Optimal Power Flow for Enhanced TTC with Optimal Number of SVC by using Improved Hybrid TSSA

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ABSTRACT

In this paper, the hybrid tabu search and simulated annealing (TSSA) method are modified for improving. The main point of modification is to apply sine value into the value of the temperature of simulated annealing. This modification aims to reduce the disadvantage of the original hybrid TSSA. This disadvantage means the value of each parameter is only increased to the maximum value of the temperature of simulated annealing. The optimal number of flexible alternating current transmission system (FACTS) controller determining method is used to determine optimal number of FACTS. SVC is used as FACTS controller in this paper. The split search space method is integrated to manage search space of static var compensator (SVC) operating point. The allocations of SVCs are used to enhance total transfer capability (TTC). Test results on the IEEE 118-bus system and the practical Electricity Generating Authority of Thailand (EGAT) 58-bus system show that the proposed improved hybrid TSSA with optimal number determining method of SVC give higher TTC and less number of SVC than test results from evolutionary programming (EP) and original hybrid TSSA.

Keywords: Optimal Power Flow, Optimization, Tabu Search, Simulated annealing, SVC

1. INTRODUCTION

Due to the demands of electrical power, electricity demand hits its highest point every year. The installation of the new power plant is the standard choice to response to this demand. However, the usage time of building a new power plant is long. The interested alternative is to improve the efficiency of the power system. The popular improvement is to enhance total transfer capability (TTC) by installing flexible alternating current transmission system (FACTS) controllers [1] or distributed generations (DG) [2] with the concept of optimal power flow (OPF). FACTS controllers look more flexible than DG according to their function. FACTS controllers can adjust their parameter settings. For example, the unified power flow controller (UPFC) can adjust voltage and angle. The thyristor-controlled series capacitor (TCSC) can adjust reactance. Thyristor-controlled phase shifter (TCPS) can adjust the angle. Static var compensator (SVC) can inject var into the power system [3].

The maximum benefits of installation of FACTS controllers are to install with optimal allocations. The allocations of FACTS controller mean suitable parameter settings, locations, type, and number [4].

There are many methods that are used to evaluate allocation of these FACTS controllers. The heuristics optimization techniques such as genetic algorithm (GA) [5], evolutionary algorithm (EA) [6], evolutionary programming (EP) [7], particle swarm optimization (PSO) [8], tabu search (TS) [9, 10], and simulated annealing (SA) [11] are used to solve complicated optimization problems [12, 13]. These methods perform their efficiency well. Moreover, the bio-inspiration methods such as grey wolf optimizer (GWO) [14], dragonfly optimizer (DGO) [15], bee algorithm (BA) are used, too [16].

However, these methods have their limitation. The chances to stick in the local area are the main limitation. Many researchers developed hybrid methods such as hybrid PSO [17], hybrid EA [18], and hybrid TSSA [19] to step over this limitation.

The contents of this paper are about the modification of the original hybrid TSSA. The aim of modification is to enhance the performance of the original hybrid TSSA. The main modification is to apply the sine value of sine function into the main equation of the original hybrid TSSA. The optimal number of FACTS controller determining method is integrated. The SVC static model is defined to use in this paper. The objective function of this paper is to enhance TTC from the base case. The goal of this enhancement is to maximize TTC without violences. The IEEE 118-bus system bus and Electricity Generating Authority of Thailand (EGAT) 58-bus system are used as test systems. Test results are compared with test results from EP and original hybrid TSSA.

2. PROBLEM FORMULATION

Power transfer capability is defined as TTC value [20-23]. The TTC means the overall power which is transferred from generators to load buses in power

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systems. The real and reactive power is transferred between source buses to sink buses. The constraints such as generation limit, voltage limits, line flow limits, and FACTS controllers operating limits are used. SVC is used as FACT controller in this paper. In addition, SVC is represented by the static model [24].

To determine the maximum TTC, with the optimal number and allocation of SVC, the objective function is formulated in (1).

$$\max F = \sum_{i=1}^{ND\_BUS} P_{Di} - \sum_{i=1}^{NL} P_{Li} \quad (1)$$

Subject to

$$P_{Gi} - P_{Di} - \sum_{j=1}^{N} V_i V_j Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j) = 0 \quad (2)$$

$$Q_{Gi} - Q_{Di} + Q_{vi} + \sum_{j=1}^{N} V_i V_j Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j) = 0 \quad (3)$$

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max}, i = 1,2,3,\ldots,\mathrm{NG} \quad (4)$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max}, i = 1,2,3,\ldots,\mathrm{NG} \quad (5)$$

$$V_i^{\min} \le V_i \le V_i^{\max}, i = 1,2,3,\ldots,\mathrm{N} \quad (6)$$

$$|S_{Li}| \le S_{Li}^{\max}, i = 1,2,3,\ldots,\mathrm{NL} \quad (7)$$

$$0 \le Q_{Vi} \le Q_{Vi}^{\max}, i = 1,2,3,\ldots,\mathrm{n} \quad (8)$$

Where

P_{Di}	real power loads in the ith bus,
P_{Li}	losses in line flow at the ith line,
ND_BUS	number of load buses,
NL	number of lines,
P_{Gi}	real power generation at the ith bus,
N	total number of buses,
V_i	voltage magnitude at the ith bus,
V_j	voltage magnitude at the jth bus,
δ_i	voltage angles of the ith bus,
δ_j	voltage angles of the jth bus,
Q_{Gi}	reactive power generation at the ith bus,
Q_{Di}	reactive power load at the ith bus,
θ_{ij}	the angle of the element in the ijth bus admittance matrix,
Q_{vi}	fixed injected reactive power of SVC at the ith bus,
$\|S_{Li}\|$	the ith line or transformer loading,
NG	number of generators,
$P_{Gi}^{\min}, P_{Gi}^{\max}$	the lower and upper limit of real power generation at the ith bus,
$Q_{Gi}^{\min}, Q_{Gi}^{\max}$	the lower and upper limit of reactive power generation at the ith bus,
$V_i^{\min}, V_i^{\max}$	the lower and upper limit of voltage magnitude at the ith bus,
$S_{Li}^{\max}$	the ith line or transformer loading limit,
$Q_{Vi}^{\max}$	the upper limit of injected reactive power of SVC at the ith bus

3. PROPOSED METHOD

3.1 Original hybrid TSSA

The original hybrid TSSA is proposed in [25]. This method has merged the approach of TS and SA. The main algorithm is based on TS [26]. Each individual of SA is presented for generating new individual for TS for the next iteration. In addition, the probabilistic acceptance criterion of SA is used [27]. The flowchart of the the original hybrid TSSA is as fig 1.

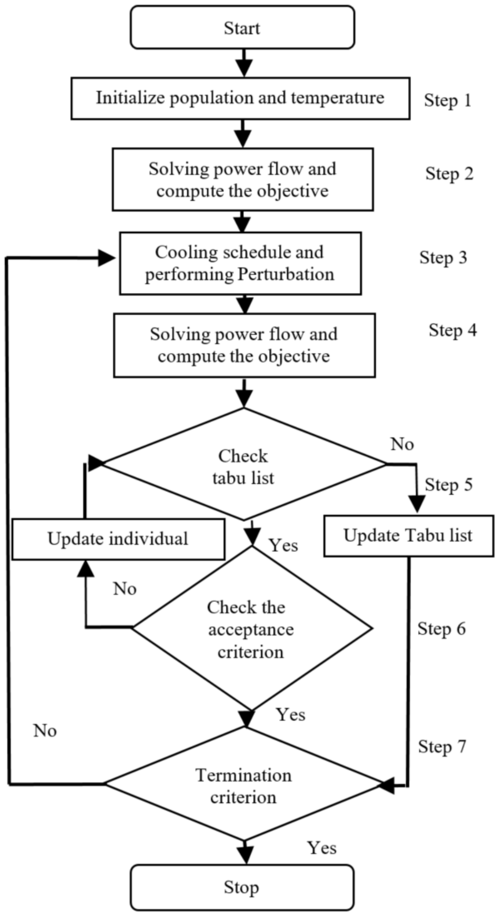

Fig.1: *Flow chart of the original hybrid TSSA.*

Each parameter of the individual is initialized randomly by using (9).

$$x_i = x_i^{\min} + u(x_i^{\max} - x_i^{\min} \quad (9)$$

Where

x_i	value of the ith element,
$x_i^{\min}, x_i^{\max}$	lower and upper limits of the ith element,

and

u uniform random in the interval [0,1].

Each individual is generated by randomness. The initial individual bases on the uniform probability distribution function. In addition, the constraints are

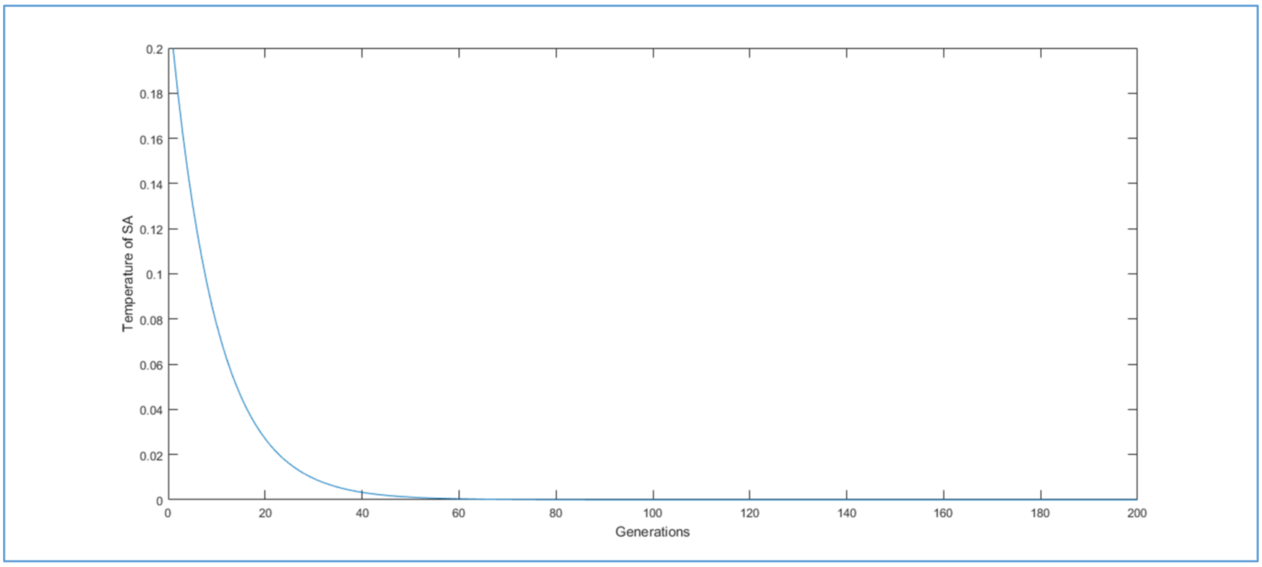

Fig.2: *Curve of sample SA temperature value.*

used to limit the ranges of randomness. An individual is randomly generated by (10).

$$S(k,m)_T = S_T^{(k,0)} + (T_k \, {}^*[U]^* F_U) \tag{10}$$

$$T_k = r^{(k-1)} \, {}^* T_1 \tag{11}$$

Where

T_1 initial temperature equals to 0.2,
$S_T^{(k,0)}$ the initial individual at iteration kth,
$[U]$ a diagonal matrix of uniform randomly generated a number between 0 and 1, and
T_k the temperature at iteration kth,
k iteration counter,
r reducing rate equals to 0.9,
$S_T^{(k,m)}$ trial m neighborhood individual at iteration kth,
F_U the upper limit of the SVC parameter.

The sample of the curve of SA value is shown in fig 2.

The probabilistic acceptance criterion of SA is used instead of the aspiration level (AL) of TS. The acceptance criterion is designed for the decision movement of the current neighborhood solution, which is in the tabu list (TL). The probabilistic acceptance criterion is given as follows [28].

$$p^k = \frac{1}{1 + \exp(\Delta / T_k)} \tag{12}$$

Where
p^k probabilistic acceptance criteria of current neighborhood individual at iteration kth,
Δ difference between the objective function of the current neighborhood individual in the second set $\{SS_T^{(k,m)}\}$ and the best individual reached or $(F(S_C^k) - F_B)$,
$(F(S_C^k))$ the objective function of individual S_C^k,
S_C^k current neighborhood individual at iteration k, and
F_B best objective function.

3.2 Improved hybrid TSSA

According to the chances of sticking in the local search space areas which is described in section 1: introduction, the performance improvement of the original hybrid TSSA is created.

Due to the value of sine function which upon with the changing of the sine curve, the changing direction of each variable can be smoothly increased or decreased. This means, there is more chances to step over from local search space than one direction changing or non-direction changing. The sine curve is shown in fig 3.

The characteristics of this sine curve are 8000 samples per second and 60Hz. These characteristics can be used to evaluate the best solutions in this paper. In addition, these characteristics have been evaluated from trials and errors by experimental.

The sine function is applied by multiple value of sine function into the value of SA temperature. This application is expressed in (13). The changing direction of each variable can be increased or decreased.

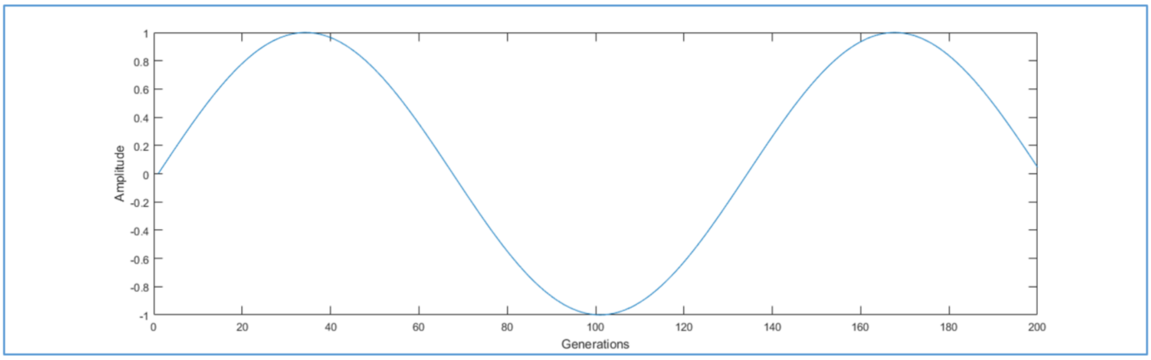

Fig.3: *Curve of sample sine function value.*

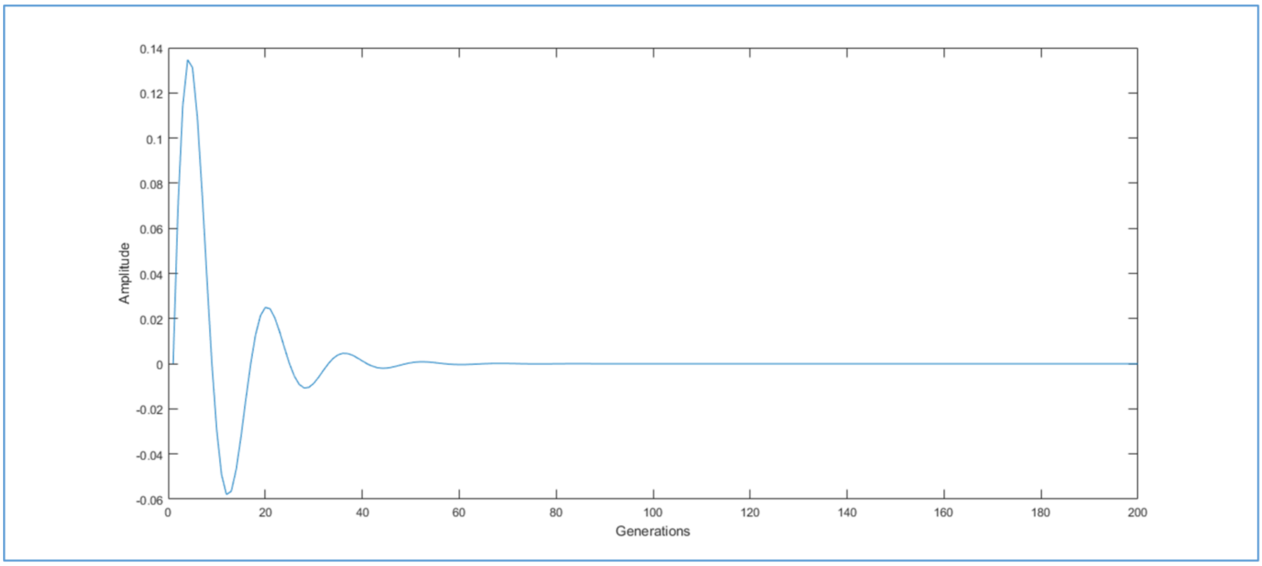

Fig.4: *Curve of sample applied SA with the sine function value.*

$$S_T^{(k,m)} = S_T^{(k,0)} * (SV_k * T_k * [U] * F_U) \quad (13)$$

Where

SV_k sine value at iteration k

The curve of applied SA with the sine function value is shown in fig 4.

This improving SA value by using sine function value is expected to step over the search space local area.

3.3 Optimal number of FACTS controller determining method

The algorithm of optimal number of FACTS controller determining method is proposed by Chansareewittaya and Jirapong in [7, 27, 28]. This algorithm is used to evaluating the optimal number of SVC by calculating from objective function value.

The following index is calculating using the optimal value of the objective function by using (14) and (15).

$$INC_i = \frac{\Delta Z_i}{\Delta Z_{i-1}} \quad (14)$$

$$|\Delta\Delta Z_i| = |\Delta Z_i - \Delta Z_{i-1}| \quad (15)$$

Where

INC_i index to check out the increasing number of FACTS controller, subscript i denotes the number of FACTS controller,

$\Delta Z_i, \Delta Z_{i-1}$ the optimal value of the objective function when applying ith and $i-1$th FACTS controller,

$\Delta\Delta Z_i, \Delta\Delta Z_{i-1}$ variation of the objective value when the number of FACTS controller is increased from $i-1$ to i, This is increased when INC_i is greater than INC_{i-1} and INC_i is greater than $BestINC$ value, and

$BestINC$ maximum value of INC.

The numbers of SVC will be increased by using (14) and (15) until the stopping criteria is reached. Moreover, the split search space method is used to manage the search space of the SVC operating point. The search space of the operating point of SVC is split into n search spaces depended on the number of SVC. If the number of FACTS controller equals one, minimum and maximum values of operating points are used by the initial value. If the number of FACTS controllers is greater than one, the search space will be split. The flowchart of the optimal number of FACTS controllers is shown in fig 5.

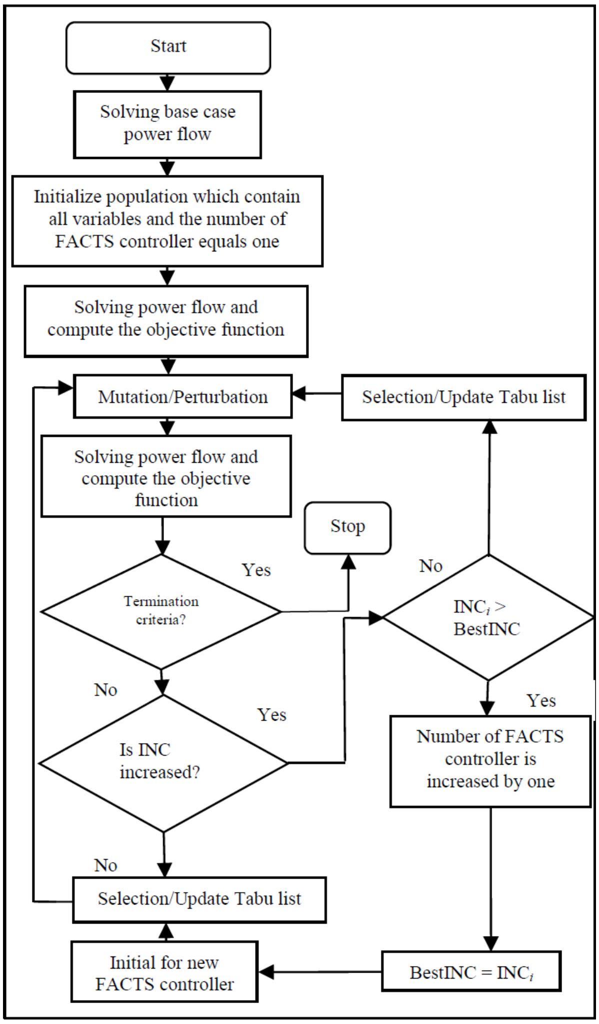

Fig.5: *The flowchart of the optimal number of FACTS controller method.*

4. CASE STUDY AND EXPERIMENTAL RESULTS

The IEEE 118-bus system and EGAT 58-bus systems are used to demonstrate the placement of SVC with the optimal number by using search space managing methods. Base case TTC is calculated by using the full Newton-Raphson method with OPF. The reactive power injection limit of SVC $0 \leq Q_{vi} \leq 10$is Mvar.

The compared methods are EP and original hybrid TSSA. EP is a well-known modern heuristics method. There are many optimization problems that are optimized by using EP [29, 30]. The advantages of EP are the ability to self-adapt the search for optimum solutions [31]. Moreover, the flexibility of evolutionary algorithms to address general optimization problems using virtually any reasonable representation and performance index, with variation operators that can be tailored for the problem at hand, and selection mechanisms tuned for the appropriate level of stringency [32]. Moreover, EP is simple and easy to implement. Another compared method is the original hybrid TSSA [33] which is the based method for the proposed method. In addition, both the compared method is used in [33].

The population size of EP, original hybrid TSSA, and improved hybrid TSSA are 30. The maximum iteration number is set to 200.

4.1 IEEE 118-bus system

The IEEE 118-bus system consisting of 54 generating plants, 64 load buses, and 186 lines is shown in fig 6. Bus 69 is set as a swing bus. Base case TTC of the IEEE 118-bus system equals 1433.00 MW. The system data can be found in [34].

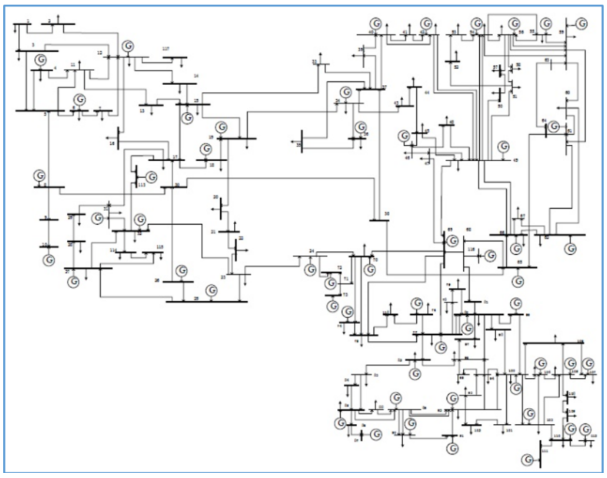

Fig.6: *Diagram of the IEEE 118-bus system.*

The best and average values of TTC from improved hybrid TSSA are better than those from EP and original hybrid TSSA. The average TTC from improved hybrid TSSA is better than the original hybrid TSSA equals 6.05%. Especially, the best TTC is better than the original hybrid TSSA equals 19.87%. The the standard deviation TTC from improved hybrid TSSA is 152.78% higher than standard deviation TTC of original hybrid TSSA. This means, the proposed method evaluates new values of parameters that have chances to step over the local area. These chances can evaluate the answer which is the global answer. Moreover, the usage time of improved hybrid TSSA is slightly higher than the original hybrid TSSA.

The best, average, worst TTC, and usage time from EP, original hybrid TSSA, and improved hybrid TSSA are shown in table 1.

Table 1: *Best, average, worst TTC and usage time from EP, original hybrid TSSA, and improved hybrid TSSA.*

TTC (MW)	EP	Original hybrid TSSA	Improved hybrid TSSA
Best	2965.43	2996.34	3591.99
Average	2637.92	2815.47	2985.95
Worst	2432.38	2589.63	1433.00
Standard deviation	144.04	152.78	393.93
Usage time (minutes)	40.65	30.11	30.12

The number and allocation of FACTS controller from EP, original hybrid TSSA, and improved hybrid TSSA are shown in table 2.

Table 2: *Number and allocation of FACTS controller from EP, original hybrid TSSA, and improved hybrid TSSA.*

Method	EP	Original hybrid TSSA	Improved hybrid TSSA
Number of FACTS Controllers	2	2	2
Location /Parameter of FACTS Controller	Bus2 /2.197 (Mvar)	Bus 21 /7.005 (Mvar)	Bus 38 /0.921 (Mvar)
	Bus 27 /6.903 (Mvar)	Bus 113 /4.019 (Mvar)	Bus 2 /9.467 (Mvar)

4.2 Thailand 58-bus system

In this case study, a reduced practical test system from EGAT 230 kV and 500 kV network is used as another test system. The EGAT 58-bus system consisting of 17 generating plants, 41 load buses, and 77 lines as shown in fig 7 is used [28]. Bus 1 is set as a swing bus which. Base case TTC of the system equals 10261.50 MW. The system data can be found in an appendix.

The best and average values of TTC from the proposed method are better than test results from EP and original hybrid TSSA. The best and average TTC from improved hybrid TSSA are better than the original hybrid TSSA equals 1.38% and 1.37%, respectively. The standard deviation TTC value is bigger

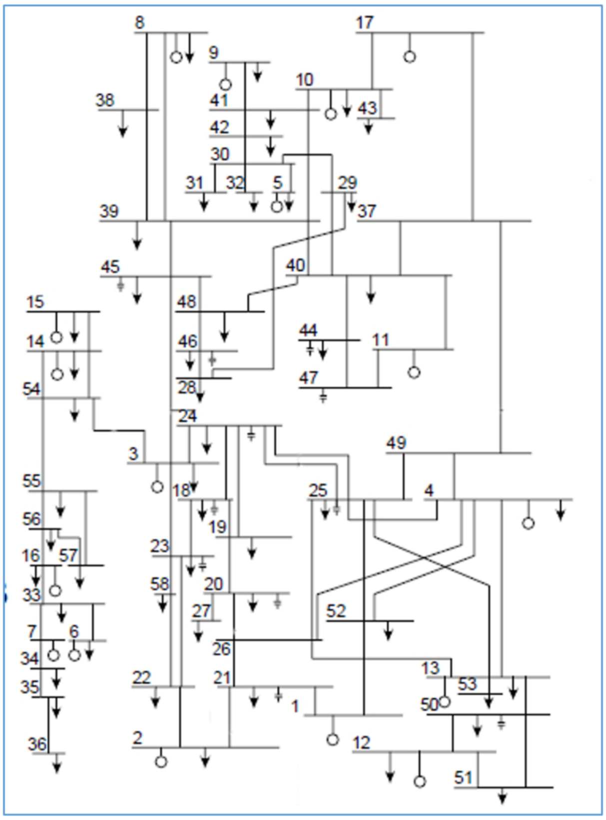

Fig.7: *Diagram of the EGAT 58-bus system.*

than 100% difference due to the best and worst TTC value. There is some sub-evaluating which gives the worst TTC value lower than compared methods. The usage time of improved hybrid TSSA of this test system is still slightly higher than the original hybrid TSSA. The best, average, worst TTC, and usage time from EP, original hybrid TSSA, and improved hybrid TSSA are shown in table 3.

Table 3: *Best, average, worst TTC and usage time from EP, original hybrid TSSA, and improved hybrid TSSA.*

TTC (MW)	EP	Original hybrid TSSA	Improved hybrid TSSA
Best	15380.40	16521.14	16748.97
Average	14674.74	15559.92	15774.23
Worst	14701.50	15402.91	12836.26
Standard deviation	317.11	322.81	835.00
Usage time (minutes)	33.28	19.37	19.38

The number and allocation of FACTS controller from EP, original hybrid TSSA, and improved hybrid TSSA are shown in table 4. The number of SVC which is determined by the proposed method is less than the number of SVC from EP. Moreover, the total

Mvar of SVCs from the proposed method is less than Mvar of SVCs from hybrid TSSA. The total Mvar can use to estimate the installation cost of SVC. This means the proposed method can the determine installation of SVCs with the lowest investment cost by comparing with EP and original hybrid TSSA.

Table 4: *Number and allocation of FACTS controller from EP, original hybrid TSSA, and improved hybrid TSSA.*

Method	EP	Original hybrid TSSA	Improved hybrid TSSA
Number of FACTS Controllers	3	2	2
Location /Parameter of FACTS Controller	Bus 8 /1.545 (Mvar)	Bus 3 /2.815 (Mvar)	Bus 48 /0.197 (Mvar)
	Bus 12 /5.203 (Mvar)	Bus 46 /5.504 (Mvar)	Bus 13 /0.034 (Mvar)
	Bus 18 /6.931 (Mvar)	-	-

5. CONCLUSION

In this paper, the proposed improved hybrid TSSA with the optimal number of FACTS controller determining method is used to evaluate TTC. The sine wave is applied to the hybrid TSSA. This application creates various parameter changing. The value of each parameter can be increased or decreased. This is the difference from the original hybrid TSSA which the value of each parameter is only increased. This difference enhances chances to step over from the local search space. Moreover, the optimal number of FACTS controller determining method and search space managing methods are integrated. The results indicate that improved hybrid TTC and additional technique can enhance TTC from the base case in both test system, especially in practical Thailand system. Moreover, the optimal number of FACTS controller determining method can reduce time by comparing to the increasing number of FACTS controller manually for looking for the optimal number of FACTS controller. Therefore, the installation SVC with a suitable number and optimal allocation are beneficial for the further expansion plans.

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Appendix

Bus data of EGAT 58-bus

Bus			Volt	Angle	Load		Generator				Inject	V_{min}	V_{max}	Pg_{min}	Pg_{max}	Pd_{min}	Pd_{max}
No	Area	Code	Mag.	Degree	MW	Mvar	MW	Mvar	Qmin	Qmax	Mvar	p.u.	p.u.	MW	MW	MW	MW
1	1	1	1.018	0.000	0.000	0.000	1967.987	442.327	-416.400	850.000	0.000	0.900	1.100	1000.000	2500.000	0.000	0.000
2	1	2	1.000	-8.285	1108.889	233.554	1969.900	1065.902	-546.000	1155.000	0.000	0.900	1.100	1000.000	2500.000	1108.890	1605.000
3	1	2	1.017	-7.791	56.600	-355.359	218.000	339.592	-80.000	400.000	0.000	0.900	1.100	100.000	300.000	56.600	82.000
4	1	2	1.010	-3.209	174.600	-54.300	338.980	283.201	-120.000	300.000	0.000	0.900	1.100	150.000	500.000	174.600	262.000
5	1	2	1.020	13.094	184.800	-10.000	698.400	53.949	-223.200	270.000	0.000	0.900	1.100	350.000	1000.000	184.800	277.000
6	1	2	1.055	3.818	142.200	-16.400	149.700	7.881	-74.000	141.000	0.000	0.900	1.100	100.000	200.000	142.200	213.000
7	1	2	1.040	9.296	-45.400	8.800	719.500	-18.446	-209.200	271.500	0.000	0.900	1.100	400.000	1000.000	-45.400	-68.000
8	1	2	1.050	23.335	31.000	-4.600	499.600	41.918	-104.000	216.800	0.000	0.900	1.100	250.000	750.000	31.000	47.000
9	1	2	1.050	30.194	73.700	-23.800	499.800	-51.109	-130.000	166.400	0.000	0.900	1.100	250.000	750.000	73.700	111.000
10	1	2	1.060	21.354	74.800	31.800	575.100	315.945	-200.000	400.000	0.000	0.900	1.100	300.000	1000.000	74.800	112.000
11	1	2	1.000	12.297	0.000	-60.000	880.000	49.188	-160.000	240.000	0.000	0.900	1.100	400.000	1500.000	0.000	0.000
12	1	2	1.028	9.686	430.500	61.000	1206.540	137.742	-446.400	540.000	0.000	0.900	1.100	500.000	1500.000	430.500	646.000
13	1	2	1.028	1.317	81.200	19.000	1639.542	478.680	-421.200	870.000	0.000	0.900	1.100	750.000	2000.000	81.200	122.000
14	1	2	1.050	3.175	36.200	-10.200	639.700	51.091	-107.000	194.000	0.000	0.900	1.100	300.000	1000.000	36.200	54.000
15	1	2	1.060	5.550	5.800	2.200	149.900	5.780	-57.000	114.000	0.000	0.900	1.100	100.000	200.000	5.800	9.000
16	1	2	1.050	-5.263	77.800	5.400	0.000	-6.061	-50.000	300.000	0.000	0.900	1.100	0.000	0.000	77.800	117.000
17	1	2	1.050	17.924	0.000	341.800	1113.700	-349.717	-450.000	1000.000	0.000	0.900	1.100	500.000	1500.000	0.000	0.000
18	2	0	0.981	-10.559	387.287	-18.556	0.000	0.000	0.000	0.000	-0.769	0.900	1.100	0.000	0.000	387.290	560.000
19	2	0	0.975	-9.948	885.183	416.935	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	885.180	1281.000
20	2	0	0.980	-8.458	839.053	217.071	0.000	0.000	0.000	0.000	-0.385	0.900	1.100	0.000	0.000	839.050	1214.000
21	2	0	0.990	-7.468	999.300	233.400	0.000	0.000	0.000	0.000	-1.540	0.900	1.100	0.000	0.000	999.300	1499.000
22	2	0	0.983	-10.074	446.168	76.918	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	446.170	646.000
23	2	0	0.978	-10.538	607.365	287.977	0.000	0.000	0.000	0.000	-0.769	0.900	1.100	0.000	0.000	607.370	879.000
24	2	0	1.003	-9.058	825.576	-335.663	0.000	0.000	0.000	0.000	-0.695	0.900	1.100	0.000	0.000	825.580	1195.000
25	2	0	0.997	-3.814	184.600	23.200	0.000	0.000	0.000	0.000	-1.668	0.900	1.100	0.000	0.000	184.600	277.000
26	2	0	0.986	-6.995	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	0.000	0.000
27	2	0	0.979	-8.666	315.344	-0.415	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	315.340	456.000
28	2	0	0.948	-1.355	241.500	74.700	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	241.500	362.000
29	2	0	0.991	5.252	48.000	5.100	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	48.000	72.000
30	2	0	1.011	10.613	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	0.000	0.000
31	2	0	0.981	5.682	210.900	51.000	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	210.900	316.000
32	2	0	1.008	10.269	175.500	40.400	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	175.500	263.000
33	2	0	1.048	3.777	179.700	26.700	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	179.700	270.000
34	2	0	1.012	0.598	125.200	23.000	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	125.200	188.000
35	2	0	1.005	-5.153	54.300	-24.400	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	54.300	81.000

Bus			Volt	Angle	Load		Generator				Inject	V_{min}	V_{max}	Pg_{min}	Pg_{max}	Pd_{min}	Pd_{max}
No	Area	Code	Mag.	Degree	MW	Mvar	MW	Mvar	Qmin	Qmax	Mvar	p.u.	p.u.	MW	MW	MW	MW
36	2	0	0.992	-9.708	228.900	13.200	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	228.900	343.000
37	2	0	1.035	9.474	0.000	615.300	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	0.000	0.000
38	2	0	1.030	19.451	36.500	21.300	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	36.500	55.000
39	2	0	1.003	10.061	87.300	17.100	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	87.300	131.000
40	2	0	1.015	7.791	78.800	87.000	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	78.800	118.000
41	2	0	1.034	19.888	-34.100	27.000	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	-34.100	-51.000
42	2	0	1.031	15.877	9.000	9.500	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	9.000	14.000
43	2	0	1.059	18.660	122.200	4.800	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	122.200	183.000
44	2	0	0.986	6.482	313.800	36.000	0.000	0.000	0.000	0.000	-0.833	0.900	1.100	0.000	0.000	313.800	471.000
45	2	0	0.972	-1.299	71.000	105.000	0.000	0.000	0.000	0.000	-0.834	0.900	1.100	0.000	0.000	71.000	107.000
46	2	0	0.941	-2.878	291.100	91.200	0.000	0.000	0.000	0.000	-1.563	0.900	1.100	0.000	0.000	291.100	437.000
47	2	0	0.986	9.277	508.200	152.400	0.000	0.000	0.000	0.000	-0.833	0.900	1.100	0.000	0.000	508.200	762.000
48	2	0	0.953	-1.287	231.900	155.400	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	231.900	348.000
49	2	0	0.990	1.999	0.000	0.000	0.000	0.000	0.000	0.000	1.333	0.900	1.100	0.000	0.000	0.000	0.000
50	2	0	1.011	5.353	307.800	163.800	0.000	0.000	0.000	0.000	-1.537	0.900	1.100	0.000	0.000	307.800	462.000
51	2	0	1.015	6.748	96.000	28.400	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	96.000	144.000
52	2	0	1.012	-0.930	302.000	182.700	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	302.000	453.000
53	2	0	1.031	0.257	97.200	-8.200	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	97.200	146.000
54	2	0	1.017	-5.214	319.800	122.100	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	319.800	480.000
55	2	0	1.020	-7.008	195.000	6.800	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	195.000	293.000
56	2	0	1.045	-6.199	33.200	5.400	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	33.200	50.000
57	2	0	1.027	-7.550	49.600	30.300	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	49.600	74.000
58	2	0	0.961	-11.716	623.225	424.606	0.000	0.000	0.000	0.000	0.000	0.900	1.100	0.000	0.000	623.230	902.000

Line information of EGAT 58-bus

Bus		R	X	1/2B	a	Rating
NL	NR	p.u.	p.u.	p.u.		MVA
1	52	0.0002	0.0021	0.0173	1.0000	972
2	22	0.0002	0.0027	0.0501	1.0000	1508
3	24	0.0012	0.0087	0.0393	1.0000	369
3	45	0.0035	0.0251	0.1129	1.0000	567
3	54	0.0026	0.0210	0.0791	1.0000	263
4	52	0.0017	0.0179	0.0365	1.0000	245
4	13	0.0021	0.0222	0.0453	1.0000	422
6	33	0.0025	0.0214	0.0759	1.0000	50
7	34	0.0048	0.0383	0.1444	1.0000	509
8	38	0.0054	0.0438	0.0406	1.0000	208
8	39	0.0107	0.0833	0.3253	1.0000	357
9	41	0.0090	0.0454	0.1671	1.0000	512
10	43	0.0058	0.0424	0.1867	1.0000	152
12	51	0.0022	0.0159	0.0715	1.0000	392
14	15	0.0041	0.0325	0.1228	1.0000	175
17	10	0.0014	0.0208	0.0000	1.0520	502
18	19	0.0007	0.0050	0.0052	1.0000	253
18	23	0.0018	0.0146	0.0134	1.0000	25
18	24	0.0019	0.0140	0.0145	1.0000	280
19	20	0.0002	0.0027	0.0223	1.0000	1060
19	24	0.0017	0.0128	0.0132	1.0000	286
20	26	0.0001	0.0012	0.0389	1.0000	2423
20	27	0.0002	0.0011	0.0044	1.0000	365
21	2	0.0004	0.0041	0.0347	1.0000	422
21	26	0.0005	0.0041	0.0184	1.0000	238
21	1	0.0011	0.0116	0.0945	1.0000	1286
22	23	0.0001	0.0018	0.0149	1.0000	594
22	58	0.0009	0.0102	0.0215	1.0000	393
23	3	0.0018	0.0104	0.0470	1.0000	670
23	58	0.0005	0.0060	0.0127	1.0000	492
24	25	0.0019	0.0214	0.0397	1.0000	486
24	4	0.0019	0.0214	0.0397	1.0000	547
25	52	0.0017	0.0179	0.0365	1.0000	324
25	13	0.0021	0.0222	0.0453	1.0000	487
25	26	0.0009	0.0096	0.0196	1.0000	668
26	4	0.0009	0.0096	0.0196	1.0000	827
26	13	0.0024	0.0148	0.1212	1.0000	1141
28	29	0.0052	0.0372	0.1673	1.0000	365
28	46	0.0059	0.0432	0.1892	1.0000	67
29	30	0.0049	0.0347	0.1557	1.0000	326
29	40	0.0079	0.0584	0.2629	1.0000	116
30	5	0.0008	0.0088	0.0738	1.0000	618
30	31	0.0057	0.0413	0.1820	1.0000	260
30	32	0.0005	0.0036	0.0158	1.0000	216
30	42	0.0087	0.0632	0.2797	1.0000	186
33	7	0.0038	0.0300	0.1132	1.0000	416
33	16	0.0140	0.1032	0.4603	1.0000	213
34	35	0.0044	0.0352	0.1325	1.0000	348
35	36	0.0044	0.0346	0.1303	1.0000	278
37	40	0.0004	0.0075	0.0000	0.9940	659
37	17	0.0008	0.0112	5.1761	1.0000	1803
37	49	0.0084	0.0114	2.1319	1.0000	1324
39	40	0.0024	0.0277	0.0718	1.0000	186
39	41	0.0107	0.0538	0.1982	1.0000	386
39	45	0.0049	0.0381	0.1503	1.0000	614
40	44	0.0072	0.0525	0.2354	1.0000	104
40	48	0.0032	0.0341	0.2784	1.0000	580
40	11	0.0041	0.0770	0.1956	1.0000	123
41	42	0.0060	0.0450	0.1841	1.0000	200
41	10	0.0079	0.0593	0.2428	1.0000	98
44	47	0.0024	0.0176	0.0788	1.0000	319
45	48	0.0025	0.0185	0.0829	1.0000	110
46	48	0.0015	0.0110	0.0494	1.0000	295
47	11	0.0006	0.0068	0.0556	1.0000	939
49	25	0.0014	0.0208	0.0000	1.0000	579
49	4	0.0014	0.0208	0.0000	1.0000	535

Bus		R	X	1/2B	a	Rating
NL	NR	p.u.	p.u.	p.u.		MVA
50	12	0.0025	0.0184	0.0828	1.0000	487
50	51	0.0014	0.0103	0.0463	1.0000	271
50	13	0.0026	0.0192	0.0877	1.0000	416
53	13	0.0018	0.0197	0.1667	1.0000	117
54	55	0.0020	0.0163	0.0617	1.0000	240
54	14	0.0027	0.0213	0.3219	1.0000	881
55	56	0.0196	0.1545	0.1456	1.0000	39
55	57	0.0111	0.0883	0.0886	1.0000	24
56	16	0.0029	0.0216	0.0945	1.0000	105
57	56	0.0084	0.0689	0.0673	1.0000	59

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