OPTIMAL LOCATION OF TCPST FOR LINE FLOW SECURITY ENHANCEMENT USING PSO-TVAC TECHNIQUE

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***Abstract*— Power system security enhancement is a major concern for the proper operation of a power system. In this paper, the task of security enhancement is performed by optimal placement of a FACTS device Thyristor Controlled Phase Shifting Transformer (TCPST). TCPST is a series FACTS device that can be used for reducing power losses and for controlling the power flows in various lines. However, due to the huge cost of the FACTS device, it is essential to find the optimal location and sizing of the device in a power system to obtain maximum benefits of the device.**

As a first step, the probable locations of TCPST are pre-selected based on the values of Line Overload Sensitivity Index (LOSI) calculated for each branch in the system for most severe contingencies. Then, for this reduced set of possible locations, Particle Swarm Optimization with Time Varying Acceleration Coefficients (PSO-TVAC) has been applied to obtain the optimal location and size of TCPST. To demonstrate the effectiveness of the proposed approach, it has been implemented on standard IEEE 30-bus system and is found to be highly satisfactory.

***Keywords*— PSO-TVAC, TCPST, NRLF method, FACTS device.**

I. Introduction

With the deregulation of electricity market, the traditional practices of power system operation and control have been completely changed. Better utilization of the existing power system resource to increase capabilities by installing FACTS controllers with economic cost has become essential [1]. The FACTS devices are capable of changing the system parameters in a fast and effective way. The benefits brought by FACTS devices include improvement of system stability, enhancement of system reliability, and reduction of operation and transmission investment cost [2]. A few research works were done [3], [4] on the FACTS controllers for improving static performance of r is to know the real power allocation of generators and to find the best location of FACTS controllers such that overall system the power system. There is also a great need for studying the impact of FACTS controllers and their impact on the power generation cost are also reported [5].

FACTS devices are the solid state converters having capability of improving power transmission capacity, improving bus voltage profile, enhancing power system stability, minimizing transmission losses etc [6, 7]. The flexible AC transmission system is a transmission system which use reliable high speed thyristor based high speed control elements designed based on state of the art developments in power semiconductor devices [8]. The concept of FACTS controllers was first defined by Hingorani in 1988.

The FACTS devices certainly play an important and major role in the operation and control of modern power system. FACTS devices are able to influence and voltages to different degrees depending on the type of device. Typically the devices are divided as shunt connected, series connected and combination of both. Thyristor Controlled Phase Shifting Transformer (TCPST) is series connected device that directly affects the power flows in transmission line to improve power system operation. TCPST is used to minimize the total real and reactive power generation limits, voltage limits, transmission line limits and FACTS parameter limits. In Ref. [9], the location of FACTS devices in the power system are obtained on the basis of static and dynamic performance. The organization of this paper is as follows. Modeling of TCPST and problem formulation is described in section II. The results on the IEEE 30 bus systems are presented in section VII. Finally the conclusion and future scope are given.

II. Modelling of TCPST

The structure of a TCPST is given in Fig.1. The shunt connected transformer draws power from the network and provides it to the series connected transformer in order to introduce a voltage VT at the series branch. Compared to conventional phase shifting transformers, the mechanical tap changer is replaced by a thyristor controlled equivalent. The purpose of the TCPST is to control the power flow by shifting the transmission angle.

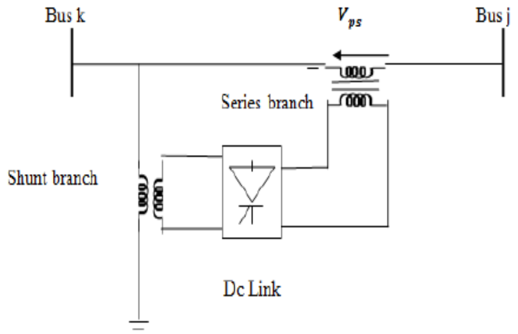

Fig.1 Structure of TCPST

The model of the transmission line with Thyristor-Controlled Phase Shifting Transformer (TCPST) is shown in Fig. 2. This device can control the voltage phase shift angle. By varying the voltage phase shift angle, active power flow is controlled. The active power flow of an overloaded line can be decreased with negative phase shift and that of a under-loaded line can be increased up to almost the rated capacity.

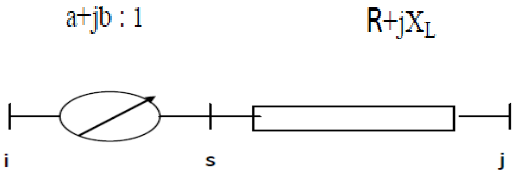

Fig. 2. Equivalent Circuit of TCPST

The real and reactive power flows from bus i to bus j can be derived as:

$$P_{ij} = \frac{V_i^2 G_k}{t_s^2} - \frac{V_i}{t_s} V_j G_k \cos(\delta_i - \delta_j - \Phi) - \frac{V_i}{t_s} v_j v_i B_k \sin(\delta_i - \delta_j - \Phi) \tag{1}$$

$$Q_{ij} = \frac{V_i G_k}{t_s^2} - \frac{V_i}{t_s} V_j G_k \sin(\delta_i - \delta_j - \Phi) - \frac{V_i}{t_s} v_j B_k \cos(\delta_i - \delta_j - \Phi) \tag{2}$$

$$P_{ji} = V_j^2 G_k - \frac{V_i}{t_s} V_j G_k \cos(\delta_i - \delta_j - \Phi) - \frac{V_i}{t_s} v_j B_k \sin(\delta_i - \delta_j - \Phi) \tag{3}$$

The real and reactive power loss (P_{lk}, Q_{lk}) in the line having the TCPST can be expressed as:

$$P_{Lk} = \frac{V_i^2 G_k}{t_s^2} + V_j^2 G_k - 2\frac{V_i}{t_s} V_j G_k \cos(\delta_i - \delta_j - \Phi) \tag{4}$$

The range of the phase shift angle considered in this paper is:

$$-10 \text{ deg.} \leq \phi_{\text{TCPST}} \leq 10 \text{ deg.}$$

Insertion of TCPST having a complex tapping ratio $a+jb$: 1 will modify the Y-bus matrix $[Y]$ as

$$[Y_{modi}] = \begin{bmatrix} \frac{Y_{ii}}{T_s^2} & -\frac{Y_{ij}}{T_s^*} \\ -\frac{Y_{ji}}{T_s} & Y_{jj} \end{bmatrix}$$

Where, $T_s = a+jb = t_s \angle\phi$

III. Line Flow Security Index

The severity of a contingency can be evaluated by using an over loading index;

$$OLI = \sum_{l \in nl} \frac{W}{2n} \left(\frac{\Delta Pl^{avg}}{Pl^{max}}\right)^{2n} \tag{5}$$

Where n =2 , nl is the no. of overloaded lines. Pl^{max} is the maximum power flow limit of line, Pl^{avg} is the average power folwing in an overloaded line.

$$\Delta Pl^{avg} = Pl^{avg} - Pl^{max}$$

n is the exponent and W is a real non-negative weighing coefficient which may be used to reflect the importance of lines.

OLI will be zero when all the lines are within their maximum power flow limits and will reach a high value when there are overloads. Thus, it provides a good measure of severity of the line overloads for a given state of the power system. Most of the works on contingency selection algorithms utilize the second order over loading indices which, in general, suffer from *masking effects*.

The lack of discrimination, in which the over loading index in for a case with many small violations may be comparable in value to the index for a case with one huge violation, is known as masking effect. By most of the operational standards, the system with one huge violation is much more severe than that with many small violations. *Masking effect* to some extent can be avoided using higher order terms in calculation of over loading indices that is n > 1. However, in this study, the value of exponent has been taken as 2 and W = 1.

Let, the OLI defined at for the base case loading is defined by OLI^{BL}. OLI indices defined in (5) are also computed at an increased loading and decreased loading scenario. The increased loading scenario considers all the loads increased by 5% from their base values and the decreased loading scenario has been simulated with the loads decreased by 5% from their base values. Also let, the corresponding *OLI*, calculated at each overloaded lines, are termed as OLI^{IL} and OLI^{DL} respectively. The average over loading index OLI^{avg} has been computed for various line outage contingencies as follows:

$$OLI^{avg} = \left(\frac{OLI^{BL} + OLI^{IL} + OLI^{DL}}{3}\right) \qquad (6)$$

IV. Line Overload Sensitivity Index

To enhance the security of the system, the TCPST has to be placed at the suitable locations. To determine the best location of TCPST, an index called Line Overload Sensitivity Index (LOSI) is calculated for all the remaining lines. The LOSI_l for branch "*l*" is defined as the sum of the normalized power flow through branch "*l*" to all the considered contingencies 'C', expressed as:

$$\mathrm{LOSI}_l = \sum_{c=1}^{N_c}\left(\frac{P_l^c}{P_l^{max}}\right) \qquad (7)$$

where P_l^c = MW flow in line '*l*' during contingency "C.

Let, the LOSI defined at branch "*l*" for the base case loading is defined by $LOSI_l^{BL}$. In order to achieve optimal location of TCPST, valid under change in system loading, LOSI indices defined in (7) are also computed at an increased loading and decreased loading scenario by 5% from their base values. Let, the corresponding LOSI, calculated at each overloaded lines, are termed as $LOSI_l^{IL}$ and $LOSI_l^{DL}$ respectively. The optimal location of TCPST has been decided by an average line overload severity index, computed for every line, as defined below:

$$\mathrm{LOSI}_l = \left(\frac{LOSI_l^{BL} + LOSI_l^{IL} + LOSI_l^{DL}}{3}\right) \qquad (8)$$

The branches are ranked based on their corresponding LOSI_l values. For placement of TCPST, the lines connected between two generation buses were ignored irrespective of their average LOSI values. In this paper, around 30%-35% lines having highest values of average LOSI were considered as possible locations for TCPST and for these possible locations of TCPST, PSO-TVAC algorithm has been applied for determining the optimal location and size of TCPST.

V. Particle Swarm Optimization

Particle swarm optimization is a population based evolutionary computing technique that traces its evolution to the emergent motion of a flock of birds searching for food. It scatters random particles i.e. solutions into the problem space. These particles, called swarms, collect information from each other through their respective positions [10, 11]. The particles update their positions using their own experience and the experience of their neighbors. The update mode is termed as the velocity of particles. The position and velocity vectors of the ith particle of a *d*-dimensional search space can be represented as $X_i = (x_{i1}, x_{i2}, \ldots\ldots\ldots x_{id})$ and $V_i = (v_{i1}, v_{i2}, \ldots\ldots v_{id})$ respectively.

On the basis of the value of the evaluation function, the best previous position of a particle is recorded and represented as

$$pbest_i = (X_{t1}, X_{t2} \ldots\ldots X_{td}).$$

If the *gth* particle is the best among all particles in the group so far, it is represented as

$$pbest_g = gbest = (X_{t1}, X_{t2}, \ldots\ldots\ldots X_{td}).$$

Then, the new velocities and the positions of the particles for the next fitness evaluation are calculated using the following two equations

$$v_{id}^{k+1} = C[w \times v_{id}^{k} + c_1 \times rand_1 \times \left(pbest_{id} - x_{id}\right) + c_2 \times rand_2 \times \left(gbest_{gd} - x_{id}\right)] \qquad (9)$$

$$x_{id}^{k+1} = x_{id} + v_{id}^{k+1} \qquad (10)$$

Here w is the inertia weight parameter, C is constriction factor, c_1, c_2 are cognitive and social coefficients, and $rand_1$ and $rand_2$ are two separately generated uniformly distributed random numbers in the range [0, 1]. The first part of (9) known as “inertia” or “momentum” and it represents the previous velocity. The second part of (9) is termed as the "cognitive" or “memory” component and represents the personal thinking of each particle. The third part is known as the "social knowledge" component that shows the collaborative effect of the particles, in finding the global optimal solution. The social component always pulls the particles toward the global best particle found so far.

Initially, a population of particles is generated with random positions, and then random velocities are assigned to each particle. The fitness of each particle is then evaluated according to a user defined objective function. At each iteration, the velocity of each particle is calculated according to (9) and the position for the next function evaluation is updated according to (10). Each time if a particle finds a better position than the previously found best position; its location is stored in memory.

VI. PSO-Time varying acceleration coefficients

The idea behind time varying acceleration coefficients development is to enhance the global search in the early part of the optimization and to encourage the particles to converge towards the global optima at the end of the search. This can be achieved by varying the acceleration coefficients c_1 and c_2 with time such that the cognitive component is reduced while the social component is increased as the search proceeds. With a large cognitive component and small social component at the beginning, particles are allowed to move around the search space instead of moving toward the population best during early stages. On the other hand, a small cognitive component and a large social component allow the particles to converge to the global optima in the latter part of the optimization process. The acceleration coefficients are expressed as:

$$c_1 = \left(c_{1f} - c_{1i}\right)\frac{iter}{iter_{\max}} + c_{1i} \qquad (11)$$

$$c_2 = \left(c_{2f} - c_{2i}\right)\frac{iter}{iter_{\max}} + c_{2i} \qquad (12)$$

Where C_{1i}, C_{1f} , C_{2i} and C_{2f} are initial and final values of cognitive and social acceleration factors respectively. The PSO-Time varying acceleration coefficients (PSO-TVAC) algorithm has been applied in this paper, because this algorithm avoids premature convergence in the early stages of the search and enhances convergence to the global optimum solution during the latter stages of the search.

VII. PSO_TVAC for optimal location and sizing of TCPST

For implementation of PSO_TVAC approach for optimal placement and sizing of TCPST, first, overloading line index for various single line outages are calculated using Newton-Raphson load flow (NRLF) method and eqn(5), and the contingencies are ranked in the order of their severity. For most severe three line outages, Line Overloading Sensitivity Index for remaining lines of a power system is computed using NR load flow method, eqn(7) and (8). Then, these are ranked in decreasing order of their LOSI values. For placement of TCPST, the lines connected between two generation buses are ignored irrespective of their LOSI values [9].

Around 30%-35% lines having highest values of LOSI are selected as possible locations for TCPST. For these possible locations of TCPST, PSO_TVAC algorithm has been applied for determining the optimal location and size of TCPST using following steps:

(i) Initialization:-

Initially the particle is defined as a vector which contains the randomly selected TCPST location (the line at which a TCSC is placed) and its size as shown below.

Particle: [$\lambda\ \phi$]
Where λ is the TCPST line location number and ϕ is the TCPST size in degree.

(ii) Calculation of fitness function:-
The constrained optimization problem of optimal location of TCPST device is converted into an unconstrained optimization problem using penalty factor PF corresponding to the constraints violation as: Fitness function = Objective function J + Penalty Factor

$$f(x) = J + PF$$

Thus, the fitness function used in PSO-TVAC algorithm consists of two terms: *J* the original fitness function i.e. *OLI* and the penalty factor PF corresponding to the constraints violation.

(iii) For each individual particle, compare the particles fitness value with its P_{best}. If the current value is better than the P_{best} value, then set this value as the P_{best} and the current particle's position, x_i, as p_i .

(iv) Identify the particle that has the best fitness value. The value of its fitness function is defined as g_{best} and its position as P_g. Update the velocity and position of all particles using (9) - (12).

(v) Repeat steps (ii)-(v) until a stopping condition is met (e.g., maximum number of iterations or a good fitness value).

VIII. Result and discussions

Effectiveness of the proposed PSO-TVAC method is demonstrated by applying it on IEEE 30- bus system [12]. The IEEE 30-bus system consists of 1 slack bus, 5 generation buses, 24 load buses, and 41 transmission lines. In this paper, line flow security enhancement or over loading index reduction is considered as the objective to determine the optimal location of TCPST. For optimal placement of TCPST, most severe line outage contingencies were found on the basis of their average *OLI* values as shown in Table 1. As can be observed from Table 1, line outage 10, 36 and 27 are the most severe three line outages. For these 3 most severe line outage contingencies, average Line Overload Sensitivity Index for various lines of a power system is computed and ranked in decreasing order. The average LOSI values for all the 41 lines are shown in Table 2.

For TCPST placement, line no. 1 is not considered as one of the possible locations for TCPST placement because it is connected between two generation buses 1 and 2. Similarly, line no. 5 is also not considered for TCPST placement due its connection between generation buses 2 and 5.

For optimal placement of TCPST, the first 15 lines (line nos. 40, 29, 33, 32, 28, 35, 31, 30, 20, 41, 14, 18, 12, 15 and 17) having highest values of average LOSI values were considered as possible locations. For these possible locations for TCPST placement, PSO-TVAC algorithm has been applied for determining the optimal location and size of TCPST.

With population size 15, the PSO_TVAC algorithm converged in 60 iterations, giving optimal location for TCSC as line no. 40 and setting of TCPST as 0.01411°. The overloading index reduced from 3.7931 to 1.9061. To validate the proposed approach, the PSO-TVAC algorithm has also been applied considering all the 38 lines as possible locations for TCPST placement. In this case also, the same results were obtained, but the cpu time requirement was more. Thus, the proposed approach is found to faster and accurate as well. The TCPST placement results are shown in Table 3, while Fig. 3 shows the convergence characteristic of PSO-TVAC for outage of line no. 10. As can be observed from Table 3, TCPST optimum location for one contingency is not optimum for other contingencies and more than one TCSC are required to enhance line flow security under various contingencies.

Table 1: OLI Ranking for IEEE 30-Bus System

S. No.	Line outage	Average OLI	OLI^{BL}	OLI^{IL}	OLI^{DL}	Rank
1.	10	3.80553	3.7931	4.3363	3.2872	I
2.	36	2.94406	2.9247	3.4477	2.4598	II
3.	27	1.7065	1.6997	1.9725	1.4473	III

4.	15	1.16216	1.1488	1.4501	0.8876	IV
5.	18	1.15176	1.1467	1.3405	0.9681	V

Table 2 Line Overload Sensitivity Index for IEEE 30-bus system

Rank	Line No.	LOSI	Rank	Line No.	Average LOSI	Rank	Line No.	Average LOSI	Rank	Line No.	Average LOSI
1	40	4.3187	11	14	1.2768	21	39	1.179	31	22	1.0826
2	29	4.0557	12	18	1.2441	22	5	1.1782	32	11	1.0717
3	33	3.8296	13	12	1.2415	23	1	1.1767	33	23	1.0136
4	32	2.5679	14	15	1.2282	24	24	1.1709	34	34	0.9927
5	28	1.8695	15	17	1.2258	25	38	1.1563	35	26	0.9043
6	35	1.8455	16	4	1.2013	26	25	1.1545	36	8	0.9034
7	31	1.7728	17	3	1.1963	27	37	1.1524	37	27	0.8627
8	30	1.6442	18	9	1.1921	28	21	1.1524	38	36	0.7932
9	20	1.4965	19	2	1.1855	29	7	1.1294	39	10	0.7431
10	41	1.348	20	6	1.1813	30	19	1.1033	40	13	0
									41	16	0

Table 3: Results of TCPST Placement in IEEE 30-Bus System

S. No.	Line out	TCPST location	TCPST value	Over loading index (OLI)		Elapsed Time (sec.)	
				Without TCPST	With TCPST	Population size 15	Population size 38
1	10	40	0.01411	3.7931	1.9061	0.08584	0.40166
2	36	15	0.05079	2.9247	2.8609	0.08820	0.48510
3	27	29	0.00252	1.6997	0.0899	0.07243	0.36866

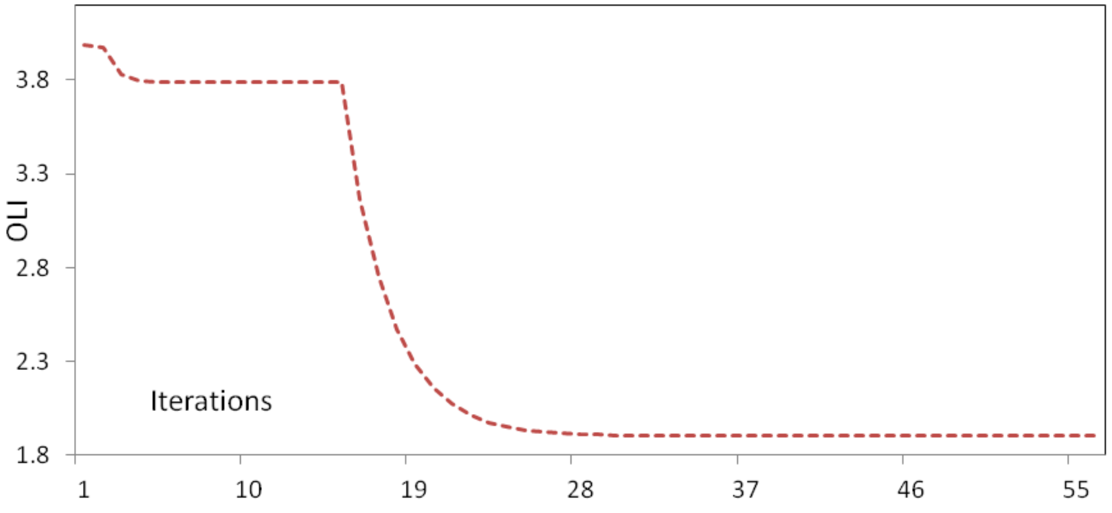

Fig. 3 Convergence characteristic of PSO-TVAC for outage of line no. 10

IX. Conclusion

This paper presents PSO-TVAC based approach for determining optimal location of TCPST for line flow security enhancement of a power system. On the basis of Line Overload Sensitivity Index, a subset of lines for possible location of TCPST was obtained considering the three most severe line outage contingencies. PSO-TVAC algorithm has been applied for this subset of lines only. Effectiveness of the proposed approach has been tested on the standard IEEE 30-bus system and is found to faster as well as accurate. This has been observed that TCPST optimum location for one contingency is not optimum for other contingencies and more than one TCPST are required to enhance line flow security under various contingencies.

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