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Optimal Choice and Allocation of FACTS Devices for Security-Constrained Economic Dispatch

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Abstract

Flexible AC transmission systems (FACTS) devices have provided new control facilities in power systems. Simultaneous optimization of type, location and parameters for FACTS devices is an important issue when a given number of FACTS devices are applied to the power system with the purpose of increasing system loadability. This paper presents the application of simulated annealing algorism (SA) to find optimal type, location and parameters of FACTS devices to achieve security-constrained economic dispatch (SCED). The overall cost function, which includes generation cost and installation cost of FACTS devices, should be minimized. The SCED constraints are generators, transmission lines and FACTS limits. Two types of FACTS devices are utilized in this study namely STATCOM as a shunt type and TCSC as a series type. In this study simulations were performed on IEEE 14-bus. Results of simulations are encouraging and could efficiently be employed for power system operations.

Keywords: Allocation, Security-constrained economic dispatch (SCED), FACTS and simulated annealing (SA).

1. Introduction

Recently developed flexible AC transmission systems (FACTS) devices with the advancing technology of power electronics have provided new control facilities in power systems in both steady state power flow control and dynamic state stability control; FACTS devices increase system loadability and controllability [1, 2].

FACTS devices, such as SVC, TCSC, STATCOM, SSSC and UPFC can be connected in series or shunt (or a combination of the two) to achieve numerous control functions, like voltage regulation, system damping and power flow control [3].

Nowadays the increasing in the amount of unplanned power exchange causes some transmission lines to be overloaded, or congested. Therefore, power systems need to be managed in order to use the available network efficiently. The introduction of FACTS devices opened up new opportunities for controlling the power flow and extending the loadability of the available power transmission network while minimizing the total generation cost. It is important to ascertain the optimal type and location for placement of these devices because of their considerable costs.

Many researches were made on the optimal location of FACTS devices [4, 5]. However, their impact on the power generation costs is not wholly considered yet.

Traditional optimization methods such as mixed integer linear and nonlinear programming have been investigated to address this issue; however difficulties arise due to multiple local minima and overwhelming computational effort.

In order to overcome these problems, Evolutionary Computation Techniques have been employed to solve the optimal allocation of FACTS devices. Different algorithms such as Particle Swarm (PS) [4], Genetic Algorithm (GA) [6], and Evolutionary Programming [7] have been tested for finding the optimal placement of devices and their sizes, with promising results.

This paper proposes an application of simulated annealing algorithm (SA) to find optimal choice, location and size of FACTS devices for minimizing the overall cost function in a power system including the installation cost of FACTS devices with equality and inequality constraints at overloading condition. Two types of FACTS devices are utilized in this study namely STATCOM and TCSC. IEEE 14-bus test system [8] is used as an example to illustrate the methodology.

This paper is organized as follows: FACTS models are described in section 2. Then in section 3, the problem statement is described. The simulated annealing for optimal choice and allocation of FACTS devices is discussed in details in section4. The simulation results are given in section 5. Finally, brief conclusions are deduced.

2. FACTS Modeling In Steady State

2.1 STATCOM Model

STATCOM is a shunt FACTS device which can be used for increasing system loadability and controllability. STATCOM is always located on a load bus. The bus on which STATCOM is being connected is converted from PQ bus to PV bus [9]. STATCOM modeling was done as per suggestions in [10]. The following power flow equations are obtained for the STATCOM connected to bus k according to fig.1:

$$Y_{vR} = \frac{1}{Z_{vR}} = G_{vR} + jB_{vR} \qquad (1)$$

$$E_{vR} = V_{vR}(\cos\delta_{vR} + \sin\delta_{vR}) \qquad (2)$$

$$S_{vR} = V_{vR}\, I_{vR}^{*} = V_{vR}\, Y_{vR}^{*}(V_{vR}^{*} - V_{K}^{*}) \qquad (3)$$

$$P_{vR} = V_{vR}^{2}G_{vR} + V_{vR}V_{K}[G_{vR}\cos(\delta_{vR} - \theta_{K}) + B_{vR}\sin(\delta_{vR} - \theta_{K})] \qquad (4)$$

$$Q_{vR} = -V_{vR}^{2}B_{vR} + V_{vR}V_{K}[G_{vR}\sin(\delta_{vR} - \theta_{K}) - B_{vR}\cos(\delta_{vR} - \theta_{K})] \qquad (5)$$

$$P_{K} = V_{K}^{2}G_{vR} + V_{K}V_{vR}[G_{vR}\cos(\theta_{K} - \delta_{vR}) + B_{vR}\sin(\theta_{K} - \delta_{vR})] \qquad (6)$$

$$Q_{K} = -V_{K}^{2}B_{vR} + V_{K}V_{vR}[G_{vR}\sin(\theta_{K} - \delta_{vR}) - B_{vR}\cos(\theta_{K} - \delta_{vR})] \qquad (7)$$

The operating range of STATCOM is from 0 to 250 MVA.

2.2 TCSC Model

TCSC model in [11] is used in this study. TCSC is modelled as variable reactance (X_c) in series with transmission line. Fig. 2 shows a model of a transmission line along with TCSC connected between buses ‘‘i’’ and ‘‘j’’. The bus admittance matrix is updated according to the size and location of TCSC. The effective reactance (X_{eff}) with the series capacitive compensation is given by (8):

$$X_{eff} = X_{ij} - X_c \qquad -0.2X_{ij} < X_c < 0.8X_{ij} \qquad (8)$$

The change in the line flow due to series capacitance can be represented as a line without series capacitance with power injected at the receiving and sending ends of the line as shown in Fig. 3. The real and reactive power injections due to series capacitor (TCSC) at buses i and j are given by the following equations [12].

$$P_i^F = V_i^2\Delta G_{ij} - V_iV_j[\Delta G_{ij}\cos(\delta_i - \delta_j) + \Delta B_{ij}\sin(\delta_i - \delta_j)] \qquad (9)$$

$$Q_i^F = -V_i^2\Delta B_{ij} - V_iV_j[\Delta G_{ij}\sin(\delta_i - \delta_j) - \Delta B_{ij}\cos(\delta_i - \delta_j)] \qquad (10)$$

$$P_j^F = V_j^2\Delta G_{ij} - V_iV_j[\Delta G_{ij}\cos(\delta_i - \delta_j) - \Delta B_{ij}\sin(\delta_i - \delta_j)] \qquad (11)$$

$$Q_j^F = -V_j^2\Delta B_{ij} + V_iV_j[\Delta G_{ij}\sin(\delta_i - \delta_j) + \Delta B_{ij}\cos(\delta_i - \delta_j)] \qquad (12)$$

Where:

$$\Delta G_{ij} = \frac{x_c r_{ij}(x_c - 2x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)}$$

$$\Delta B_{ij} = -\frac{x_c(r_{ij}^2 - x_{ij}^2 + x_c x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)}$$

3. Problem Description

The problem is to find the best type of FACTS devices, its location and size (MVA) while minimizing the generation cost in addition to FACTS devices cost. In general, when the load requirements increase, some transmission lines will carry more than their capacities. Line limit must taking into account in economic dispatch (ED) for secure operation of power system, but this will increase the generation cost. When line limits constraint considered in ED The problem is called security-constrained economic dispatch (SCED). Adding FACTS devices in power system will decrease the generation cost and increase the loadability of power system. With Appropriate choice of type, location and size of FACTS devices the generation cost along with FACTS installation cost will be minimized while the power system operates in secure state. The FACTS devices which utilized in this study are STATCOM and TCSC. The objective function to minimize the system generation cost in addition to FACTS installation cost is presented in (13).

The constrained optimization problem is converted to a non-constrained optimization problem by adding penalty for violation of constraints.

$$F=F\,(P_{gi}) + P_f\,|j-1| + \sum_{j=1}^{N} C_{facts} \tag{13}$$

Where:

$$F1\,(P_{gi}) = \sum_{i=1}^{Ng} a_i P_{gi}{}^2 + b_i P_{gi} + c_i \tag{14}$$

a_i, $b_i$and c_i are cost coefficients of generator i .

$$j= \prod_{line} OVL_{\ line} * \prod_{bus} VS_{\ bus} \tag{15}$$

$$OVL=\begin{cases} 1 & S_{pq} < S_{pqmax} \\ \exp\left(\lambda\left|1-\frac{S_{pq}}{S_{pqmax}}\right|\right), & S_{pq} \geq S_{pqmax} \end{cases} \tag{16}$$

$$VS=\begin{cases} 1 & 0.9 < V_b < 1.1 \\ \exp(\lambda|1-V_b|)\,, & \text{otherwise} \end{cases} \tag{17}$$

S_{pq} is complex power flow between buses p and q, S_{pqmax} is thermal limit for the line between buses p and q, λ is small positive constant equal to 0.1, P_f is penalty factor with high value, N is number of utilized FACTS devices.

OVL is related to the line loading and penalizes overloads in the lines. When the line loading is less than 100% its value equal to 1. If the line loading exceeds 100% the value of OVL increases exponentially with the overload. VS is related to voltage level. For voltage levels comprised between 0.9 pu and 1.1 pu, the value of VS is equal to 1. Outside this range, the value increases exponentially with the voltage deviation. So that the value of j will be larger than 1 when any line carries more than its capacity or any bus voltage outside the range from 0.9 pu to 1.1 pu. To accelerate the convergence, the product of OVL at every line and VS at every bus is taken.

Based on the Siemens AG Database [13], the cost of FACTS devices in ($/KVA) is given in (18) and (19) [14]:

$$C_{stat}=0.0003\ S^2 - 0.2691\ S+188.22\ \$/KVA \tag{18}$$
$$C_{tcsc}=0.0015\ S^2 - 0.713\ S+153.7\ \$/KVA \tag{19}$$

$$C'=C_{stat} \quad \text{if STATCOM device is used} \tag{20}$$

$$C'=C_{tcsc} \quad \text{if TCSC device is used} \tag{21}$$

$$C_{facts}= (\ C'*\ S*1000*\alpha)/8760\ \$/h \tag{22}$$

S is the operating range of FACTS device in MVA, C_{facts} is the installation cost of FACTS in $/h, α is the capital recovery factor and it is equal to 0.1295 in this study [15].
Objective function Subjected to the following constraints:

$$E\,(g, x) =0 \tag{23}$$

$$B_1(g), B_2(x) \geq 0 \tag{24}$$

Where E (g, x) =0; represents the conventional power flow equations, $B_1(g), B_2(x) \geq 0$; are the inequality constrains for FACTS devices and the optimal power flow respectively. g; is a vector that represents the variables of FACTS devices. x; represents the operating states of the power system. The inequality constraints for SCED considered in this study are the upper and lower limits for generation power, voltage limits at different buses, line capacity limits and FACTS devices limits.

4. Simulated Annealing Optimization Method

The SA algorithm, proposed by Kirkpatrick et al in 1983, is a powerful optimization technique [16], which exploits the resemblance between a minimization process and the annealing process of the molten metal. The annealing process begins with a high temperature and the metal is slowly cooled so that the system maintains the thermal equilibrium at every stage, until the energy of the system acquires the global minimum value. The physical annealing process is simulated in the SA technique for the determination of global or near-global optimal solutions of the difficult combinatorial optimization problems involving non-linear objective functions and complex constraints. A temperature parameter, T, is defined and gradually reduced in the optimization process of SA. At each temperature, an iterative procedure is performed.

A trail solution is obtained in neighborhood of the current solution. If the cost of the trial solution is lower than that of the current solution, then it is accepted and used to generate another trial solution; else, the solution is accepted only when its transition probability of acceptance P (T), given by Boltzmann distribution, is greater than a randomly generated number between 0 and 1.

$$P(T) = e^{\frac{-\Delta F}{T_t}} \qquad (25)$$

At each temperature, the procedure for generating and testing the trial solutions are repeated for an appropriate number of iterations in order to allow the algorithm to settle into its thermal equilibrium i.e. a balanced state. The combination of initial temperature T_{ini}, temperature steps α and the number of iterations at each temperature n is known as the annealing schedule, which is usually selected empirically. The temperature is then reduced by the following geometric function:

$$T_{t+1} = \alpha * T_t \qquad (26)$$

And the above mentioned iterative process is repeated till there is no significant improvement in the solution after a prespecified number of iterations. It can also be terminated when the maximum number of iterations is reached. It is to be noted that accepting deteriorated solutions in the above process enables the SA solutions to jump out of the local optimum solution points and paves the way to seek global optimum solutions.

The algorithm as shown in flowchart of fig.4 can be summarized through the following steps:

Step 1: initially read input data including system data, FACTS data and annealing schedule.

Step 2: generate a random feasible solution $[P_0\ V_0\ X_0\ L_0\ ST]$ Where P_0 represent a vector of initial generators output except for slack bus. V_0 represent a vector of initial voltages at PV buses and slack bus. X_0 represent a vector of FACTS control variables (bus voltage of STATCOM bus or reactance of TCSC). L_0 represent initial location of FACTS devices (STATCOM bus or TCSC line). ST represent a vector of the FACTS device type (it takes two values, “1” for STATCOM device and “2” for TCSC device).

Step 3: perform load flow, and then calculate the current cost function according to (13).

Step 4: set iteration counter i to 1.

Step 5: generate trial solution in neighborhood of current solution. In generation of trial solution, choose one variable randomly from the control variables $[P_0\ V_0\ X_0\ L_0\ ST]$. This variable is changed randomly within its constraints.

Step 6: perform load flow, and calculate trial cost according to (13). If it is lower than the current cost function, this trial solution is accepted as current solution; else, the solution is accepted only when its transition probability of
acceptance P (T), given by Boltzmann distribution (25), is greater than a randomly generated number between 0 and 1.

Step 7: i=i+1. If $i \leq n$, where n is number of iterations at each temperature, go to step5; else, go to step8.

Step 8: check for stopping criteria, if it satisfied stop; else, $T_{t+1} = \alpha * T_t$ and then go to step 4.

Stopping criteria:

1) A given minimum value of the temperature (T_{min}) has been reached.
2) A certain number of iterations (N_r) has passed without acceptance of a new solution.

5. Simulation Results

IEEE 14 bus system, as shown in Fig. 5, has been used to test the effectiveness of the proposed approach. The generator data found in table 1 and line limits found in table 2 [15]. System data and results are based on a 100 MVA and bus 1 is the reference bus. In order to verify the proposed approach and illustrate the impacts of FACTS devices, three cases for test systems were investigated:

Case 1: ED without FACTS, with line limits ignored.
Case 2: SCED without FACTS.
Case 3: A) SCED with one FACTS device.
B) SCED with two FACTS devices.

In this study, Newton Raphson method has been used for power flow. SA is used for handling the optimization problem with parameters shown in Appendix 1. Two types of FACTS devices namely STATCOM and TCSC are utilized. The software was written in MATLAB 7.10.0.499 package. Additionally, for evaluation of the proposed approach, system load is assumed to increase to 125%, 150% and 175%. The results are shown in table 3, table 4 and fig (6-8). The following discussion can be observed:

5.1 For 125% Loading Condition

When line limits are ignored, power generation cost of case 1 equal to 5655.8$/h. For this case, line 7 carries more than its limit as shown in fig.6. The generator G5, which having high incremental fuel cost, produces its minimum limit. The generator G2, which having low incremental fuel cost, produces maximum power.

When line limits are considered in case 2, line 7 carries its maximum thermal limits, which present a congestive condition. This condition will prevent loads to be served from generators as obtained from the cheapest combination of generator outputs as in case 1. The cost of generation in case 2 is equal to 5854.00 $/h.

Case 3 contains the results of optimal choice, allocation and sizing of FACTS devices for SCED. As can be observed from table 3, TCSC is the optimal choice when using one FACTS device and its optimal location is line 4. The generator outputs redispatched as shown in table 3 while maintaining all lines operate under their limits as shown in fig 6. The total cost has been reduced by 188.4$/h.

When using two FACTS devices the optimal choice is two TCSC in lines 3 and 4. The total cost has been reduced by 190.7 $/h while all lines operate under their limits as shown in fig 6.

5.2 For 150% Loading Condition

When line limits are ignored, power generation cost of case 1 equal to 6779.30$/h. For this case, three lines carry more than their limits as shown in fig.7. The generator G5, which having high incremental fuel cost, produces its minimum limit. The generator G2, which having low incremental fuel cost, produces its maximum limit. When line limits are considered in case 2, line 7 carries its maximum thermal limits, which present a congestive condition. This condition will prevent loads to be served from generators as obtained from the cheapest combination of generator outputs as in case 1. The cost of generation in case 2 is equal to 7609.30$/h.

Case 3 contains the results of optimal choice, allocation and sizing of FACTS devices for SCED. As can be observed from table 3, TCSC is the optimal choice when using one FACTS device and its optimal location is line 4. The generator outputs redispatched as shown in table 3 while maintaining all lines operate under their limits as shown in fig 7. The total cost has been reduced by 611.2$/h.

When using two FACTS devices the optimal choice is two TCSC in lines 10 and 4. The total cost has been reduced by 739.5 $/h while maintaining all lines operate under their limits as shown in fig 7.

5.3 For 175% Loading Condition

When line limits are ignored, power generation cost of case 1 equal to 8144.3$/h. For this case, five lines carry more than their limits as shown in fig.8. The generator G5, which having high incremental fuel cost, produces its minimum limit. The generator G2, which having low incremental fuel cost, produces its maximum limit. When line limits are considered in case 2, there are four lines operate near their maximum limits, which present a congestive condition. This condition will prevent loads to be served from generators as obtained from the cheapest combination of generator outputs as in case 1. The cost of generation in case 2 is equal to 9590.90$/h.

Case 3 contains the results of optimal choice, allocation and sizing of FACTS devices for SCED. As can be observed from table 3, TCSC is optimal choice when using one FACTS device and its optimal location is line 4. The generator outputs redispatched as shown in table 3 while maintaining all lines operate under their limits as shown in fig 8. The total cost has been reduced by 622.1$/h.

When using two FACTS devices the optimal choice is two TCSC in lines 3 and 4. The total cost has been reduced by 776.4 $/h while maintaining all lines operate under their limits as shown in fig 8.
The optimal location and control Parameters of TCSC for different loading conditions are shown in table 3.

6. Conclusions

In this study, a simulated annealing algorithm is proposed to determine the optimal choice of FACTS devices and their optimal locations in power system. The overall system cost function, which includes generation cost and installation cost of FACTS devices, is minimized. The FACTS devices namely TCSC and STATCOM are utilized. The Simulations were performed on IEEE 14-bus test system.

Simulation results validate the efficiency of this approach in minimizing the overall system cost function using FACTS devices. Furthermore, the types of FACTS devices, their locations and rated values are optimized simultaneously. When ED is performed with line limits ignored, the cheapest combination of generator outputs are achieved. Considering the limits, one or more lines reach their maximum thermal limit, which present a congestive condition. This condition will prevent loads to be served from generators obtained from the cheapest combination of generator outputs. TCSC can provide control of line impedance. Therefore, it was utilized effectively in this paper to reduce operational and investment costs and increase power transfer capability of the existing power transmission lines. Simulation results show that TCSC is more efficient than STATCOM in reducing overall system cost function and increasing power transfer capability.

7. Appendix 1

The parameters of simulated annealing used in this study

parameter	The value
Initial temperature (T_{ini})	60
Cooling factor (α)	0.95
Number of iteration at each temperature (n)	100
N_r	1000
T_{min}	0.01

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Table .1 generator data of the IEEE 14-bus test system [15]

G_i	Bus. No	a_i	b_i	c_i	P_{gi}^{min}(pu)	P_{gi}^{max}(pu)	Q_{gi}^{min}(pu)	Q_{gi}^{max}(pu)
G_1	1	100	15	0.02	0.3	2	-0.5	0.5
G_2	2	100	10	0.01	0.2	2.7	-0.8	1
G_3	3	100	30	0.05	0.2	2	-0.8	0.8
G_4	6	100	20	0.03	0.4	2	-0.7	0.7
G_5	8	100	30	0.05	0.2	2.5	-0.8	0.8

Table .2 Line Limits for IEEE 14-Bus Test System [15] Line number

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
From bus	1	1	2	2	2	3	4	4	4	5	6	6	6	7	7	9	9	10	12	13
To bus	2	5	3	4	5	4	5	7	9	6	11	12	13	8	9	10	14	11	13	14
Line limit (pu)	1	0.6	1	1	0.6	1.2	0.4	1	0.5	0.5	1.2	1	0.8	1.2	0.8	1	1.2	1	1.5	0.4

Table .3 Results Of The IEEE 14-Bus Test System At Different Loading Conditions

variable	Case 1			Case 2			Case 3 " SCED with FACTS devices"					
	ED without FACTS			SCED without FACTS			One FACTS device			Two FACTS devices		
loading	125%	150%.	175%.	125%.	150%.	175%.	125%.	150%.	175%	125%.	150%.	175%.
Pg1(MW)	30.033	67.695	127.32	30.006	30.130	35.736	30.027	56.992	65.270	30.070	58.719	62.848
Pg2(MW)	238.14	270.00	270.00	233.59	257.58	270.00	238.49	270.00	270.00	238.28	270.00	270.00
Pg3(MW)	20.025	20.046	20.086	20.030	35.484	49.425	20.002	20.043	27.780	20.001	20.138	58.089
Pg4(MW)	24.027	24.132	34.961	24.004	24.028	27.857	24.013	26.066	40.025	24.043	34.390	50.304
Pg5(MW)	20.000	20.050	20.080	28.208	54.196	85.098	20.005	30.845	67.168	20.009	20.136	26.855
V1(pu)	1.1000	1.1000	1.1000	1.0100	1.0420	1.0350	1.1000	1.0540	1.0530	1.1000	1.0630	1.0570
V2(pu)	1.1000	1.1000	1.1000	1.0500	1.0700	1.0430	1.1000	1.0800	1.0800	1.1000	1.0800	1.0760
V3(pu)	1.0610	1.0800	1.0660	1.0500	1.0600	1.0500	1.0630	1.0620	1.0500	1.0600	1.0450	1.0370
V4(pu)	1.1000	1.1000	1.1000	1.1000	1.1000	1.0640	1.1000	1.1000	1.1000	1.1000	1.1000	1.1000
V5(pu)	1.1000	1.0700	1.1000	0.9000	0.9720	0.9180	1.0940	0.9780	0.9850	1.1000	1.0390	1.0490
STATCOM bus	--------	--------	--------	--------	--------	-------	--------	--------	--------	--------	--------	--------
STATCOM size MVA	--------	--------	--------	--------	--------	-------	--------	--------	--------	--------	--------	--------
STATCOM cost($/h)	--------	--------	--------	--------	--------	-------	--------	--------	--------	--------	--------	--------
TCSC line 1	--------	--------	--------	--------	--------	-------	2-4	2-4	2-4	2-4	5-6	2-4
TCSC line 2	--------	--------	--------	--------	--------	-------	-------	-------	-------	2-5	2-4	2-3
TCSC size 1(MVA)	--------	--------	--------	--------	--------	-------	2.5387	5.9877	6.4910	1.7229	2.7484	6.8215
TCSC size 2(MVA)	--------	--------	--------	--------	--------	-------	--------	--------	--------	0.5408	5.7961	6.1935
TCSC total cost($/h)	--------	--------	--------	--------	--------	-------	5.7008	13.232	14.311	5.1091	18.986	28.690
Total losses	8.4790	13.423	19.200	12.089	12.918	14.865	8.7870	15.446	16.997	8.6480	14.883	14.846
Total cost($/h)	5655.8	6779.3	8144.3	5854.0	7609.3	9590.9	5665.6	6998.1	8968.8	5663.3	6869.8	8814.5

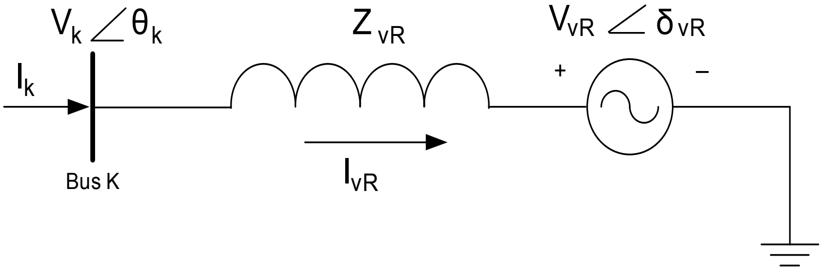

Figure 1. STATCOM model.

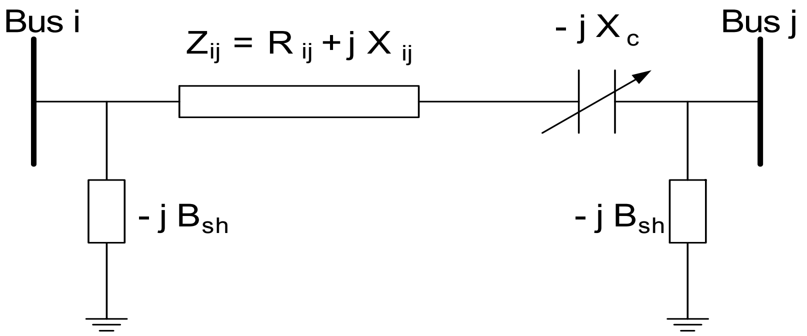

Figure 2. Model of transmission line with TCSC.

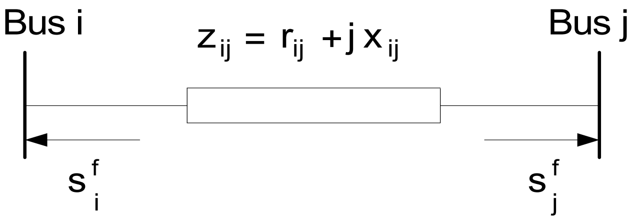

Figure 3. Power injection model of TCSC.

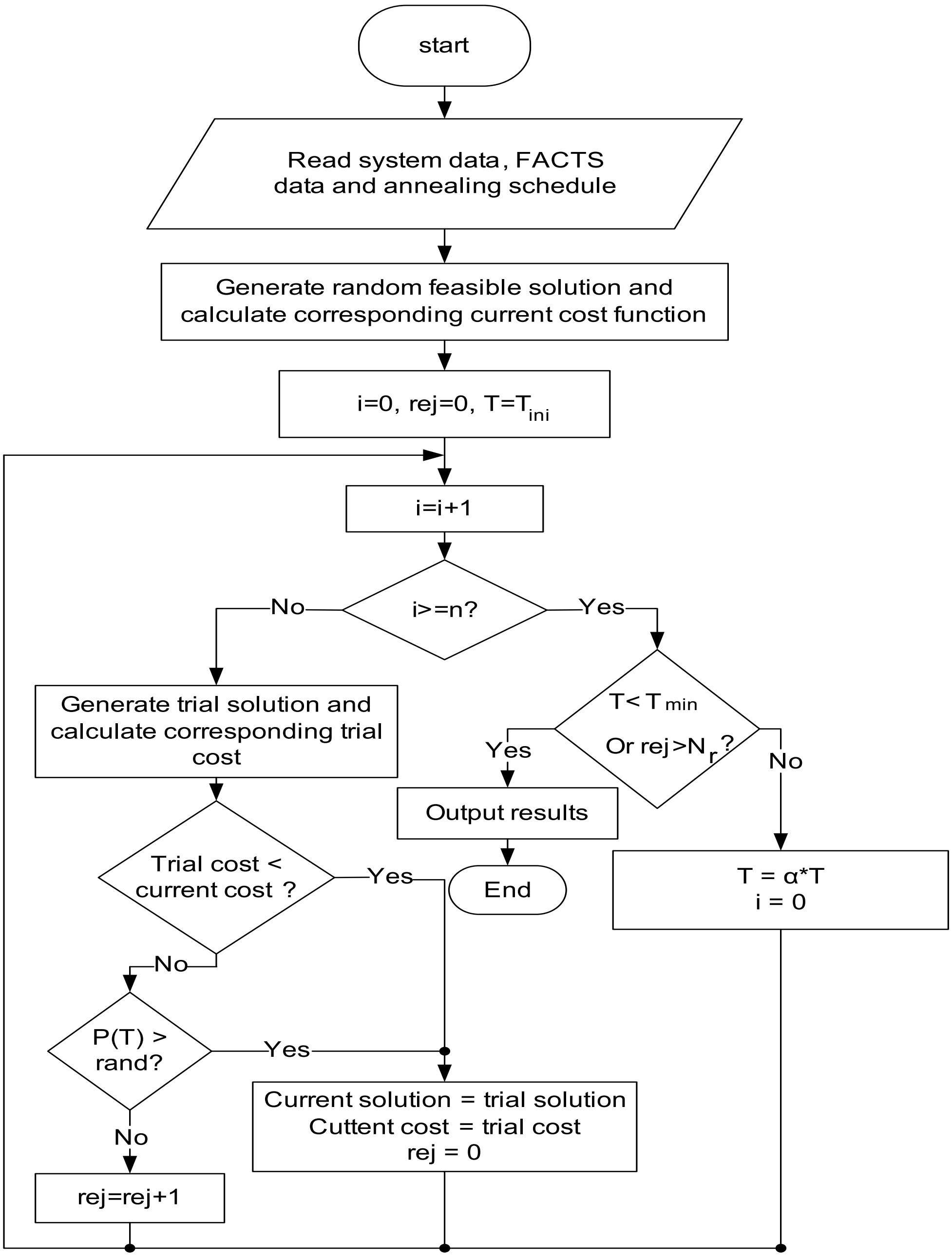

Figure 4. flowchart of the SA optimization.

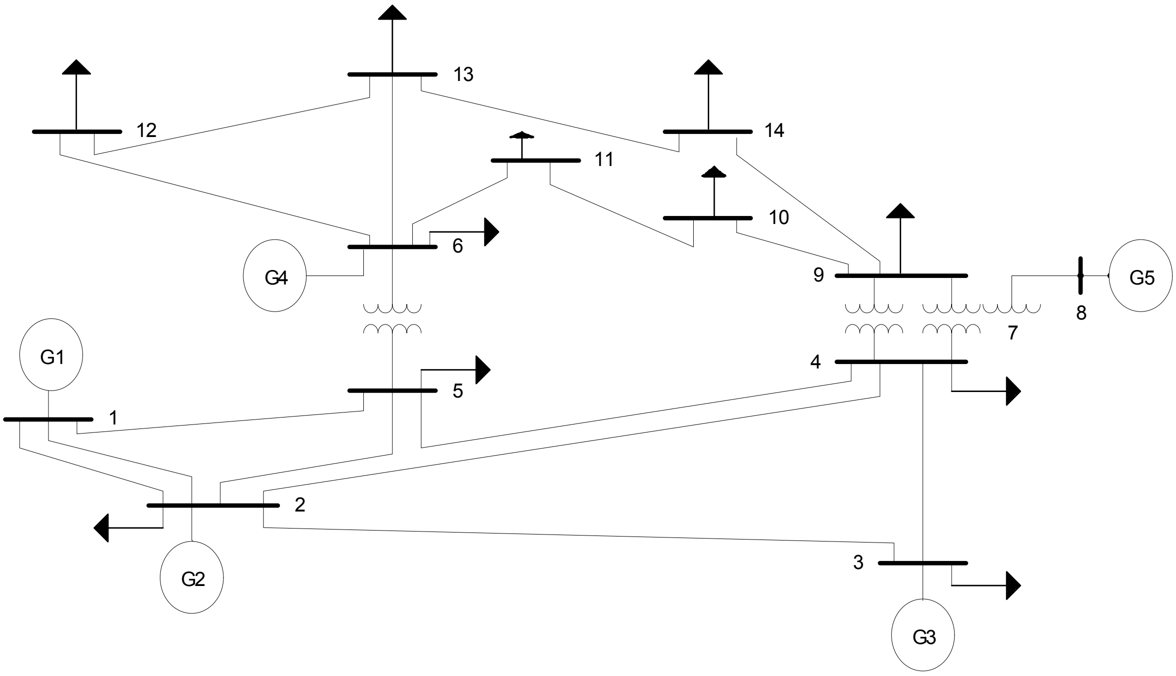

Figure 5. IEEE 14-bus test system.

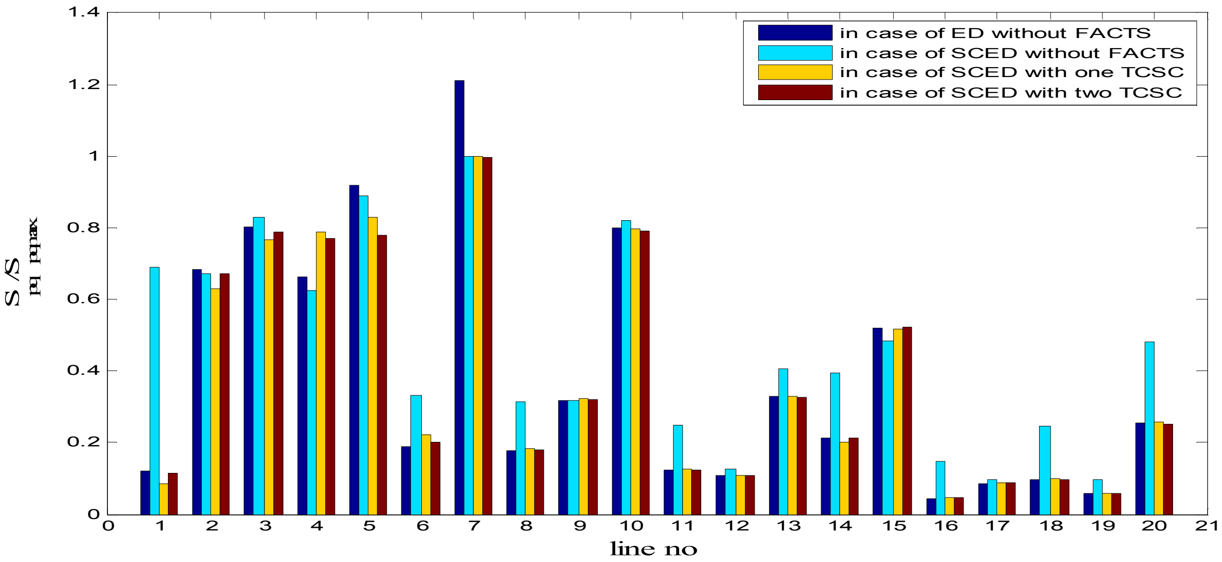

Figure 6. Complex power line ratio in IEEE 14-bus system for 125% loading.

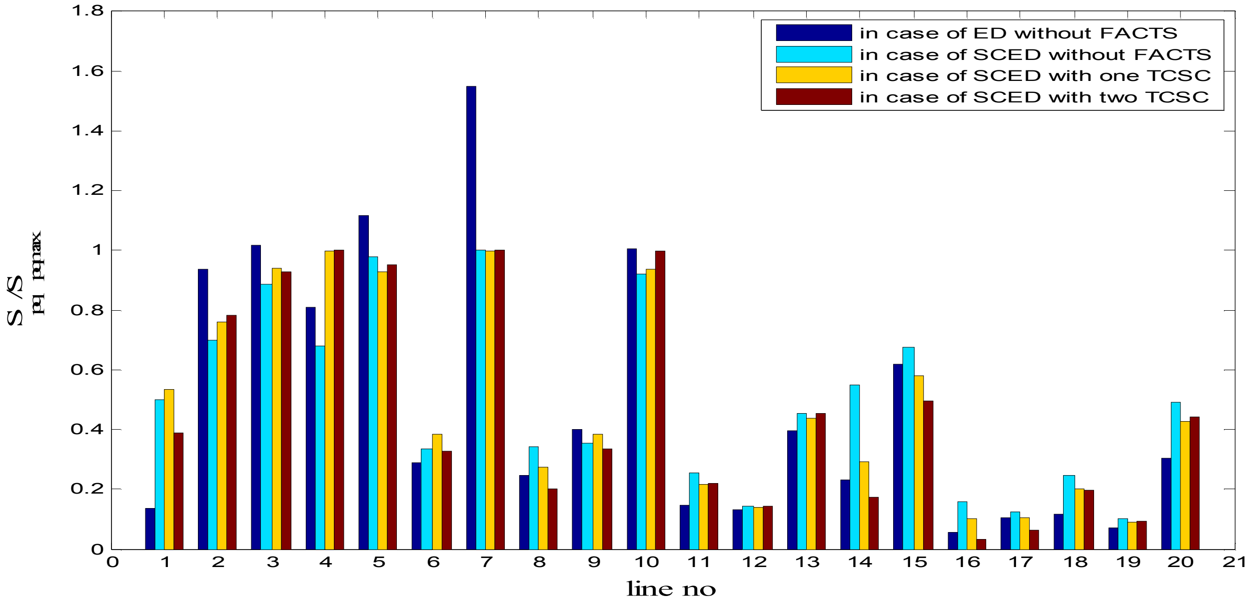

Figure 7. Complex power line ratio in IEEE 14-bus system for 150% loading.

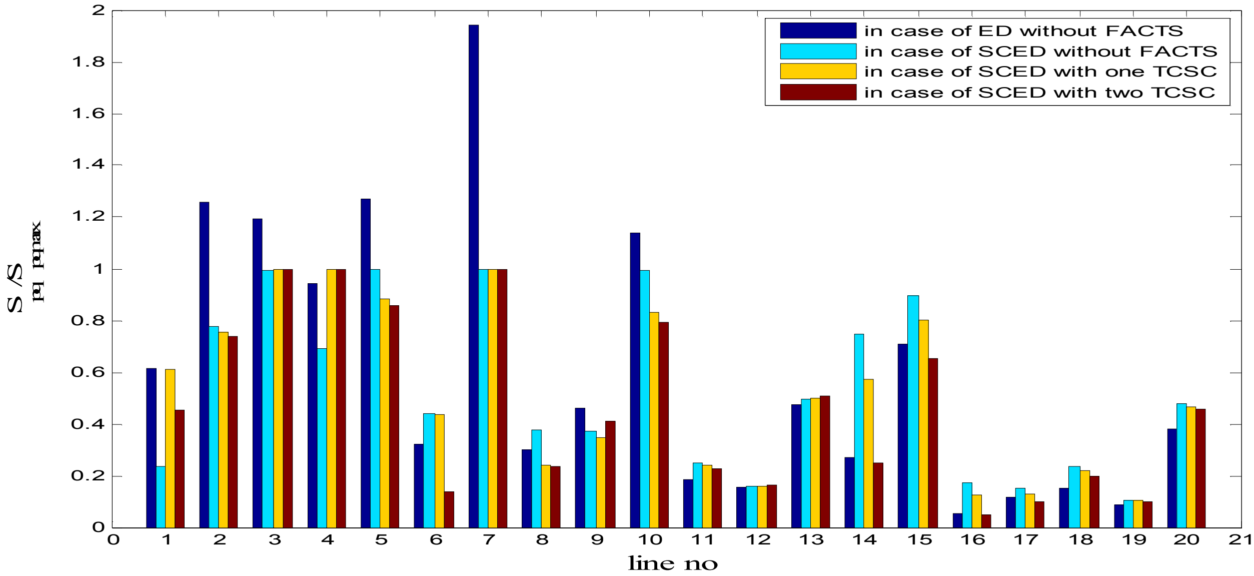

Figure 8. Complex power line ratio in IEEE 14-bus system for 175% loading.