

Optimal Allocation of TCSC Using Heuristic Optimization Technique

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Abstract

With the massive increase in the population and, as a result of the expansion of the power grid, new problems such as loss power in network retaliation were created. So studies on this issue began. These studies led to the emergence of FACTS devices. The Flexible AC transmission System (FACTS) devices, such as, thyristor controlled series compensators (TCSC) may be used to enhance system performance by controlling the power flows in the network. Optimal location and setting of this devices are considered complicated and multi-objective problems. It is important to limit the number of TCSCs and to locate optimally these devices in the power system because of their considerable costs. In this paper, efficient heuristic optimization technique, is employed to find the optimal location and setting of a thyristor controlled series capacitor (TCSC) device in a modified system. To demonstrate the effectiveness of the proposed approach, IEEE 30-bus test system has been studied.

Key words: Optimal location, Severity index, Stressed power system, Power loss minimization, TCSC, Voltage profile

INTRODUCTION

The continual expansion of the electric power system in the world and population growth are the main factors for which the demand of electricity continues to increase. The dispatchers are required to operate the system closer to its thermal limits and increase its transit capacity of power. The control of the power system can be obtained through the implementation of devices based on power electronic with high-speed response, recently developed and called FACTS (Flexible Alternative Current Transmission System) [1]. FACTS devices, such as controllable series capacitors (TCSC), can help to reduce the transmission congestion, resulting in an increased loadability, lowered system loss and improved stability of the network. [2]. Various matters associated with the employ of FACTS devices are proper location, appropriate setting, investment cost, and controller interactions.

Various methods have been used to determine the optimal location of FACTS devices to enhance loadability in transmission system within steady state security. The authors in [3] used genetic algorithm GA to seek the optimal placement of multi-type of FACTS devices in power system. The system loadability is employed as an index performance. In [4] the optimal location for single and multi-type FACTS devices to improve system loadability with minimum cost of installation was determined by using Particle Swarm Optimization (PSO) [5] proposes an algorithm for the optimal location and control of FACTS devices for enhancing the loadability in transmission system by using PSO and Differential Evolution (DE) for pool and hybrid model in deregulation electricity market.

In any power system, unexpected outages of lines or transformers occur due to faults or other disturbances. These events, referred to as contingency, may cause significant overloading of transmission lines or transformers, which in turn may lead to viability crisis of the power system. Several studies deal with the optimization techniques for corrective control of power system security [6-9]

The purpose of this paper is to locate a given number of TCSCs devices in order to maximize the transmitted power and to eliminating the insecurity of the power system

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Month of Submission : 06-2017
Month of Peer Review : 06-2017
Month of Acceptance : 07-2017
Month of Publishing : 08-2017

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stressed by the augmentation of the loads and the severe contingencies. Then, optimization technique will be applied to find the best locations and parameter setting of TCSCs, in order to reduce the TCSCs installation cost and the total real power losses. Evolutionary algorithms have been used to solve this nonlinear optimization problem, such as, the second version of nondominated sorting genetic algorithm (NSGA-II). To demonstrate the effectiveness of the proposed approaches, IEEE 30-bus test system has been used.

MODELING OF TCSC

The model of transmission line with a TCSC installed between buses *i* and *j* is shown in Figure 1. In steady state, the TCSC can be considered as additional reactance (-jxc). The real and reactive power flow from bus-*i* to bus-*j* and from bus-*j* to bus-*i* of the line having TCSC can be given by:

$$P_{ij} = V_i^2 G_{ij} - V_i V_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) \tag{1}$$

$$Q_{ij} = -V_i^2 (B_{ij} + B_{sh}) - V_i V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) \tag{2}$$

$$P_{ji} = V_j^2 G_{ij} - V_i V_j (G_{ij} \cos \delta_{ij} - B_{ij} \sin \delta_{ij}) \tag{3}$$

$$Q_{ji} = -V_j^2 (B_{ij} + B_{sh}) + V_i V_j (G_{ij} \sin \delta_{ij} + B_{ij} \cos \delta_{ij}) \tag{4}$$

SEVERITY INDEX

The severity index can be utilized to indicate the severity of system loading and is written as [9]:

$$SI_L = \sum_{l \in L_0}^{n_l} W_l \left(\frac{S_l}{S_l^{\max}} \right)^{2n} \tag{5}$$

Where S_l & S_l^{\max} represent the apparent power flow and the rated capacity of line (*l*), respectively; w_l & represent the weighing factor which may be used to reflect the relative importance of lines; 2 is the integer exponent used to penalize more or less overloads variations L_0 represents the set of the overloaded lines. The line flows are obtained from Newton– Raphson load flow calculations. When all lines are in their thermal limits, the SI_l & will be small and takes a high value wfhn they are overloaded. Thus, it supplies a good measure of severity of line overloads for a given state of power system. In this study, the value of exponent has been taken as 1 and we assume that all lines are equal importance ($w_l = 1$).

LOADABILITY ENHANCEMENT

Problem Formulation

The objective of this work is to find the optimal number, location and parameter setting of multiple TCSCs devices

in order to improve system loadability of the power system stress within security and stability margins. The optimization problem is formulated as multi-objective optimization problem which minimize cost of installation of FACTS devices and active power losses in the transmission lines.

1) Objectives functions

a) cost of installation of FACTS devices (CI_F): The installation cost of TCSC presented in Siemens AG Database [4,10], is in form of polynomial cost function and it is given by:

$$C_{TCSC} = 0.0015.S^2 - 0.713.S + 153.75 \tag{6}$$

Where *S* is the size of the TCSC in MVAR.

$$S = |Q_2| - |Q_1| \tag{7}$$

Where Q_2 and Q_1 are the reactive power flow in the line after and before the installation of TCSC device in MVAR, respectively.

To compute the annual capital cost of FACTS, Following assumption have been made:

- Project life time (α): 5 years
- Interest rate: 5 %.

The annual capital cost of FACTS in (US\$/h) can be found as:

$$C_{TCSC} = C_{TCSC} * S * \frac{1000}{8760} * \frac{r(1+r)^n}{(1+r)^n - 1} \tag{8}$$

The total cost of installation cost of TCSC devices can be expressed as follows:

$$CI_F = \sum_{j=1}^{N_{TCSC}} C'_{TCSC,j} \tag{9}$$

Where N_{TCSC} is the number of TCSC devices.

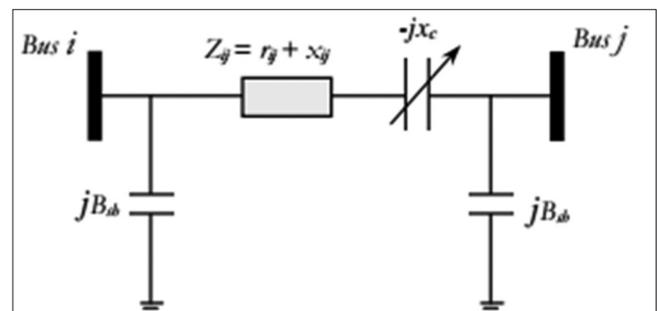


Figure 1: Model of transmission line with TCSC

b) Real power losses (RPL) The real power losses can be expressed by the following equation.

$$RPL = \sum_{i=1}^N \sum_{j=1}^N Y_{ij} V_i V_j \cos(\delta_{ij} - \theta_{ij}) \tag{10}$$

Y_{ij} and θ_{ij} are respectively modulus and argument of the ij-th element of the nodal admittance matrix Y.

The cost and the real power losses are optimized with the following constraints.

2) Equality and inequality constraints: The equality constraints are the load flow equations given by the following relation:

$$P_{Gi} - \lambda P_{Di} = P_i \tag{11}$$

$$Q_{Gi} - \lambda Q_{Di} = Q_i \tag{12}$$

Where,

λ is the loadability factor in p.u. that P_{Gi} and Q_{Gi} are generated real and reactive powers at bus i, respectively. P_{Di} and Q_{Di} are real and reactive power loads at bus i, respectively. P_i and Q_i are real and reactive power loads at bus i, respectively.

The inequality constraints are as follows:

- Unit limits:

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max} ; i \in N_g \tag{13}$$

- TCSC reactance constraint:

$$X_{TCSC}^{min} \leq X_{TCSC} \leq X_{TCSC}^{max} \tag{14}$$

- Line flow and bus voltage limits: The thermal limit for transmission lines and the voltage limit for the buses are indicated by a factor J[4].

$$J = \prod_{line} OVL(line) \cdot \prod_{bus} VSB(bus) \tag{15}$$

This factor is defined as the product of two terms. The first one, called OVL, indicates the violation of line flow limits. The second part, VSB, concerns the voltage levels for each bus of the network.

$$OVL = \begin{cases} 1; & \text{if } P_{ij} \leq P_{ij}^{max} \\ \exp\left(\mu_{OVL} \left| 1 - \frac{P_{ij}}{P_{ij}^{max}} \right| \right); & \text{if } P_{ij} > P_{ij}^{max} \end{cases} \tag{16}$$

$$VSB = \begin{cases} 1; & \text{if } 0.9 \leq V_b \leq 1.1 \\ \exp(\mu_{VSB} |1 - V_b|); & \text{if } \text{Otherwise} \end{cases} \tag{17}$$

Where P_{ij} and P_{ij}^{max} are the real power flow between buses i and j the thermal limit for the line between buses i and j respectively. μ_{OVL} and μ_{VSB} are respectively two coefficients both equal to 0.1.

Optimization Algorithm

The goal is to determine the maximum amount of power that the power system is able to supply without violating line flow and bus voltage limits constraints, by locating a given number of TCSCs.

Starting for an initial load, the NSGAI described in section (VI-B) is executed recursively. If the maximum number of generations is reached, the best individual is stored with its cost of installation, real power losses and λ value. Then, all loads are increased in the same proportion and the NSGA-II algorithm starts again. The optimization process is shown in Figure 2.

(N-1) CONTINGENCY ANALYSIS AND POWER SYSTEM STRESS

Stressed power system, either due to increasing loading or due to severe contingency, often lead to situation where system no longer remains in the secure operating region. The power system is generally stressed by means of several causes such as the variation of load and the outage of lines, transformers or generators.

In this part, we perform a (N-1) contingency analysis considering the outage of lines and we select the worst contingency based on severity index. This contingency will be included in the optimization problem. Furthermore, the

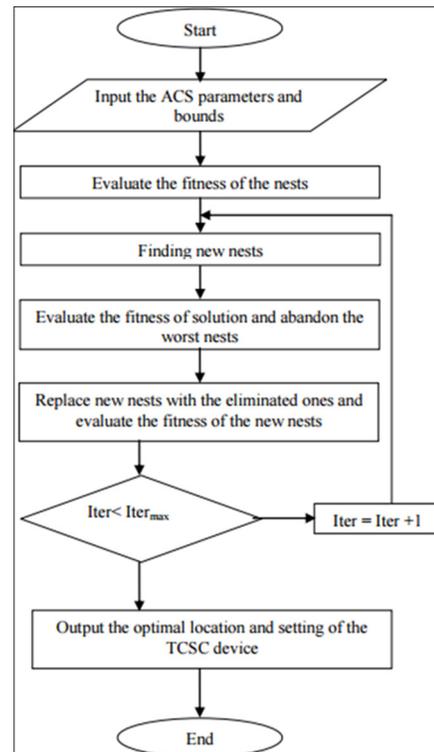


Figure 2: Flow chart of the optimization procedure

stress of power system is modeled by a variation in the same proportion of the load with 10% of the base case. For this scenario, objective functions and constraints are the same ones as in previous section (IV-A).

MULTI-OBJECTIVE OPTIMIZATION USING GENETIC ALGORITHM

Multi-Objective Optimization Overview

Many optimization problems in the world involve simultaneous optimization of several objectives. Multiobjective optimization having such conflicting objective functions gives rise to a set of optimal solutions, instead of one optimal solution because no solution can be considered to be better than any other. These optimal solutions are known as Pareto-optimal solutions. A multi-objective problem can be defined as follows:

$$\text{Minimize } f_i(x) \quad i = 1, \dots, N_{obj} \quad (18)$$

$$\begin{cases} g_j(x) = 0 & j = 1, \dots, M \\ h_k(x) \leq 0 & k = 1, \dots, K \end{cases} \quad (19)$$

Where f_i is the objective function; v is a decision vector. NSGA-II algorithm (Non-dominated Sorting Genetic Algorithm version II), based on the non-dominated sorting concept is presented below.

Overview of NSGA-II

The non-dominated sorting genetic algorithm (NSGA) proposed by [12] was one of the first such Multiobjective evolutionary algorithms (EAs). It is a very effective algorithm but it's not elitist. Thus, it does not keep their Pareto optimal solutions found during the generation. Moreover, it requires the setting of parameter sharing σ_{Share} affecting the convergence program and the distribution of Pareto optimal solutions. To overcome these difficulties, new techniques have been implemented. Deb and Al. [13] proposed an improved version of the approach NSGA called NSGA-II. In the latter approach, with each generation (t), two populations of parents and children respectively P_t and Q_t of the same size T are combined to create a population U .

$$R_t = (P_t \cup R_t) \quad (3)$$

SIMULATION RESULTS

The IEEE 30-bus test system composed of 6 generators, 21 loads and 41 transmission lines has been used to demonstrate the validation and effectiveness of the proposed method. The bus data and line data of this test system are taken from [14,15]. Generator real power outputs are taken as control variables. The lower and upper

voltage magnitude limits at all load buses, are taken as 1.10 and 0.90, respectively.

The level of the applied compensation of the TCSC varies generally between 20% inductive and 80% capacitive [3,11].

Optimal Number of TCSCs for Increasing System Loadability

The number and placement of TCSC is considered as discreet variables, where all the transmission lines of the system, have been nominated for TCSC installation.

The influence of the number of Multiple TCSCs on the system loadability is shown. in Figure 4. The maximum value of system loadability λ has been obtained with a minimum number of 8 TCSCs devices and it is equal to 1.35 pu. After placing this optimal numbers of devices, it was observed that λ is saturated. It is due to the voltage or thermal limits violation.

2) TCSC operation in (N-1) contingency and variation of load:

In this section, firstly, we consider (N-1) contingency for base load condition to identify the severe contingencies. Secondly, we study the effect of the installation of TCSCs devices in IEEE30 bus system in the severest contingency cases.

For this reason, a NSGA-II algorithm is implemented to determine the optimal placement and the optimal parameter setting of the TCSCs in the power system in order to alleviate the lines overloads and the bus voltage violations under these critical contingencies.

For each line outage contingency in the system, we determine the all congested lines, and then we must classify there after the lines outages according to the value of the severity index.

Contingency analysis was conducted on the stressed power system and the first four severe contingency cases are produced in table III along with the overloaded lines and the severity index.

The power flow on the congested lines before and after placing the TCSCs devices in the system and the computed value of SIL with optimal solutions obtained by applying NSGA-II are given in table III. From this table, for each contingency scenario in this system, it is found that the overloads of all lines are eliminated by TCSC optimized and by the use of the proposed optimization technique which gives zero-severity index. The optimal location, the parameter setting of TCSCs devices and the generator real

Table 1. Overloaded lines and computed value of severity index for heavy load ($\lambda=1.35$ PU.)

Overloaded Lines	Before placing TCSC			After placing TCSC				SI _L
				First function objectives: RPL		Second function objectives: CI _F		
	S _{ij} (Mvar)	S _{max} (Mvar)	SI _L	S _{ij} (Mvar)	Min RPL(pu)	S _{ij} (Mvar)	Min CI _F (US\$/h)0	
1-2	206.2212	130	9.1922	101.9687	0.108	114.1090	0.6917	0
2-6	69.4060	65		47.2216		54.5625		
6-8	35.7625	32		12.3641		12.9748		

Table 2. Optimal results after installing multiple TCSCS

	Optimal placement of TCSC	Optimal setting of TCSC		Generator real power output (MW) : P _{g1} , P _{g2} , P _{g3} , P _{g8} , P _{g11} , P _{g13}		
Min RPL	25-26 ; 28-27	-0.2362	-0.0438	161.5434	80.00	50.00
	19-20 ; 22-24	-0.0441	-0.0397	32.00	30.00	39.83
	16-17 ; 9-11	0.0187	-0.1638			
	27-30 ; 10-20	-0.0787	-0.0569			
Min CI_F	25-26 ; 27-29	-0.0906	0.0703	182.7425	79.83	48.4300
	10-17 ; 15-23	-0.0501	-0.0504	32.00	30.00	22.16
	14-15 ; 6-7	-0.0027	-0.0656			
	29-30 ; 23-24	-0.1024	-0.0828			

Table 3. Overloaded lines and computed value of severity index before and after placing tcsc in (n-1) contingency case

Outage of Lines	Overloaded lines	before placing TCSC				after placing TCSC				
		S _{ij} (Mvar)	S _{max} (Mvar)	SI _L	Rank	for minimum RPL		for minimum CI _F		SI _L
						S _{ij} (Mvar)	RPL (pu.)	S _{ij} (Mvar)	CI _F (US\$/h)	
1-2	1-3	253.3190	130	32.0021	1	87.1914	0.0746	115.3324	0.7203	0
	3-4	234.3793	130			81.8196		108.5139		
	4-6	146.4885	90			62.9982		71.9684		
1-3	1-2	234.2709	130	15.0826	2	86.0789	0.0625	122.9268	0.5194	0
	2-4	76.8261	65			41.6678		54.1982		
	2-6	82.4172	65			45.9480		57.0342		
3-4	1-2	231.0956	130	14.2609	3	114.3280	0.0608	83.1841	0.4056	0
	2-4	75.4731	65			53.3285		40.5633		
	2-6	81.3814	65			56.1710		44.8495		
2-5	1-2	138.8152	130	9.5096	4	39.0423	0.0962	88.8365	0.5721	0
	2-4	67.2057	65			39.3905		47.1119		
	2-6	92.0035	65			53.4714		62.5483		
	4-6	108.7091	90			61.9903		68.4364		
	5-7	98.0798	70			60.8519		61.5369		

power output for the minimum installation cost of multiple TCSCs devices and the minimum real power losses are shown in the table IV.

Figure 5 shows, Pareto-optimal front for installation cost of TCSCs devices and active power losses for line 1-2 outage.

CONCLUSION

In this paper, a new method for determining the optimal number, optimizing the desired parameter for TCSC devices and their optimal allocation in a stress-strength

system is proposed. This algorithm is proposed in order to improve the system loadability and to enhance the steady-state security of the network. The problem is formulated as a multi-objective optimization problem. Two objective functions are considered, which are the installation cost of the TCSCs devices and the real power losses. The system loadability was employed as measure of power system performance and the severity index was utilized as measure of severity of line overloads for a given state of power system. From the obtained results on the test system, it can be observed that the TCSC can significantly improve the system loadability and the security of the power system by eliminating the overloaded lines.

Table 4. Optimal control setting for 30 bus test after installing tcscs in (n-1) contingency and variation of load ($\lambda=1.1$ Pu.)

Outage of lines	Min RPL			Min C _f		
	Optimal placement of TCSC	Optimal setting of TCSC	Generator real power output (MW): P ₁₀ , P ₂₀ , P ₃₀ , P ₄₀ , P ₁₀ , P ₁₁	Optimal placement of TCSC	Optimal setting of TCSC	Generator real power output (MW): P ₁₀ , P ₂₀ , P ₃₀ , P ₄₀ , P ₁₀ , P ₁₁
1-2	4-6 ; 21- 22 ; 10-21 28-27 ; 23-24 ; 25-26 19-20 ; 6-7	-0.0195 -0.0058 -0.0205 -0.2697 -0.1451 -0.1241 -0.0434 0.0134	87.1887 80.00 50.00 32.00 30.00 40.00	14-15 ; 25-27 ; 28-27 18-19 ; 25-26 ; 23-24 10-20 ; 19-20	-0.0583 -0.0450 -0.1420 -0.0613 0.0234 0.0420 -0.1295 -0.0088	115.3312 75.38 49.63 32.00 19.66 30.44
1-3	12-16 ; 16-17 ; 28-27 29-30 ; 12-13 ; 15-18 23-24 ; 6-10	-0.0432 0.0368 -0.3155 -0.0291 -0.0439 0.0415 -0.0439 -0.4448	86.0523 80.00 50.00 31.9400 30.00 40.00	14-15 ; 28-27 ; 15-18 12-16 ; 6-9 ; 18-19 19-20 ; 4-12	0.0146 -0.0718 -0.0610 -0.1484 -0.0011 -0.0036 -0.0213 0.0207	122.3320 74.07 49.84 31.07 20.05 23.40
3-4	15-18 ; 25-27 ; 16-17 19-20 ; 29-30 ; 1-3 24-25 ; 15-23	-0.0553 -0.1258 -0.1383 -0.0508 -0.0228 -0.0924 -0.2202 -0.0780	116.5469 79.91 50.00 32.00 20.25 21.60	27-29 ; 9-10 ; 10-21 10-22 ; 10-20 ; 28-27 25-26 ; 14-15	-0.0126 -0.0643 -0.0139 -0.0468 -0.0879 -0.3111 -0.3029 -0.0351	85.8169 80.0 50.00 32.00 30.00 40.00
2-5	14-15 ; 21-22 ; 27-29 9-11 ; 10-20 ; 29-30 1-3 ; 10-17	0.0398 -0.0107 0.0412 -0.0493 -0.0757 -0.0608 -0.0287 0.0136	89.3585 80.00 50.00 32.00 30.00 40.00	14-15 ; 15-18 ; 23-24 27-29 ; 29-30 ; 25-26 18-19 ; 6-9	0.0088 -0.0534 -0.1947 0.0634 -0.0680 -0.3040 -0.0778 -0.0231	155.5923 46.02 50.00 32.00 20.09 20.54

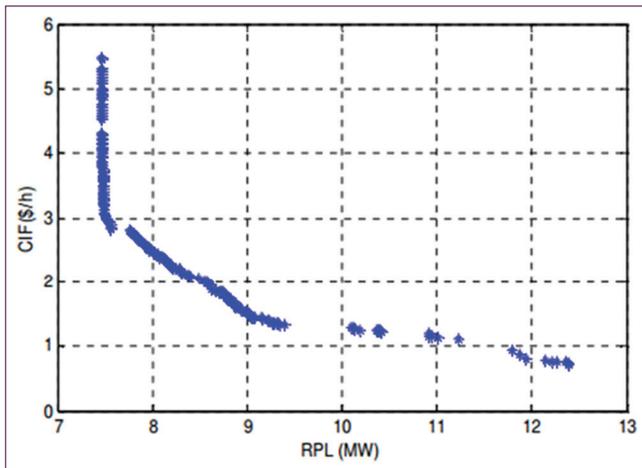


Figure 5: Pareto-optimal front using NSGII algorithm of real power losses and installation cost of TCSC for line 1-2 outage

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How to cite this article: Nafar M, Ramezanpour A. Optimal Allocation of TCSC Using Heuristic Optimization Technique. Int J Sci Stud 2017;5(5):245-250.

Source of Support: Nil, **Conflict of Interest:** None declared.