CHAPTER5

EXPERIMENTAL RESULTS

5.1 Problem formulation of single-objective function

The single-objective function is formulated as maximization of TTC represented by 5.1. Power transfer capability is defined as TTC value, which can be transferred from generators in source buses to load buses in power systems subjected to real and reactive power generations limits, voltage limits, line flow limits, and FACTS controllers operating limits.

The sum of real power loads in the load buses at the maximum power transfer is defined as the TTC value. Four types of FACTS controllers include: TCSC, TCPS, UPFC, and SVC. TCSC is modeled by the adjustable series reactance [16]. TCPS and UPFC are modeled using the injected power model [17]. SVC is modeled as shunt-connected static var generator or absorber [18].

Maximize

$$F = \sum_{i=1}^{ND\_SNK} P_{Di} \tag{5.1}$$

Subject to

$$P_{Gi} - P_{Di} + \sum_{k=1}^{m(i)} P_{Pk}\left(\alpha_{Pk}\right) + \sum_{k=1}^{n(i)} P_{Uk}\left(V_{Uk}, \alpha_{Uk}\right) - \sum_{j=1}^{N} V_i V_j Y_{ij}\left(X_S\right)\cos\left(\theta_{ij}\left(X_S\right) - \delta_i + \delta_j\right) = 0 \tag{5.2}$$

$$\begin{aligned} &Q_{Gi} - Q_{Di} + \sum_{k=1}^{m(i)} Q_{Pk}\left(\alpha_{Pk}\right) + \sum_{k=1}^{n(i)} Q_{Uk}\left(V_{Uk}, \alpha_{Uk}\right) + Q_{Vi} \\ &+ \sum_{j=1}^{N} V_i V_j Y_{ij}\left(X_S\right)\sin\left(\theta_{ij}\left(X_S\right) - \delta_i + \delta_j\right) = 0 \end{aligned} \tag{5.3}$$

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max}, \forall i \in NG \tag{5.4}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max}, \forall i \in NG \tag{5.5}$$

$$V_i^{\min} \le V_i \le V_i^{\max}, \forall i \in N \tag{5.6}$$

$$|S_{Li}| \le S_{Li}^{\max}, \forall i \in NL \tag{5.7}$$

$$VCPI_i \le 1, \forall i \in N \tag{5.8}$$

$$|\delta_{ij}| \le \delta_{ij}^{crit}, \forall i \in NL \tag{5.9}$$

$$X_{Si}^{\min} \le X_{Si} \le X_{Si}^{\max} \tag{5.10}$$

$$\alpha_{Pk}^{\min} \le \alpha_{Pk} \le \alpha_{Pk}^{\max} \tag{5.11}$$

$$V_{Uk}^{\min} \le V_{Uk} \le V_{Uk}^{\max} \tag{5.12}$$

$$\alpha_{Uk}^{\min} \le \alpha_{Uk} \le \alpha_{Uk}^{\max} \tag{5.13}$$

$$Q_{Vi}^{\min} \le Q_{Vi} \le Q_{Vi}^{\max} \tag{5.14}$$

$$0 < location_k \le N \text{ or } NL \tag{5.15}$$

where

F the objective function,

$P_{Gi}^{\min}, P_{Gi}^{\max}$ lower and upper limits of real power generation at bus *i*,

$Q_{Gi}^{\min}, Q_{Gi}^{\max}$ lower and upper limits of reactive power generation at bus *i*,

$V_i^{\min}, V_i^{\max}$ lower and upper limits of voltage magnitude at bus *i*,

$S_{Li}^{\max}$ *i*th line or transformer loading limit,

δ_{ij}^{crit} critical angle difference between bus *i* and *j*,

$X_{Si}^{\min}, X_{Si}^{\max}$ lower and upper limits of TCSC at line *i*,

$\alpha_{Pi}^{\min}, \alpha_{Pi}^{\max}$ lower and upper limits of TCPS at line *i*,

$V_{Ui}^{\min}, V_{Ui}^{\max}$ lower and upper voltage limits of UPFC at line *i*

$\alpha_{Ui}^{\min}, \alpha_{Ui}^{\max}$ lower and upper angle limits of UPFC at line *i*,

$Q_{Vi}^{\min}, Q_{Vi}^{\max}$ lower and upper limits of SVC at bus *i*,

N, NL	number of buses and branches,
NG	number of generator buses,
ND_SNK	number of load buses in a sink area,
V_i, V_j	voltage magnitudes at bus i and j,
δ_i, δ_j	voltage angles of bus i and j,
P_{Gi}, Q_{Gi}	real and reactive power generations at bus i,
P_{Di}, Q_{Di}	real and reactive loads at bus i,
$P_{Pi(\alpha Pk)}$	injected real power of TCPS at bus i,
$Q_{Pi(\alpha Pk)}$	injected reactive power of TCPS at bus i,
$P_{Ui(VUk,\alpha Uk)}$	injected real power of UPFC at bus i,
$Q_{Ui(VUk,\alpha Uk)}$	injected reactive power of UPFC at bus i,
$Y_{ij}(X_S)$, $\theta_{ij}(X_S)$	magnitude and angle of the ijth element in bus admittance matrix with TCSC included,
$m(i)$	number of injected power from TCPS at bus i,
$n(i)$	number of injected power from UPFC at bus i,
$\|SLi\|$	ith line or transformer loading,
$VCPI_i$	voltage collapse proximity indicator at bus i,
δ_{ij}	angle difference between bus i and j,
X_S	reactance of TCSC at line i,
α_{Pk}	phase shift angle of TCPS at line i,
V_{Uk}, α_{Uk}	voltage magnitude and angle of UPFC at line i,
Q_{Vi}	injected reactive power of SVC at bus i,

In this thesis, considers voltage collapse proximity indicator (VCPI), thermal line flow limit, and static angle stability constraint. The limits are treated as OPF constraints in (5.6), (5.7), (5.8) and (5.9), respectively. During the optimization, inequality constraints are enforced using a penalty function in (5.16).

$$PF = k_p h(P_{G1}) + k_q \sum_{i=1}^{NG} h(Q_{Gi}) + k_v \sum_{i=1}^{N} h(V_i) + k_s \sum_{i=1}^{NL} h\left(\left|S_{Li}\right|\right) + k_d \sum_{p=1}^{NL} h\left(\left|\delta_{ij,p}\right|\right) + k_{vi} \sum_{i=1}^{N} h\left(VCPI_i\right) \tag{5.16}$$

$$h(x) = \begin{cases} (x - x^{\max})^2 & \text{if } x > x^{\max} \\ (x^{\min} - x)^2 & \text{if } x < x^{\min} \\ 0 & \text{if } x^{\min} \le x \le x^{\max} \end{cases} \tag{5.17}$$

where

PF	penalty function,
x_{min}, x_{max}	lower and upper limits of variable x,
k_p, k_q, k_v	penalty coefficients for real power generation at slack bus, reactive power generation of all PV buses and slack bus, and bus voltage magnitude, respectively, and
k_s, k_d, k_{vi}	penalty coefficients for line loading, angle difference, and voltage stability index, respectively.

The ith particle/individual of all methods is represented by a trial solution vector as (5.18), (5.19), and (5.20).

$$V_i^T = [P_{Gi}, P_{Di}, V_{Gi}, \delta_i, n_i, Loc_i, X_{Si}, \alpha_{pi}, V_{Ui}, \alpha_{Ui}, Q_{Vi}] \tag{5.18}$$

$$n_i = \left[n_1, n_2, n_3, n_4\right] \tag{5.19}$$

$$Loc_i = \left[Loc_1, Loc_2, Loc_3, Loc_4\right] \tag{5.20}$$

where

V_{Gi}	voltage magnitude at bus i in source area excluding slack bus,
δ_i	phase angle at bus i,
n_i	number of FACT controller equal 0 or 1, where i =1, 2, 3, and 4, representing the number of TCSC, TCPS, and UPFC, SVC, respectively,
Loc_i	location vector of type i FACTS controllers, where i =1, 2, 3, and 4, representing the line location of TCSC, TCPS, and UPFC, and bus location of SVC, respectively.

The initial particle/individual is initialized randomly using sets of uniform random number distribution ranging over the limitation of each control variable as (5.21).

$$x_i = x_i^{\min} + u\left(x_i^{\max} - x_i^{\min}\right) \tag{5.21}$$

where

x_i	value of the *i*th element,
$x_i^{\min}, x_i^{\max}$	lower and upper limits of the *i*th element, and
u	uniform random in the interval [0,1].

5.2 Experimental results of single-objective function

IEEE RTS 24-bus, IEEE 30-bus, 118-bus and Thai Power 160-bus systems are used to demonstrate the optimal placement of multi-type FACTS controllers using the hybrid PSO. Test results from the hybrid PSO are compared with those from EP, TS, and PSO. The reactance limit of TCSC in p.u. is $0 \le X_{si} \le 60\%$ of line reactance, phase shifting angle limit of TCPS is $-\frac{\pi}{4} \le X_{si} \le \frac{\pi}{4}$, voltage limit of UPFC is $0 \le V_{Ui} \le 0.1$ p.u., angle limit of UPFC is $-\pi \le \alpha_{Ui} \le \pi$, and reactive power injection limit of SVC is $0 \le Q_{Vi} \le 10$ Mvar. Loads are modeled as constant power factor loads. The population sizes of EP, TS, PSO, and hybrid PSO are set to 30. The maximum iteration numbers of EP, TS, PSO, and hybrid PSO are set to 400. All test systems are evaluated 20 runs for each method. Example of comparison of convergence rate from all methods is shown as Figure 5.1.

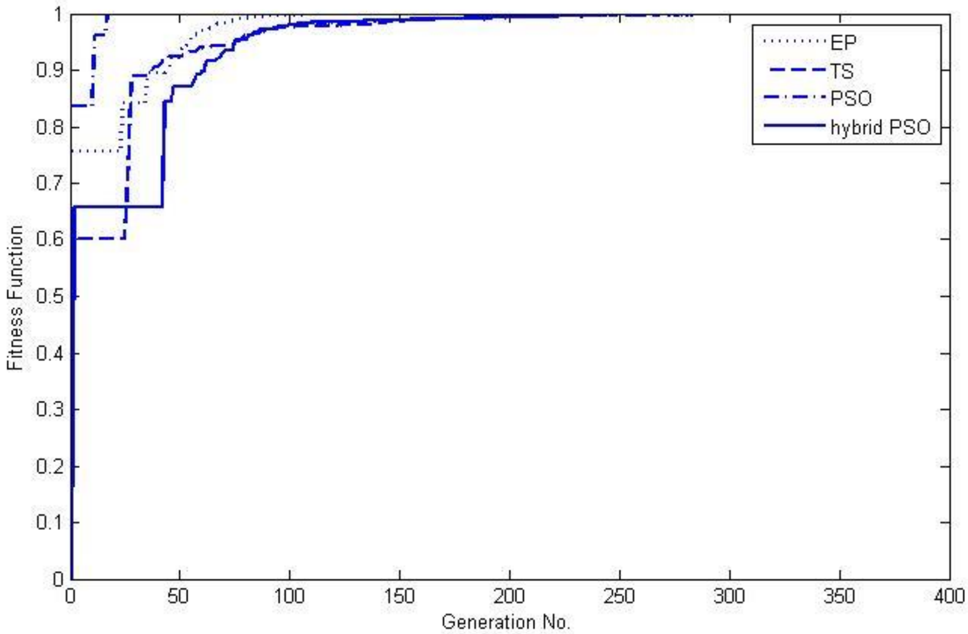

Figure 5.1 Comparison of convergence rate from all methods.

5.2.1 The IEEE RTS 24-bus system

The IEEE RTS 24-bus system, consisting of 10 generating plants, 24 load buses, and 37 lines is used as the first test system. Bus 13 is set as swing bus. Base case TTC of IEEE RTS 24-bus system equals 1131.00 MW.

The hybrid PSO gives higher TTC than EP, PSO, and TS. The best, the average and the worst TTC are 2317.97MW, 2232.90MW, and 2016.31MW, respectively. All of the best, the average, and the worst TTC from hybrid PSO are also better than those from comparing methods. The best optimal allocation of multi-type FACTS controllers from hybrid PSO is represented in Table 5.2.

Table 5.1 TTC Values on the IEEE RTS 24-bus System.

TTC (MW)/Method	EP	TS	PSO	hybrid PSO
Best	2164.71	1131.00	2255.89	2317.97
Average	2051.30	1131.00	2020.31	2232.90
Worst	1994.52	1131.00	1932.37	2016.31
Standard deviation	58.72	0.00	83.48	79.70
CPU time (min)	1.67	1.00	4.65	2.56

Table 5.2 Optimal Placement of FACTS controllers on the IEEE RTS 24-bus System

Type of FACTS Controller /Method	TCSC		TCPS		SVC		UPFC	
	location1	X_S *(p.u.)*	*location2*	α_P *(rad)*	*location3*	Q_v *(Mvar)*	*location4*	α_U *(rad)*, V_U *(p.u.)*
EP	Bus 3-24	0.0127	Bus 15-16	0.0070	Bus 8	0.0521	Bus 12-13	-0.0882, 0.0923
TS	Bus 10-11	0.0464	Bus 9-11	0.0344	Bus 12	0.0158	Bus 15-24	0.8419, 0.0467
PSO	Bus 2-3	0.0807	Bus 16-19	0.0021	Bus 10	0.0041	Bus 17-22	-0.0194, 0.0057
hybrid PSO	Bus 15-24	0.0231	Bus 15-21	0.0001	Bus 24	0.0056	Bus 6-10	-0.0011, 0.0056

5.2.2 The IEEE 30-bus system

The IEEE 30-bus system, consisting of 6 generating plants, 30 load buses, and 41 lines is used as the second test system. Bus 1is set as swing bus. Base case TTC of IEEE 30-bus system equals 164.30 MW.

From Table 5.3, TTC results from hybrid PSO are higher TTC than those from comparing methods. The best, the average and the worst TTC obtained from hybrid PSO are 361.52MW, 284.01MW, and 263.87MW, respectively. The allocation of multi-type FACTS controllers from hybrid PSO is represented in Table 5.4.

Table 5.3 TTC Values on the IEEE 30-bus System.

TTC (MW)/Method	EP	TS	PSO	hybrid PSO
Best	224.61	345.67	228.65	361.52
Average	221.62	269.71	211.13	284.01
Worst	203.79	164.30	202.49	263.87
Standard deviation	10.73	49.02	7.48	21.52
CPU time (min)	6.47	1.09	3.42	8.86

Table 5.4 Optimal Placement of FACTS controllers on the IEEE 30-bus System

Type of FACTS Controller /Method	TCSC		TCPS		SVC		UPFC	
	location1	X_S *(p.u.)*	*location2*	α_P *(rad)*	*location3*	Q_v *(Mvar)*	*location4*	α_U *(rad)*, V_U *(p.u.)*
EP	Bus 10-21	0.0089	Bus 6-7	0.0081	Bus 20	0.0176	Bus 12	0.0001, 0.0213
TS	Bus 6-28	0.0370	Bus 2-3	0.0170	Bus 23	0.0213	Bus 28-27	0.7712, 0.0057
PSO	Bus 15-23	0.0003	Bus 4-6	0.0002	Bus 26	0.0116	Bus 6-8	0.0002, 0.0297
hybrid PSO	Bus 21-22	0.0001	Bus 10-20	0.0532	Bus 17	0.0986	Bus 10-21	0.6662, 0.0540

5.2.3 The IEEE 118-bus system

The IEEE 118-bus system which consists of 54 generating plants, 64 load buses, and 186 lines. Base case TTC of IEEE 118-bus system equals 1433.00 MW. TTC results and average CPU times are showed in Table 5.5.

Better results on the best, average, and the worst TTC values could be obtained by hybrid PSO. The selection mechanism with a probabilistic updating strategy based on TS which aimed to avoid dependency on fitness function, could step over from the local optimal solutions. The allocation of all FACTS controllers are represented in Table 5.6.

Table 5.5 TTC Values on the IEEE 118-bus System.

TTC (MW)/Method	EP	TS	PSO	hybrid PSO
Best	2767.60	3189.60	2979.08	3410.78
Average	2529.94	1905.52	2832.75	3174.95
Worst	2373.30	1433.00	2656.07	2906.22
Standard deviation	126.86	742.61	94.34	132.65
CPU time (min)	40.29	15.51	16.25	16.72

Table 5.6 Optimal Placement of FACTS controllers on the IEEE 118-bus System

Type of FACTS controller /Method	TCSC		TCPS		SVC		UPFC	
	location1	X_S *(p.u.)*	*location2*	α_P *(rad)*	*location3*	Q_v *(Mvar)*	*location4*	α_U *(rad)*, V_U *(p.u.)*
EP	Bus 8-9	0.0005	Bus 89-92	0.0036	Bus 88	0.0798	Bus 93-94	0.0007, 0.0494
TS	Bus 19-20	0.0349	Bus 101-102	0.0090	Bus 12	0.0644	Bus 64-65	-1.4807, 0.0658
PSO	Bus 89-92	0.0817	Bus 80-99	0.0817	Bus 30	0.0990	Bus 89-90	-0.0017, 0.0263
hybrid PSO	Bus 49-51	0.0553	Bus 92-93	0.0430	Bus 18	0.0193	Bus 5-11	0.0581, 0.0693

5.2.4 The Thai power 160-bus system

A practical single line diagram of Thai 230 kV and 500 kV network consists of 42 generating plants, 82 load buses, and 185 lines. Base case TTC of Thai Power 160-bus system equals 11756.01 MW.

Using hybrid PSO, the best TTC value is 12458.64MW, which is 5.64% increased comparing to the base case without FACTS controllers. In addition, the TTC values are obtained by the hybrid PSO higher than those from comparing methods. The optimal placements of FACTS controllers showed in Table 5.7.The optimal placement of FACTS controllers on the Thai Power 160-bus System by using hybrid PSO are shown in Table 5.8

Table 5.7 TTC Values on the Thai Power 160-bus System.

TTC (MW)/Method	EP	TS	PSO	hybrid PSO
Best	12149.46	11756.01	12198.14	12458.64
Average	12099.90	11756.01	12132.43	12425.10
Worst	12067.00	11756.01	12036.25	12372.14
Standard deviation	22.10	0	43.59	23.56
CPU time (min)	136.01	8.84	62.06	449.98

Table 5.8 Optimal placement of FACTS controllers on the Thai power 160-bus System

Type of FACTS Controller /Method	TCSC		TCPS		SVC		UPFC	
	location1	X_S *(p.u.)*	*location2*	α_P *(rad)*	*location3*	Q_v *(Mvar)*	*location4*	α_U *(rad)*, V_U *(p.u.)*
EP	Bus 74-123	0.0650	Bus 62-68	0.0415	Bus 104	0.0446	Bus 43-3	-0.0009, 0.0003
TS	Bus 79-153	0.0352	Bus 92-55	0.0272	Bus 45	0.0648	Bus 79-152	0.5355, 0.0648
PSO	Bus 52-23	0.0086	Bus 76-77	0.0711	Bus 131	0.0938	Bus 79-157	2.5293, 0.0314
hybrid PSO	Bus 62-68	0.0004	Bus 68-55	0.0013	Bus 49	2.0500	Bus 43-3	0.0000, 0.0177

5.3 Problem formulation of multi-objective function

The multi-objective function is formulated as maximization of TTC, minimization of power losses, and minimizing cost of FACTS controller. This is represented by (5.18).

$$\min \quad [\frac{1}{TTC}, Losses, Cost] \tag{5.18}$$

Subject to

$$TTC = \sum_{i=1}^{ND\_SNK} P_{Di} \ , \tag{5.19}$$

$$Losses = \sum_{i=1}^{NL} P_{Li} \ , \tag{5.20}$$

$$Cost = C_{UPFC} + C_{TCSC} + C_{SVC} + C_{TCPS} \ , \tag{5.21}$$

$$C_{UPFC} = 0.0003S_{UPFC}{}^{2} - 0.2691S_{UPFC} + 188.22 \text{,} \tag{5.22}$$

$$C_{TCSC} = 0.0015S_{TCSC}{}^{2} - 0.7130S_{TCSC} + 153.75 \text{,} \tag{5.23}$$

$$C_{SVC} = 0.0003S_{SVC}{}^{2} - 0.3051S_{SVC} + 127.38 \text{, and} \tag{5.24}$$

$$C_{TCPS} = cBP(\overline{ft}) + IC_{TCPS} \text{,} \tag{5.25}$$

where

ND_SNK	number of load buses in a sink area,
P_{Di}	real loads at bus *i*,
Losses	sum of losses in system,
P_{Li}	loss at branch *i*,
Cost	total cost of FACTS controller,
C_{UPFC}, C_{TCSC}, and C_{SVC}	investment costs (US$/KVar) of UPFC, TCSC, and SVC,
C_{TCPS}	investment costs (US$) of TCPS, and
S_{UPFC} , S_{TCSC} , and S_{SVC}	operating range in Mvar of UPFC, TCSC, and SVC..
c	a capital cost of TCPS,
BP	base power 100MVA,
$(\overline{ft})$	power injection of the transmission line where TCPS is to be installed, and
IC_{TCPS}	installation cost of TCPS (US$) [45].

In this section, FCM/S is integrated to EP, TS, PSO, and hybrid PSO. All methods are deployed. The particle/individual numbers of all methods are set to 100. The maximum iteration numbers of all methods are set to 100.

5.4 Experimental results of multi-objective function

5.4.1 The IEEE RTS 24-bus system

In this test system, the hybrid PSO with FCM/S can provide better results of all multi-objective values of best compromise particle than comparing method. TTC from hybrid PSO with FCM/S is 3970.54MW. Especially, loss value by using hybrid PSO with FCM/S is only 16.60 MW. The best compromise optimal allocation of multi-type FACTS controllers from hybrid PSO with FCM/S is represented in Table 5.7. The Pareto-optimal fronts of IEEE RTS 24-bus by using the proposed hybrid PSO with FCM/S is shown as Figure 5.2.

Table 5.9 TTC Values, Cost of FACTS controller and Losses on the IEEE RTS 24-bus system.

Method/ Multi-objective value	TTC (MW)	1/TTC	Cost of FACT controller (M$)	Losses (MW)
EP with FCM/S	3651.71	0.00027384	75.0849	22.09
PSO with FCM/S	3884.87	0.00025741	74.9250	22.11
TS with FCM/S	1530.89	0.00065321	74.9698	53.82
hybrid PSO with FCM/S	3970.54	0.00025185	50.8315	16.60

Table 5.10 Optimal Placement of FACTS controllers on the IEEE RTS 24-bus System

Type of FACTS Controller /Method	TCSC		TCPS		SVC		UPFC	
	location1	X_S *(p.u.)*	*location2*	α_P *(rad)*	*location3*	Q_v *(Mvar)*	*location4*	α_U *(rad)*, V_U *(p.u.)*
EP with FCM/S	Bus 15-16	0.0377	Bus 15-21	0.0728	Bus 11	0.0626	Bus 16-17	-0.4317, 0.0366
TS with FCM/S	Bus 17-22	0.0944	Bus 9-11	0.0251	Bus 16	0.0005	Bus 20-23	0.0018, 0.9473
PSO with FCM/S	Bus 12-13	0.0135	Bus 21-22	0.0237	Bus 15	0.0763	Bus 12-23	-2.9000, 0.0870
hybrid PSO with FCM/S	Bus 21-22	0.0348	Bus 2-6	0.0628	Bus 21	0.0845	Bus 20-23	-0.0559, 0.0957

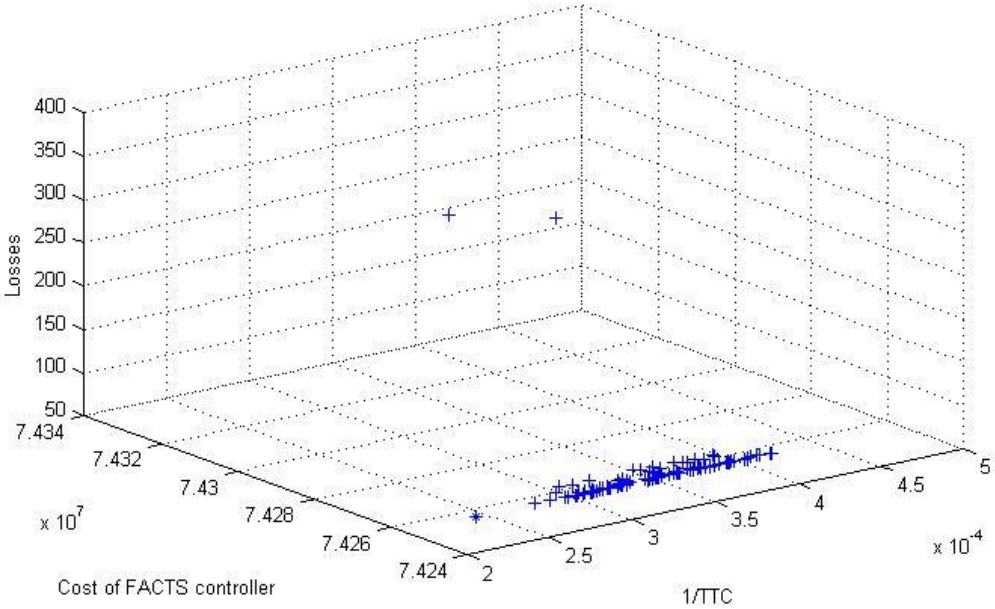

Figure 5.2 Pareto-optimal fronts of IEEE RTS 24-bus by using
the proposed hybrid PSO with FCM/S.

5.4.2 The IEEE 30-bus system

In this test system, the hybrid PSO with FCM/S can provide better cost of FACTS controller and give less loss values of best compromise particle, compared to other comparing method. The best compromise optimal allocation of multi-type FACTS controllers from hybrid with FCM/S is represented in Table 5.11. The Pareto-optimal fronts of IEEE 30-bus by using the proposed hybrid PSO with FCM/S showed as Figure 5.3.

Table 5.11 TTC Values, Cost of FACTS controller and Losses on the IEEE 30-bus system.

Method/ Multi-objective value	TTC (MW)	1/TTC	Cost of FACT controller (M$)	Losses (MW)
EP with FCM/S	435.52	0.00229611	75.1159	32.46
PSO with FCM/S	408.338	0.00244895	75.2096	42.44
TS with FCM/S	374.68	0.00266894	75.2473	40.59
hybrid PSO with FCM/S	420.64	0.00237733	51.6015	11.50

Table 5.12 Optimal Placement of FACTS controllers on the IEEE 30-bus System

Type of FACTS Controller /Method	TCSC		TCPS		SVC		UPFC	
	location1	X_S *(p.u.)*	*location2*	α_P *(rad)*	*location3*	Q_v *(Mvar)*	*location4*	α_U *(rad),* V_U *(p.u.)*
EP with FCM/S	Bus 14-15	0.0855	Bus 12-14	0.0600	Bus 15	0.0168	Bus 10-22	0.0024, 0.0954
TS with FCM/S	Bus 27-29	0.0840	Bus 12-13	0.0645	Bus 4	0.0994	Bus 6-8	-1.7306, 0.0221
PSO with FCM/S	Bus 1-3	0.0646	Bus 12-16	0.0324	Bus 8	0.0520	Bus 12-14	-0.0805, 0.0742
hybrid PSO with FCM/S	Bus 21-22	0.0531	Bus 1-2	0.0912	Bus18	0.0167	Bus 6-8	1.3879, 0.0351

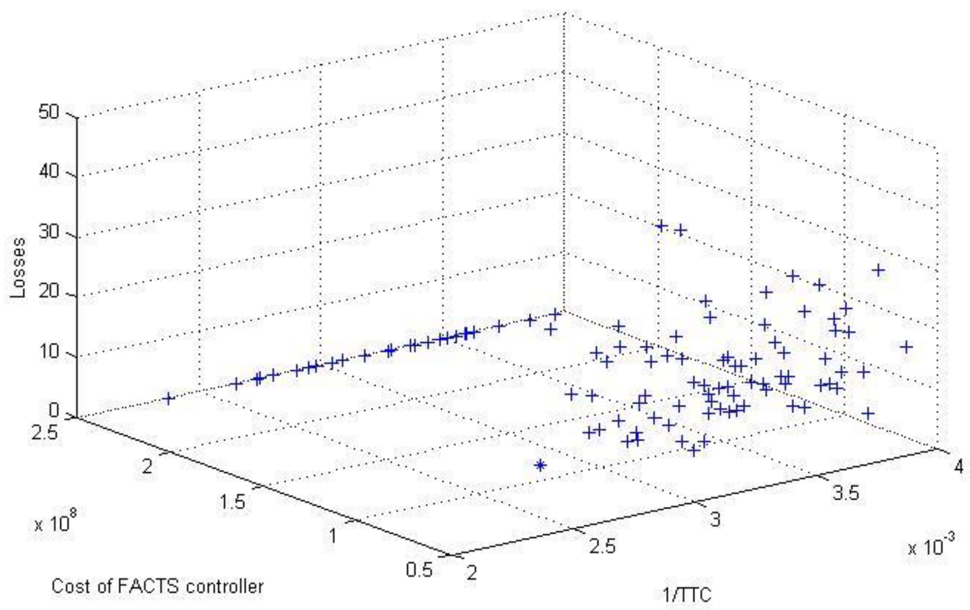

Figure 5.3 Pareto-optimal fronts of IEEE 30-bus by using the proposed hybrid PSO with FCM/S.

5.4.3 The IEEE 118-bus system

In this test system hybrid PSO with FCM/S can provide better all multi-objective values of best compromise particle than comparing method.TTC from hybrid PSO with FCM/S is 3509.31MW, cost of FACTS controller is 23.5100 M$, and loss is 35.92 MW. The Pareto-optimal fronts of IEEE 118-bus by using the proposed hybrid PSO with FCM/S is shown as Figure 5.4.

Table 5.13 TTC Values, Cost of FACTS controller and Losses on the IEEE 118 bus system.

Method/ Multi-objective value	TTC (MW)	1/TTC	Cost of FACT controller (M$)	Losses (MW)
EP with FCM/S	3205.43	0.00031197	235.6475	39.93
PSO with FCM/S	3675.89	0.00027204	75.2407	300.22
TS with FCM/S	1456.83	0.00068642	74.9744	141.41
hybrid PSO with FCM/S	3509.31	0.00028496	23.5100	35.92

Table 5.14 Optimal Placement of FACTS controllers on the IEEE 118-bus System

Type of FACTS Controller /Method	TCSC		TCPS		SVC		UPFC	
	location1	X_S *(p.u.)*	*location2*	α_P *(rad)*	*location3*	Q_v *(Mvar)*	*location4*	α_U *(rad)*, V_U *(p.u.)*
EP with FCM/S	Bus 24-70	0.0875	Bus 23-32	0.0039	Bus 71	0.0865	Bus 80-97	0.6153, 0.0837
TS with FCM/S	Bus 37-29	0.0333	Bus 26-30	0.0792	Bus 25	0.0752	Bus 114-115	-0.0793, 0.0631
PSO with FCM/S	Bus 104-105	0.0833	Bus 71-73	0.0268	Bus 58	0.0052	Bus 11-12	-3.0301, 0.0968
hybrid PSO with FCM/S	Bus 8-9	0.0060	Bus 89-92	0.0345	Bus 88	0.0553	Bus 89-90	0.8116, 0.0607

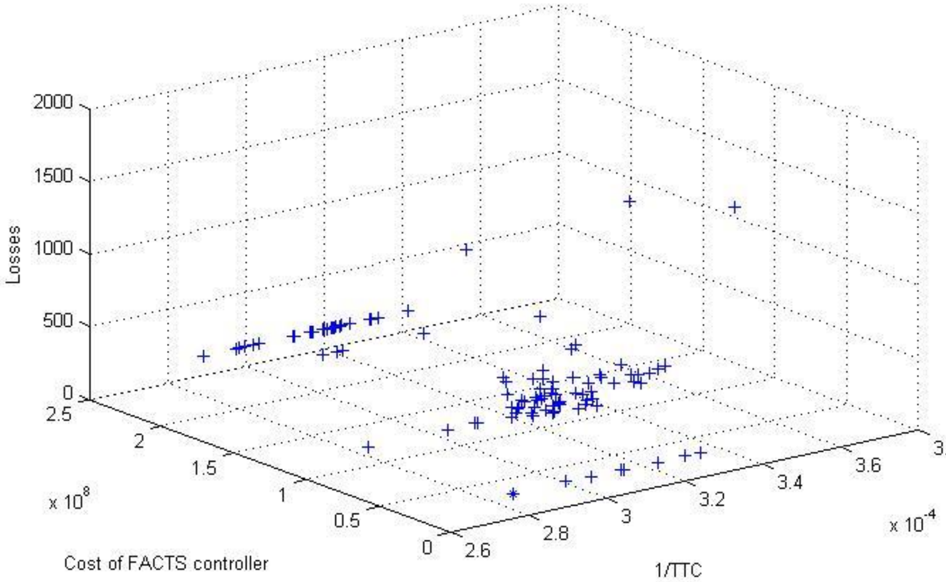

Figure 5.4 Pareto-optimal fronts of IEEE 118-bus by using the proposed hybrid PSO with FCM/S.

5.4.4 The Thai Power 160-bus system

In this test system hybrid PSO with FCM/S can provide better TTC and cost of FACTS controller of best compromise particle than other comparing method. TTC from hybrid PSO with FCM/S is 32723.54 MW and cost of FACTS controller is 32.9104 M$. The Pareto-optimal fronts of Thai power 160-bus by using the proposed hybrid PSO with FCM/S showed as Figure 5.5.

Table 5.15 TTC Values, Cost of FACTS controller and Losses on the Thai Power 160-bus system.

Method/ Multi-objective value	TTC (MW)	1/TTC	Cost of FACT controller (M$)	Losses (MW)
EP with FCMS	29898.73	0.00003344	23.6364	27.46
PSO with FCMS	32576.30	0.00003069	22.9653	49.48
TS with FCM/S	11902.42	0.00008401	74.8262	252.41
hybrid PSO with FCM/S	32723.54	0.00003055	32.9104	48.78

Table 5.16 Optimal Placement of FACTS controllers on the Thai Power 160-bus System

Type of FACTS Controller /Method	TCSC		TCPS		SVC		UPFC	
	location1	X_S *(p.u.)*	*location2*	α_P *(rad)*	*location3*	Q_v *(Mvar)*	*location4*	α_U *(rad)*, V_U *(p.u.)*
EP with FCM/S	Bus 49-76	0.0111	Bus 100-147	0.0632	Bus 132	0.0338	Bus 148-82	2.3931, 0.0055
TS with FCM/S	Bus 87-90	0.0762	Bus 48-75	0.0170	Bus 18	0.0405	Bus 154-59	-1.4190, 0.0935
PSO with FCM/S	Bus 72-74	0.0031	Bus 153-154	0.0554	Bus 81	0.0660	Bus 91-46	2.4778, 0.0276
hybrid PSO with FCM/S	Bus 62-68	0.0420	Bus 52-22	0.0038	Bus 89	0.0029	Bus 97-56	-0.5026, 0.0218

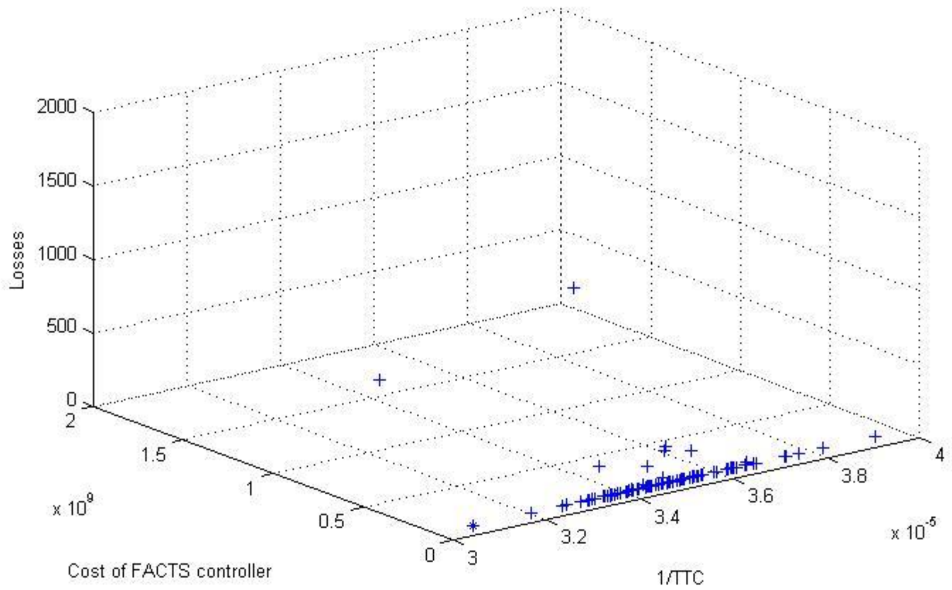

Figure 5.5 Pareto-optimal fronts of Thai Power 160-bus by using the proposed hybrid PSO with FCM/S.