Self-adaptiveness in particle swarm optimisation to enhance available transfer capability using thyristor-controlled series compensation (TCSC)

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MS received 1 August 2017; revised 12 October 2017; accepted 16 October 2017; published online 1 August 2018

Abstract. Available transfer capability (ATC) is one of the challenging criteria under the functioning of the deregulated power system. The high demand for improving ATC is generally met using flexible alternating current transmission system (FACTS) devices in the power system. However, it suffers from serious crisis during determination of the optimal location and compensation stage of FACTS. The present study uses thyristor-controlled series compensation (TCSC) devices in order to compensate for the limitation of FACTS. Further, a novel self-adapted particle swarm optimisation (SAPSO) algorithm is proposed in this study for enhancing ATC. Experiments are carried on three benchmark bus systems such as IEEE 24, IEEE 30 and IEEE 57. Performance and statistical analyses are carried out by comparing the proposed SAPSO with the conventional PSO. Eventually, the study proves the effectiveness of the proposed method in case of ATC enhancement.

Keywords. Power system; ATC; TCSC; SAPSO.

1. Introduction

The problems associated with the power system are solved using knowledge-based decision-making approach by majority of scientists till date. Among such promising methods, the artificial intelligent method plays a vital role in solving problems in the power system [1, 2]. There are diverse techniques such as bio-inspired optimisation algorithms, swarm intelligence, and Chaos theory that are classified as Artificial Intelligence (AI) algorithms [3–5]. Available Transfer Capability (ATC) is considered as the main factor in power system [1, 6]. Since there is a limitation in power system due to the reorganisation of the power system and rise of startling in demand of power, the system should be operated under the standard limits [7–9]. Furthermore, security and reliability of the power system is highly increased with ATC enhancement [10].

Currently, there is a limitation for the enhancement of ATC [11, 12], because broadening of the transmission network destroys the network [13]. Furthermore, these problems are solved by the flexible alternating current transmission system (FACTS) devices with improved strength as these devices handle the rearrangement of flow of lines and control of voltage [2, 14–16]. However, it is not cost-efficient [6, 15]. Since the FACTS devices are highly rewarding, they are mainly used for the purpose of ATC

enhancement [17–20]. Therefore, solving the problem associated with the improvement of ATC appears to be an individual optimisation problem or individual decision-making problem or both. Optimisation problems are generally categorised as multi-objective optimisation and single-objective optimisation [4]. Amid the diverse types, the proposed SAPSO plays a vital role in solving the optimisation problems under the power system [21, 22], which is implemented in this study.

2. Literature review

2.1 Related works

Several recent methodologies related to the optimisation of the FACTS devices have been developed. Initially, the ATC was improved by Rashidinejad *et al* [23] effectively using the real genetic algorithm (GA). Further, Nireekshana *et al* [10] have proposed the novel technique using a few FACTS devices such as thyristor-controlled series compensation (TCSC) and Static Var Compensator in order to enhance the ATC. In the aforementioned work, real coded GA was used so that the compensating reactance and most advantageous location related with FACTS devices was selected. Experiments were performed on both IEEE 14-bus system and IEEE 24-bus system under emergency as well as normal conditions. Accordingly, Farahmand *et al* [20]

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developed hybrid PSO to improve the ATC. This algorithm has been adapted greatly to solve multi-objective problems, and the experiment was carried out in IEEE 30-bus system and IEEE 57-bus system. Further, the Bacterial Swarm Optimisation (BSO)-based ATC improvement method was implemented by Ali and Abd-Elazim [6]. Similarly, the total transfer capability (TTC) was enhanced using a probabilistic-based method that extracted the features of the probabilistic modelling in a study by Khaburi and Haghi-fam [24]. The improvement of TTC directly enhances the ATC. Although the methods mentioned earlier have the advantage of enhancing the ATC, they suffer from the diverse drawbacks that affect the operation of the power system in case of improving the ATC [25–27]. Hence, it is difficult to attain the objective due to progressive demand in power system. Further, the convergence speed of the operation is highly affected by the cost [23] and the multi-objective problems arising in the functioning of the power system are complex [20]. Arijit De *et al* [28] formulated a model by exploiting the PSO-CP (Composite Particle) method. The proposed PSO-CP assists in escaping from the local optima and consistently achieving near-optimal point. Alexandridis *et al* [29] presented a cooperative PSO framework which permits for exploiting variable-width basis functions. This method was utilised to avoid the excessive number of design variables. De *et al* [30] presented an effective search heuristics named PSO-CP method, and a mathematical model is developed to address a maritime inventory routing problem. Hamed Soleimani and Govindan Kannan [31] presented a comprehensive model and a novel PSO-GA hybrid method to solve several kinds of problems in the field of closed-loop supply chain (CLSC). De *et al* [32] worked on ship routing and scheduling problem, and this is formulated as a Mixed Integer Non-Linear Programming Model (MINLP) solved by PSO-CP.

2.2 Research gaps

Several researchers have worked extensively on optimisation of the FACTS devices. In ref. [23], a GA method has been developed to avoid being trapped into local optimal solutions. However, a GA method does not scale well with complexity. In refs. [20, 29, 31], a hybrid PSO has been developed to solve systems of non-linearity, and it can be used to overcome the difficulty of inaccuracy occurring in PSO. Nonetheless, it does not support multi-level linear programming problem. In contrast, a GA [97] has some advantages such as security, and it ensures large key space, but it is statistically more complex. The BSO used in ref. [6] shows that it can easily perform local search. Conversely, the convergence rate of this method is slow. Moreover, the probabilistic-based method used in Ref. [24] has shown its advantages such as ease of use and

convenience, but it is time consuming. The PSO-CP approach was used in [28, 30, 32], which has maintained the entire population diversity by modeling all particles. However, it suffers from solving the numerical optimisation problems.

According to the review, earlier studies have the advantage of improving the ATC. However, there are several disadvantages affecting the operation of the power system in case of enhancing the ATC. Therefore, it is necessary to enhance the ATC using the advanced meta-heuristic optimisation algorithm.

Contribution: The main contribution of this paper is to propose an SAPSO method to solve the optimisation problems under the power system. Also, the proposed method is exploited to optimise the maximum ATC in power transmission system. Moreover, TCSC devices are utilised in the present study instead of FACTS devices.

3. Enhancement model of ATC

3.1 ATC basics

As the requirement of electricity is increased, the producers and the consumers of the power transmission system are moving in a deregulated manner. So, a single transmission system of power is used for conveying power between the generator part and consumer part. In electricity market, the number of generators can be vary that leads to the occurrence of overcapacity and jamming. Since congestion and overloading are increased, there is destruction in the flow of transmission line and the stability limit and voltage limits are increased. These issues highly affect the ATC of the power system, as ATC greatly helps to provide protection and consistency to the system. Open Access Same Time Information System (OASIS) is kept to update the ATC continuously, therefore estimation of ATC becomes tedious part. By general definition, “ATC is a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses.” The common formulation of ATC is represented in Eq. (1), where V^{ETC} represents the existing transmission commitments (ETC), V^{TTC} represents the TTC, V^{CBM} represents the capacity benefit margin (CBM), and V^{TRM} represents the transfer reliability margin (TRM). The definition of ATC with the clear description of TTC, TRM, ETC and CBM is shown in figure 1.

$$V^{ATC} = V^{TTC} - V^{TRM} - (V^{ETC} + V^{CBM}) \quad (1)$$

The description related to the other parameters of ATC such as TRM, CBM and TTC follows.

TRM: TRM refers to the measure of transmission ability of the power transfer, which is required to establish the security of the interrelated system. For the above

Figure 1. ATC definition.

measurement, the power system may be linked with few uncertainties that remain in the system.

CBM: CBM refers to the measure of transmission ability of power transfer by satisfying the needs of reliable generation. Here, the components available for easing the load are highly utilised to operate under the interconnected system.

TTC: TTC refers to the measure of the total power transferred through the system in such a way that the entire set of defined pre-contingency as well as post-contingency system conditions is satisfied.

3.2 ATC determination

There have been several experiments associated with the increment of ATC in the past few years, which have been reviewed by diverse researchers. For instance, the contour of the security boundary was considered by Li and Liu [33] for ATC determination. Further, Vaithilingam and Kumudini Devi [34] have estimated the ATC using the Support Vector Machine. Since the advent of techniques for the estimation of ATC has increased year by year, their fictional techniques are categorised into two types: (i) based on distribution factors and (ii) based on Continuous Power Flow (CPF) [35]. The aforementioned methods are used in case of DC or AC power flows. However, this experimentation is not effective as it does not need any complexity and breakdown to produce the accurate result for the overall operation for ATC determination [23]. Moreover, the CPF approaches are mainly adopted as they use the addition of linear variation at the class of buses to obtain the optimum value [3]. Therefore, the controlling parameters associated with the experimentation under CPF are moving in a linear manner. Thus, it requires the rectification process after the completion of each iteration. The present study completely depends on the power flow for the estimation of ATC.

3.3 Objective function

Let us consider a classic bus system connected with a few external devices. The ATC should be estimated for the

power system. Subsequently, this study focuses on the estimation of ATC of the system accessible with TCSC. The requirement of external devices under such instances is less as the number of TCSC to be connected depends on the users. The objective problem model is represented in Eq. (2), where A_t indicates the group of line indices and B_t indicates the compensation level of t^{th} TCSC in the bus system, $[A_t^*, B_t^*]$ represents the best connection in the group of line.

$$[A_t^*, B_t^*] = \arg \max_{[A_t, B_t]} ATC; 0 \leq t \leq N_T - 1 \quad (2)$$

4. ATC enhancement by SAPSO

4.1 Standard PSO

PSO [21, 22] is the type of evolutionary algorithm introduced by Kennedy and Eberhart in 1995. The operation of PSO is based on the behaviour of flocking of birds to solve the optimisation problems. Thus, the PSO algorithm is named as the effective optimisation algorithm in real time. Starting with the execution of PSO algorithm, a random solution is initialised, and the optimum solution is searched through updating the generations. Each particle P_m comprises the position vector, velocity vector and memory vector. The position vector is represented by X_m , the velocity vector is represented by V_m and memory vector is represented by X_m^{best} . The solution associated with the problem of optimisation is provided by the position vector, whereas the best solution derived with the search of one particle is considered as the memory vector. The particle flies with particular velocity in the dimensional space, where the velocity is attuned according to the flying skill of the corresponding particle along with its colleagues. The particle may search for its better position though this operation. Subsequently, the particle is updated as in Eq. (3), whereas the updating of the velocity is represented in Eq. (4), where r_1 and r_2 represents the random variables that are equally distributed and in the range of $[0,1]$, c_1 and c_2 represents the accelerating constants, X_g^{best} represents the best solution searched by entire particles, and w_m represents the inertia weight of the particle. The convergence speed of the algorithm completely depends on the inertia weight.

$$X_m(t+1) = X_m(t) + V_m(t+1) \quad (3)$$

$$V_m(t+1) = w_m V_m(t) + c_1 r_1 (X_m^{best}(t) - X_m(t)) + c_2 r_2 (X_g^{best}(t) - X_m(t)) \quad (4)$$

The pseudo-code of the standard PSO algorithm is illustrated as follows.

ALGORITHM:1	PSEUDO	CODE	OF
STANDARD PSO			
Set the value of c_1 , c_2 , r_1 and r_2			
Initialise the particles m , $m = 1, 2, \dots, N$			
For each m			
Randomly initialise X_m and V_m			
Compute the fitness function from X_m as $f(X_m)$			
Identify the best position X_m^{best} and find its fitness function $f(X_m^{best})$			
If $f(X_m) > f(X_m^{best})$, then			
Set $X_m^{best} = X_m$			
end			
Identify the best solution X_g^{best} of entire particle and find its fitness $f(X_g^{best})$			
If $f(X_m^{best}) > f(X_g^{best})$, then			
Set $X_g^{best} = X_m^{best}$			
end			
Update the position using eq. (3)			
Update the velocity using eq. (4)			
end			
Continue till maximum iteration			

4.2 Proposed SAPSO

The SAPSO is an algorithm based on balancing the inertia weight, which is set as a self-improvement strategy. Here the inertia weight is updated based on the fitness function obtained at each position of the particles. Since the weight is updated, the adaptive solution is obtained, which satisfies the enhancement of ATC. The position of the particle in each iteration should be evaluated by adapting the inertia weight at each iteration. After completion of each iteration, the self-improvement ratio must be calculated, and the inertia weight should be increased with respect to the ratio. Computation of inertia weight based on the self-adaptive procedure is represented in Eq. (5), where $r_m(t+1)$ represents the random variable distributed at $(t+1)^{th}$ iteration and $\partial_m(t+1)$ represents the ratio associated with the self-improvement at $(t+1)^{th}$ iteration, which is expressed in Eq. (6). The fitness function of m^{th} particle at t^{th} and $(t-1)^{th}$ iterations are denoted as $f(X_m(t))$ and $f(X_m(t-1))$. Accordingly, the final global fitness $f(X_g^{best})$ is the ATC measurement.

$$w_m(t+1) = w_m(t) + [r_m(t+1) * (w_m(t) - w_m(t-1) * \partial_m(t+1))] \quad (5)$$

$$\partial_m(t+1) = \frac{f(X_m(t)) - f(X_m(t-1))}{f(X_m(t))} \quad (6)$$

The pseudo-code of the proposed SAPSO is illustrated as follows.

ALGORITHM:1	PSEUDO	CODE	OF
PROPOSED SAPSO			
1. Set the value of c_1 , c_2 , r_1 and r_2			
2. Initialise the particles m , $m = 1, 2, \dots, N$			
3. For each m			
4. For first iteration $t = 0$			
5. Randomly initialise w_m , X_m and V_m			
6. Compute the fitness function from X_m as $f(X_m)$			
7. Identify the best position X_m^{best} and find its fitness function $f(X_m^{best})$			
8. If $f(X_m) > f(X_m^{best})$, then			
9. Set $X_m^{best} = X_m$			
end			
10. Identify the best solution X_g^{best} of entire particle and find its fitness $f(X_g^{best})$			
11. If $f(X_m^{best}) > f(X_g^{best})$, then			
12. Set $X_g^{best} = X_m^{best}$			
end			
end			
13. Compute the self improvement ratio using eq. (6)			
14. For second iteration $t = 1$			
15. Update the position using eq. (3)			
16. Update the velocity using eq. (4)			
17. Repeat the steps (6) to (13)			
end			
18. Continue till maximum iteration			

The flowchart of the SAPSO for the ATC enhancement is shown in figure 2.

The pseudo-code and the flowchart of SAPSO algorithm are elucidation as follows.

1. The accelerating constants c_1 , c_2 and the random variables r_1 and r_2 are set in the initial stage.
2. The total number of particles is considered as m and the number of particles should be initialised.
3. The position X_m and velocity V_m of the particle are initialised.
4. In the first iteration at $t = 0$, the weight w_m should be randomly initialised.
5. Subsequently, the best position X_m^{best} is identified and along with it, the fitness function of X_m^{best} is computed which is represented as $f(X_m^{best})$.
6. If the fitness function of the current position is greater than the fitness function of the best position of the particle, then the best position is replaced by the current position.
7. Further, the best position of the entire particle X_g^{best} is identified, and along with it, the fitness function of X_g^{best} is computed that is represented as $f(X_g^{best})$.
8. If the fitness function of the best position is greater than the fitness of the global best position, then the global best position is replaced by the best position.

Figure 2. Flowchart of Self-Adaptive PSO algorithm.

9. The self-improvement ratio $\partial_m(t+1)$ is calculated using Eq. (6) after the each iteration.
10. In the second iteration at $t=1$, the weight w_m is improved using Eq. (5) along with the updating of the position and velocity of the particle using Eq. (3) and Eq. (4) and it repeats the steps from 4 to 8.
11. The aforementioned procedure is repeated till the completion of an entire iteration.

5. Results and discussions

5.1 Experimental procedure

The experimentation regarding the ATC enhancement in power system was carried on IEEE 24, IEEE 30 and IEEE 57 benchmark test bus systems. The corresponding experimentation was performed using the proposed SAPSO. The result obtained from the proposed SAPSO was compared with that from the conventional PSO. Basically, the ATC enhancement was estimated under two TCSC connections as per the literature. However, this study indents to estimate under five TCSC connections. The statistical report of the three bus system was taken and analysed, which are illustrated in the proceeding sub-sections.

5.2 ATC enhancement performance on IEEE 24 bus system

The performance of IEEE 24 test bus system for ATC enhancement by SAPSO is shown in table 1. The tabulation provides the information regarding the line number, the connection from the bus and to the bus and the

Table 1. Performance of ATC enhancement on IEEE 24 test bus system.

TCSC	Connections	2 TCSCs		3 TCSCs		4 TCSCs		5 TCSCs	
		PSO	SAPSO	PSO	SAPSO	PSO	SAPSO	PSO	SAPSO
1	Line no	28	22	22	7	37	36	21	15
	From bus/ to bus	16/17	13/23	13/23	3/24	20/23	20/23	12/23	9/12
	Compensation (p.u) $\times 10^{-3}$	0.17924	-0.2629	0.7	0.06034	-0.39509	0.28118	-0.7	0.23769
2	Line no	38	37	38	22	36	22	38	22
	(From bus/ to bus)	21 /22	20/23	21/22	13 /23	20/23	13/23	21/22	13/23
	Compensation (p.u) $\times 10^{-3}$	0.16065	-0.626	0.7	0.54866	-0.11985	-0.2365	-0.32637	-0.26575
3	Line no	0	0	38	10	14	1	38	26
	From bus/ to bus	0/0	0/0	21/22	6/10	9/11	1/2	21/22	15/21
	Compensation (p.u) $\times 10^{-3}$	0	0	0.7	-0.3373	0.52401	-0.3673	0.7	0.050421
4	Line no	0	0	0	0	5	1	38	38
	From bus/ to bus	0/0	0/0	0/0	0/0	2/6	1/2	21/22	21/22
	Compensation (p.u) $\times 10^{-3}$	0	0	0	0	0.0026373	-0.22587	-0.7	-0.22355
5	Line no	0	0	0	0	0	0	38	38
	From bus/ to bus	0/0	0/0	0/0	0/0	0/0	0/0	21/22	21/22
	Compensation (p.u) $\times 10^{-3}$	0	0	0	0	0	0	0.7	0.17726
ATC (MW) without TCSC		16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6
ATC (MW) with TCSC		184.6	503.3	134.2	244.6	201.4	572.9	107.7	499

Table 2. Performance of ATC enhancement on IEEE 30 test bus system.

TCSC	Connections	2 TCSCs		3 TCSCs		4 TCSCs		5 TCSCs	
		PSO	SAPSO	PSO	SAPSO	PSO	SAPSO	PSO	SAPSO
1	Line no	10	27	14	27	9	41	27	41
	From bus/ to bus	6/8	10/21	9/10	10/21	6/7	6/28	10/21	6/28
	Compensation (p.u) $\times 10^{-3}$	-0.09536	-0.17	-0.14138	-0.17	0.17	0.17	-0.16575	0.17
2	Line no	38	41	10	31	41	9	1	27
	(From bus/ to bus)	27/30	6/28	6/8	22/24	6/28	6/7	1/2	10/21
	Compensation (p.u) $\times 10^{-3}$	-0.049768	0.17	-0.16447	-0.17	0.17	0.14154	0.17	-0.17
3	Line no	38	38	6	41	41	1	13	41
	From bus/ to bus	21/22	21/22	2/6	6/28	6/28	1/2	9/11	6/28
	Compensation (p.u) $\times 10^{-3}$	0.7	0.7	-0.054805	-0.17	-0.17	0.17	0.17	0.17
4	Line no	38	38	38	38	41	41	24	41
	From bus/ to bus	21/22	21/22	21/ 22	21/22	6/28	6/28	19/20	6/28
	Compensation (p.u) $\times 10^{-3}$	-0.7	-0.7	-0.7	-0.7	0.17	0.17	0.15097	0.17
5	Line no	38	38	38	38	38	38	1	1
	From bus/ to bus	21/22	21/22	21/22	21/22	21/22	21/22	1/2	1/2
	Compensation (p.u) $\times 10^{-3}$	0.7	0.7	0.7	0.7	0.7	0.7	0.10555	0.17
ATC (MW) without TCSC		72.7	72.7	72.7	72.7	72.7	72.7	72.7	72.7
ATC (MW) with TCSC		129.6	143.5	140.5	147.9	78.7	78.7	141.7	143.5

compensation. The experimentation is done for a power system with TCSC and without TCSC. Accordingly, the line number of the two TCSCs in the first connection recommends 28 for PSO and 22 for SAPSO, whereas the compensation level is 0.17924 for PSO and -0.26293 for SAPSO. Similarly, the line numbers of 3 TCSC, 4 TCSC, and 5 TCSC for the first connections are 22 for PSO and 7 for SAPSO, 37 for PSO and 36 for SAPSO and 21 for PSO and 15 for SAPSO. The compensation of 3 TCSC, 4 TCSC and 5 TCSC connections are estimated as 0.7 for PSO and 0.06034 for SAPSO, -0.39509 for PSO and 0.28118 for

SAPSO and -0.7 for PSO and 0.23769 for SAPSO. The same procedure is carried out for five connections, and a similar output is obtained. Thus, the ATC enhancement without TCSC connection provides the normal ATC of basic load system. Subsequently, the percentage of ATC measurement with TCSC using the proposed SAPSO method is 172% enhanced than using conventional PSO for two TCSC connections. To the same extent, the percentage of ATC measurement with TCSC for the proposed SAPSO method for 3TCSC, 4TCSC and 5TCSC is 82%, 184%, and 363% better than the conventional PSO.

Table 3. Performance of ATC enhancement on IEEE 57 test bus system.

TCSC	Connections	2 TCSCs		3 TCSCs		4 TCSCs		5 TCSCs	
		PSO	SAPSO	PSO	SAPSO	PSO	SAPSO	PSO	SAPSO
1	Line no	80	49	80	80	80	49	80	42
	From bus/ to bus	9/55	36/37	9/55	9/55	9/55	36/37	9/55	25/30
	Compensation (p.u) $\times 10^{-3}$	0.5	-0.5	0.5	0.5	0.5	-0.5	0.5	-0.49925
2	Line no	80	80	80	49	80	1	80	80
	(From bus/ to bus)	9/55	9/55	9/55	36/37	9/55	1/2	9/55	9/55
	Compensation (p.u) $\times 10^{-3}$	0.5	0.5	0.5	-0.5	0.5	0.5	0.5	0.5
3	Line no	41	41	80	1	80	1	80	49
	From bus/ to bus	6/28	6/28	9/55	1/2	9/55	1/2	9/55	36/37
	Compensation (p.u) $\times 10^{-3}$	0.17	0.17	0.5	0.5	0.5	-0.5	0.5	-0.5
4	Line no	41	41	41	41	80	1	80	1
	From bus/ to bus	6/28	6/28	6/28	6/28	9/55	1/2	9/55	1/2
	Compensation (p.u) $\times 10^{-3}$	0.17	0.17	0.17	0.17	0.5	0.5	0.5	-0.5
5	Line no	1	1	1	1	1	1	80	80
	From bus/ to bus	1/2	1/2	1/2	1/2	1/2	1/2	9/55	9/55
	Compensation (p.u) $\times 10^{-3}$	0.17	0.17	0.17	0.17	0.17	0.17	0.5	-0.5
ATC (MW) without TCSC		3	3	3	3	3	3	3	3
ATC (MW) with TCSC		3	42.9	3	42.9	3	42.9	3	77.1

Table 4. Statistical analysis of IEEE 24, IEEE 30 and IEEE 57 test bus systems.

Bus Statistics	IEEE 24 bus system		IEEE 30 bus system		IEEE 57 bus system	
	PSO	SAPSO	PSO	SAPSO	PSO	SAPSO
Best	330.5	335.8	78.7	143	3	42.9
Worst	86.2	117.4	75.7	75.7	3	3
Mean	201.2	247.4	78.1	101.24	3	24.66
Median	134.2	292.4	78.7	75.7	3	31.5
Standard deviation	115.38	89.512	1.3416	35.083	0	20.313

5.3 ATC enhancement performance on IEEE 30 bus system

The performance regarding the enhancement of ATC of the proposed SAPSO is shown in table 2. The experiment is carried out for basic load system without TCSC and the connection of the power system with TCSC. Further, it is done for 2TCSC, 3TCSC, 4TCSC and 5TCSC under five connections. The line number of 2TCSC is 10 for PSO and 27 for SAPSO. Moreover, the line number of 3 TCSC is 14 for PSO and 27 for SAPSO, 4 TCSC is 9 for PSO and 41 for

SAPSO, and 5 TCSC connection is 27 for PSO and 41 for SAPSO. The same procedure is carried out for five connections. Similarly, the compensation of the ATC enhancement of 2 TCSC is -0.09536 for PSO and -0.17 for SAPSO, 3 TCSC is -0.14138 for PSO and -0.17 for SAPSO, 4 TCSC connections is 0.17 for PSO and 0.17 for SAPSO, and 5 TCSC connection is -0.16575 for PSO and 0.17 for SAPSO. Ultimately, according to the aforementioned performance analysis, the percentage of ATC measurement of the proposed SAPSO for 2TCSC connection is 107% better than PSO; 3TCSC is 52% better than PSO, 4

Figure 3. Demonstration of ATC enhancement for 1000 iterations on (a) IEEE 24 bus system, (b) IEEE 30 bus system and (c) IEEE 57 bus system.

TCSC is same as PSO, and 5 TCSC connections are 12% better than PSO. Thus, from the overall analysis, the proposed SAPSO provides superior performance.

5.4 ATC enhancement performance on IEEE 57 bus system

The performance of ATC enhancement of IEEE 57 test bus system is shown in table 3. First, the line number of each TCSC connection for conventional and proposed PSO is determined. The line number for 2TCSC, 3TCSC, 4TCSC and 5TCSC connections are 80 for PSO and 49 for SAPSO, 80 for PSO and 80 for SAPSO, 80 for PSO and 49 for SAPSO and 80 for PSO and 42 for SAPSO. Similarly, the first set of compensation for 2TCSC, 3TCSC, 4TCSC and 5TCSC connections is 0.5 for PSO and -0.5 for SAPSO, 0.5 for PSO and 0.5 for SAPSO, 0.5 for PSO and -0.5 for SAPSO and 0.5 for PSO and 0.5 for PSO and -0.49925 for SAPSO. Accordingly, the ATC enhancement of the system with and without TCSC is performed individually. The ATC enhancement without TCSC connection is same for both PSO and SAPSO, whereas the enhancement of ATC with TCSC connection for 2TCSC, 3TCSC, 4TCSC and 5TCSC connections for proposed SAPSO are far higher than the conventional PSO algorithm.

5.5 Statistical analysis

The statistical analysis of IEEE 24, IEEE 30 and IEEE 57 bus system is shown in table 4. The best performance of SAPSO on IEEE 24 test bus system is 1.6% better than PSO, and IEEE 30 test bus system is 81% better than PSO, whereas the SAPSO of IEEE 57 test bus system is far better than conventional PSO. Similarly, the worst, mean, median and standard deviation performance of ATC enhancement on IEEE 24, IEEE 30 and IEEE 57 test bus system of proposed SAPSO is higher than conventional PSO algorithm.

The graphical representation of the appearance of ATC enhancement for 1000 iterations on IEEE 24, IEEE 30 and IEEE 57 test bus system is shown in figure 3. In IEEE 24 bus system, ATC measurement of 2TCSC, 3 TCSC, 4 TCSC and 5 TCSC connection of SAPSO is higher than the conventional PSO. On the other hand, the ATC measurement of entire TCSC connection of IEEE 30 test bus system by SAPSO is higher than the conventional PSO. Finally, the IEEE 57 test bus system also provides higher ATC. Thus, it proves that the proposed SAPSO is better than conventional PSO for enhancing ATC in power system.

6. Conclusion

Generally, ATC should be enhanced to improve the reliability of the power system. However, ATC is reduced in some cases when the power system is affected by usage of

overloaded circuits and buses with limited voltage. In this study, SAPSO algorithm was proposed in order to optimize the maximum ATC in power transmission system. Subsequently, this study has used TCSC devices instead of FACTS devices. The simulation setup was carried out on IEEE 24, IEEE 30 and IEEE 57 test bus systems. Further, the statistical analysis of the proposed SAPSO method conducted on the three test bus system was compared with the conventional PSO algorithm. The result obtained from the comparison has proved that the SAPSO enhances ATC measurement with maximum improvement than conventional PSO algorithm.

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