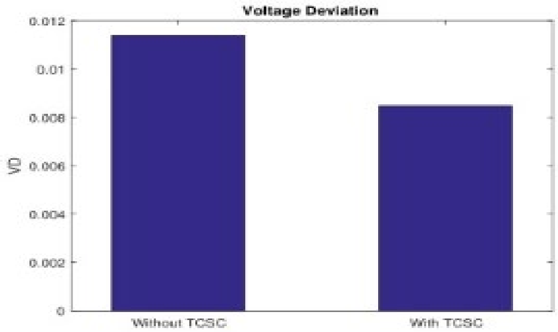
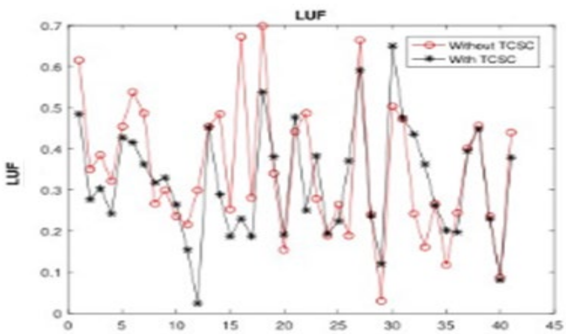


(c).



(d).

Figure 4(a). True power loss (b). 1-SM Reduction (c). Voltage deviation (d). LUF Redistribution

Here TCSC location and parameter setting is done with the help of PSO. When TCSC is applied using PSO, the maximum value of LUF of the lines has reduced from 0.699 to a low of 0.650 which is approximately a drop of 5%. Figureure number 4(a), 4(b), 4(c) and 4(d). represents true power loss, enhancement of security margin, deviation of voltage and LUF distribution in this case.

Line number 6 between buses 12 and 13 is the location of TCSC optimized with PSO with a parameter setting of -0.13 pu. From figure 4(a) we can see the active power loss has reduced to 5.52 MW from a high of 6.85 MW of unoptimized line. There is an improvement of 1-SM from a high of 0.945 to a low of 0.910 after optimization as shown in Figure 4(b). Similarly, the voltage profile has improved as the voltage deviation is reduced to 0.0847 pu from 0.0114 pu with PSO optimized lines in Figure 4(c). LUF redistribution has been shown in Figure 4(d).

Case -B: Outage of Line no 12:

LUF value calculations with TCSC for PSO and GWO optimized lines is illustrated in Table no 4. Again, the location of TCSC is obtained by the values of DLUF which are calculated with the help of LUF. When there is an outage of line number 12, there is a redistribution of LUF in all lines, such that line between bus number 12 to 15 gets overloaded. The LUF of this line becomes 0.745. Now, line number 16, 17 and 19 are connected to a common bus number 12. So DLUF is calculated for line number 16,17 and 19 are calculated with respect to line number 18. The respective DLUF values are illustrated in table number 5.

Table 4. LUF for all lines with & without TCSC for Outage of Line no 12

Line No	From	To	LUF		
			Base Case	PSO	GWO
			Without TCSC	With TCSC	With TCSC
1	1	2	0.615	0.468	0.374
2	1	3	0.351	0.27	0.219
3	2	4	0.389	0.303	0.259
4	3	4	0.322	0.249	0.222
5	2	5	0.453	0.424	0.408
6	2	6	0.533	0.41	0.362
7	4	6	0.457	0.34	0.328
8	5	7	0.269	0.321	0.348
9	6	7	0.3	0.326	0.334
10	6	8	0.232	0.261	0.227
11	6	9	0.275	0.14	0.0935
13	9	11	0.456	0.456	0.496
14	9	10	0.56	0.276	0.358
15	4	12	0.301	0.271	0.306
16	12	13	0.668	0.166	0.0368
17	12	14	0.29	0.0637	0.0546
18	12	15	0.745(Max)	0.393	0.273
19	12	16	0.381	0.304	0.232

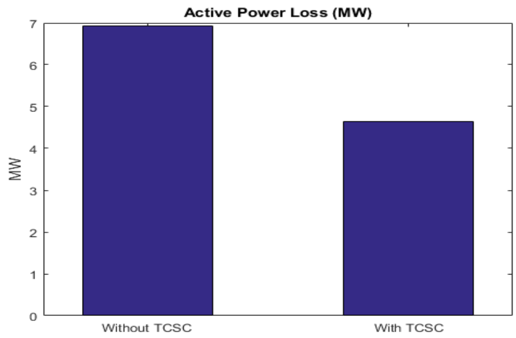
20	14	15	0.177	0.291	0.249
21	16	17	0.525	0.104	0.101
22	15	18	0.526	0.173	0.101
23	18	19	0.318	0.124	0.0274
24	19	20	0.177	0.147	0.189
25	10	20	0.25	0.19	0.229
26	10	17	0.192	0.168	0.236
27	10	21	0.637	0.604(Max)	0.557(Max)
28	10	22	0.222	0.231	0.214
29	21	23	0.0532	0.00965	0.0438
30	15	23	0.577	0.183	0.0542
31	22	24	0.441	0.456	0.423
32	23	24	0.221	0.302	0.225
33	24	25	0.149	0.287	0.221
34	25	26	0.267	0.254	0.247
35	25	27	0.185	0.167	0.202
36	28	27	0.26	0.187	0.185
37	27	29	0.401	0.385	0.375
38	27	30	0.456	0.436	0.424
39	29	30	0.235	0.224	0.217
40	8	28	0.0942	0.0829	0.0757
41	6	28	0.462	0.382	0.382

Table 5. DLUF of the lines connected to common bus 12with respect to line 18

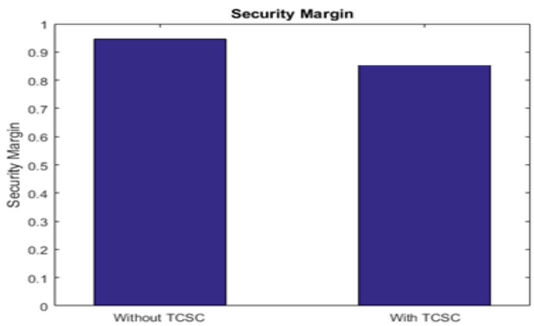
S.B.	R.B.	DLUF
12	13	0.0762(min)
12	14	0.454
12	16	0.364

Result with GWO:
Figure 5(a), 5(b), 5(c) & 5(d) demonstrates the results for reduction in true power loss, improvement in security margin, reduced voltage deviation and LUF redistribution respectively

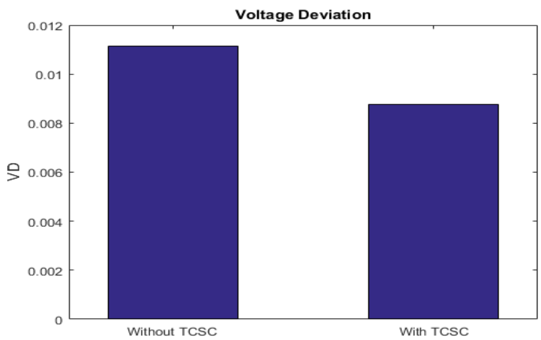
The TCSC here is located at line between bus number 12 and 13 i.e. in line number 16 by DLUF values. The size has optimised to -0.20 pu by applying GWO. Power system calculations are performed only after TCSC is optimally connected in the line optimized by DLUF and GWO. Figure number 5(a), 5(b), 5(c) and 5(d) illustrates the reduction in true power loss, deviation in voltage, improvement in security margin and redistribution of LUF. It can be depicted that GWO optimised TCSC reduces true power loss to 4.20 MW from 6.93 MW. Also, 1-SM is decreased to 0.857 from 0.945 with TCSC deployed using GWO.



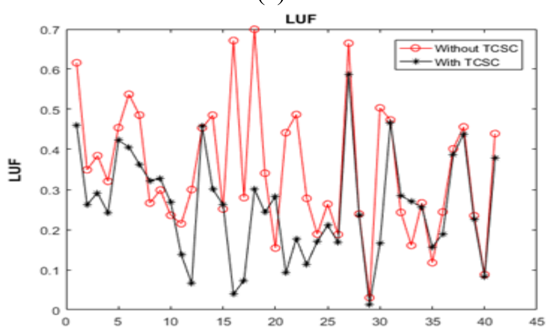
(a).



(b).



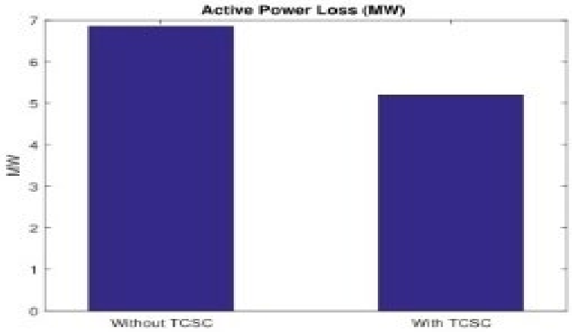
(c)



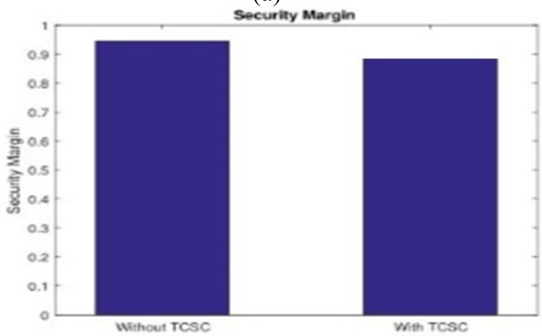
(d).

Figure 5(a). True power loss (b). 1-SM Reduction (c). Voltage deviation (d). LUF Redistribution

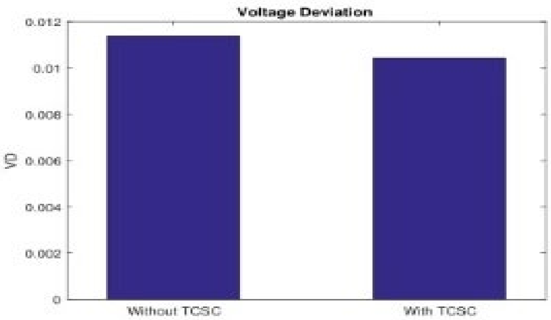
Results with PSO



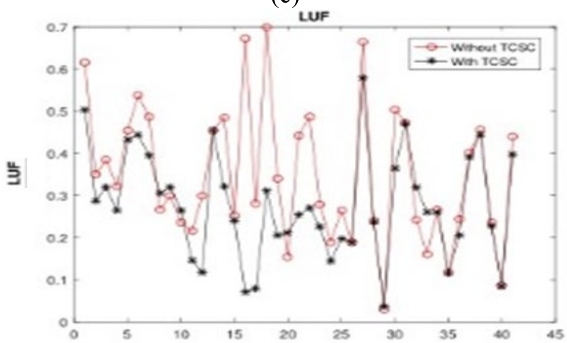
(a)



(b)



(c)



(d)

Figure 6(a). indicates reduction (b). 1-SM Reduction (c). Voltage Deviation (d). LUF Redistribution

Figure 6(a), 6(b), 6(c) & 6(d) illustrates the results for reduction in true power loss, voltage deviation, improvement in security margin and redistribution of LUF when TCSC is optimized with PSO. Here TCSC is located at line 16 between the bus 12 and 13. The parameter of TCSC is optimized to 0.191pu by applying PSO. Figure 6(a) indicates reduction in true power loss to 4.91 MW from 6.93 MW, Figure 6(b) shows that the security margin is improved to 0.926 from 0.945 to make system more stable, Figure 6(c) depicts reduction in voltage deviation and Figure 6(d) illustrates the redistribution of LUF after deploying TCSC with PSO.

Case -C: Overloading of the system by 125%:

Table 6. LUF for all lines with & without TCSC for 125% loading

Line No	From	To	LUF		
			Base Case	PSO	GWO
			Without TCSC	With TCSC	With TCSC
1	1	2	1.03 (Max)	1 (Max)	0.066
2	1	3	0.533	0.557	0.041
3	2	4	0.54	0.518	0.33
4	3	4	0.494	0.518	0.0907
5	2	5	0.614	0.61	0.559
6	2	6	0.758	0.742	0.531
7	4	6	0.689	0.705	0.671
8	5	7	0.344	0.351	0.443
9	6	7	0.374	0.377	0.42
10	6	8	0.214	0.214	0.168
11	6	9	0.299	0.299	0.291
12	6	10	0.423	0.422	0.411
13	9	11	0.471	0.471	0.471
14	9	10	0.593	0.592	0.582
15	4	12	0.417	0.419	0.401
16	12	13	0.685	0.685	0.685
17	12	14	0.34	0.34	0.338
18	12	15	0.837	0.839	0.836 (Max)
19	12	16	0.399	0.4	0.401
20	14	15	0.176	0.177	0.178
21	16	17	0.503	0.506	0.511
22	15	18	0.584	0.585	0.583
23	18	19	0.324	0.325	0.327
24	19	20	0.235	0.234	0.231
25	10	20	0.329	0.328	0.324

26	10	17	0.207	0.207	0.205
27	10	21	0.79	0.789	0.781
28	10	22	0.28	0.28	0.278
29	21	23	0.0323	0.0326	0.0339
30	15	23	0.569	0.572	0.577
31	22	24	0.554	0.554	0.55
32	23	24	0.272	0.273	0.272
33	24	25	0.153	0.153	0.152
34	25	26	0.316	0.316	0.314
35	25	27	0.193	0.192	0.189
36	28	27	0.317	0.317	0.313
37	27	29	0.5	0.5	0.495
38	27	30	0.57	0.57	0.564
39	29	30	0.293	0.293	0.29
40	8	28	0.0782	0.0781	0.0898
41	6	28	0.57	0.57	0.535

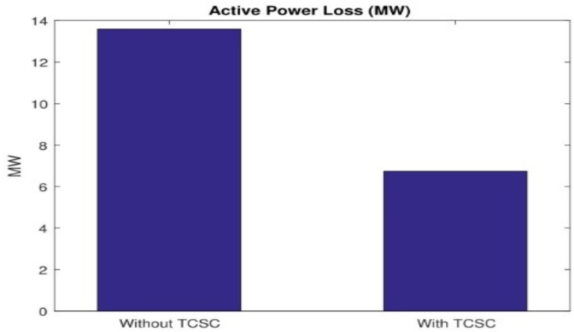
Table number 6 shows LUF values calculated prior to connection of TCSC and after TCSC connected applying GWO and PSO. This can be seen that the line between bus number 1 and 2 i.e. line 1 is overloaded and hence is congested. Line 2 is linked to the common bus 1. So, the calculation of DLUF is done for line 2 with respect to line 1. Hence the line number 2 is optimal location of TCSC. When system is overloaded by 125%, the line flows are redistributed and line number 1 is congested to have LUF value equals to 1.03pu without TCSC being connected to the system. When TCSC is optimized with PSO the LUF maximum LUF value is reduced to 0.836pu and it is further reduced to 0.652pu when optimized with GWO.

Table 7. DLUF of the lines connected to bus 1 with respect to line 1

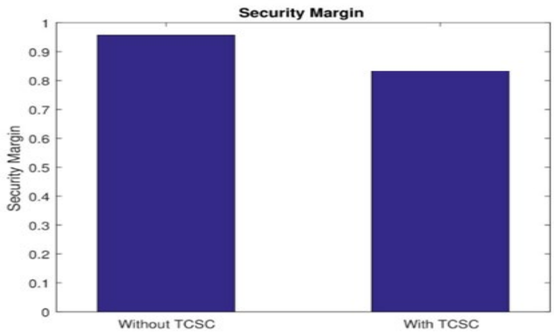
S.B.	R.B.	DLUF
1	3	0.492

Results with GWO

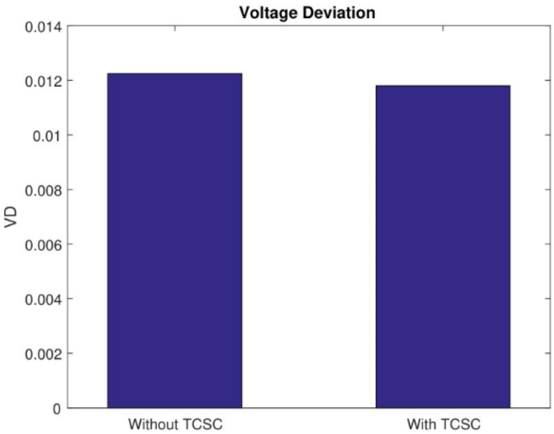
Figure 7(a),7(b), 7 (c) & 7(d) illustrates the reduction in true power loss, improved security margin, reduction in voltage deviation and redistribution of LUF when TSCS is optimized for size by GWO.



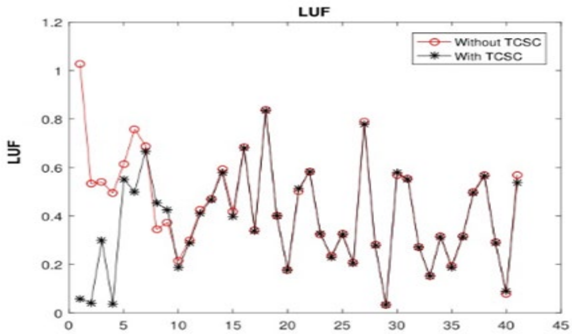
(a).



(b).



(c).



(d).

Figure 7(a). True power loss (b). 1-SM Reduction (c). Voltage Deviation (d). LUF Redistribution

TCSC is located at line between bus 1 and 3 i.e. at line number 2 with the help of DLUF calculated. The size of TCSC is optimized to -0.584pu by the application of GWO. Figure 7(a) shows the reduction of true power loss from a high of 13.6 MW to low value of 6.90 MW. Figure 7(b) illustrates improvement of security margin where the value of 1-SM has reduced from 0.967 to 0.860. Similarly, from Figure 7(c) the reduction in voltage deviation can be observed from 0.0122pu to 0.0118pu. Figure 7(d) demonstrates the redistribution of LUF in lines after TCSC being installed by applying GWO.

Result with PSO

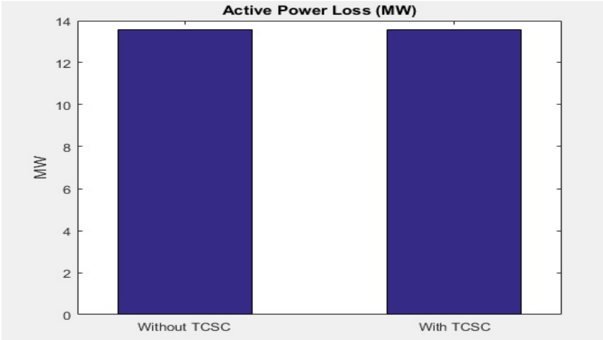
Figure 8(a),8(b), 8(c) & 8(d). illustrates the results obtained for reduction in true power loss, improvement in security margin, reduction in voltage deviation and redistribution of LUF when TCSC is connected to the system after being optimized by PSO.

After the location of TCSC is obtained at line between bus number 1 and 3 by DLUF and the TCSC parameter being optimised to -0.623pu by PSO, all power system calculations are done. The output of these calculations has been presented in Figures. Figure 8(a) shows the reduction in true power loss to 13.5 MW from 13.6 MW, Figure 8(b) represents improvement of security margin when 1-SM is reduced to 0.910 from 0.967. Figure 8 (c) demonstrates the reduction in voltage deviation from 0.0122pu to 0.0120pu.and Figure 8(d) characterizes the redistribution of LUF values with TCSC optimized by PSO.

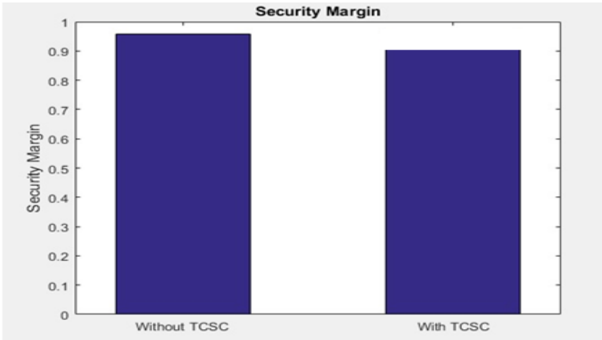
Table 8. Comparison of results obtained from GWO & PSO

Algorithm Applied	Objective Parameters / Operating Conditions	LUF (Max Value)	Active Power Loss (MW)	Voltage Deviation (pu)	1-SM (pu)	TCSC Parameter (pu)
With GWO	Normal Operation	0.587	4.79	0.00943	0.808	-0.305
	6-10 Line Outage	0.557	4.2	0.00992	0.857	-0.315
	125% Overloading	0.836	6.9	0.0118	0.860	-0.582
With PSO	Normal Operation	0.65	5.52	0.00994	0.910	-0.13
	6-10 Line Outage	0.604	4.91	0.00996	0.926	0.191
	125% Overloading	1	13.5	0.12	0.910	-0.632

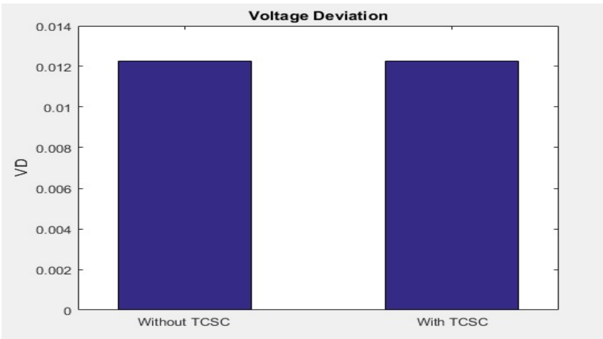
Table 8 gives a conclusive Figureure of reduction of true power loss, reduction in voltage deviation, enhanced security margin with corresponding TSCS parameter obtained under different contingency conditions and optimised by the two optimization techniques i.e. PSO and GWO



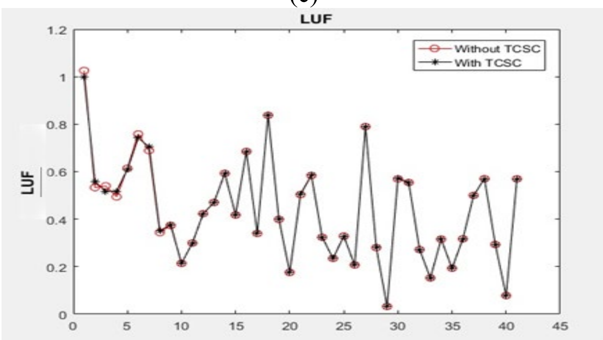
(a).



(b)



(c)



(d).

Figure 8(a). True power loss (b). 1-SM Reduction (c). Voltage Deviation (d). LUF Redistribution

7. Conclusion

In this paper GWO algorithm is implemented to alleviate the congestion by optimally sizing and allocation of TCSC. The location of TCSC is optimized using DLUF as sensitivity factor while its size being optimized by GWO and PSO. Results being validated on IEEE 30 bus system. The system is subjected to line outage and 125% overloading. In both the cases, implementation of TCSC, effectively reduces active power loss and voltage deviation while improved system security margin notably. GWO optimized TCSC implementation in the test system has reduced the active power loss approximately by 13% and voltage deviation of system by 5%. Moreover, as the value of 1-SM is reduced, the value of system security margin is improved appreciably, making system more stable. The results for active power loss, voltage deviation and 1-SM has been compared for GWO and PSO. Results evidences effectiveness of GWO over PSO.

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Anubha Gautam was born in 1978 in India. She obtained her Bachelor of Engineering from Oriental Institute of Science & Technology, Bhopal, India in 2001. She obtained Masters of Technology (Heavy electrical Equipment) form Maulana Azad National Institute of Technology, Bhopal in 2007. She is currently pursuing PhD in Electrical Engineering Department from YMCA university of Science Technology, Faridabad. She has an experience of 15 years in teaching. Her Area of interest are Power system, Power electronics and Electrical Machines.

P R Sharma was born in 1966 in India. He received his degree of Bachelor of Engineering from Punjab University in 1988 and degree of Masters of Technology in Electrical Engineering (Power System) from Regional Engineering College Kurukshetra in 1990. He received his PhD Degree from MD University, Rohtak in 2005. He started his career from industry. He has vast experience in teaching and industry. Currently he is working as Professor in Electrical Engineering department in YMCA University of Science and Technology, Faridabad. His area of interest is “Optimal location & Coordination control of FACTS devices in Power System”.

Yogendra Kumar was born in 1965 in India. He received his Bachelor of Science (Electrical) and completed Masters of Technology (Heavy Electrical Engineering). He pursued his PhD in Electrical Engineering from Indian Institute of Technology, Roorkee, India. He is at present employed in MANIT, Bhopal, India as Head of Department in Electrical Engineering guiding a number of PhD scholars. Apart from academic responsibilities he is also bearing administrative responsibilities. He is indulged in research in various fields of Electrical Engineering. His favourite field in Electrical Engineering like Power system, Heavy Electrical Machines