J. Basic. Appl. Sci. Res., 2(4)3416-3425, 2012
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ISSN 2090-4304
Journal of Basic and Applied Scientific Research
www.textroad.com

ATC Enhancement Using SSSC, a Case Study of Harmony Search Vs PSO

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ABSTRACT

Enhancement of Available Transfer Capacity is an important issue in the electric power market. The Available Transfer Capacity of a transmission network is the unutilized transfer capabilities of the network that can be used for the further transfer of power. This paper proposes the use of Static Synchronous Series Compensator in order to alleviate the congestion in transmission lines to maximize the Available Transfer Capacity between desired network buses and compares two optimization methods to reach a more reliable algorithm for this problem. Harmony Search Algorithm is applied and a new method is proposed to restrict the number of lines which should be considered as the candidate of placing the Static Synchronous Series Compensator to speed up the convergence. The optimal size of the Static Synchronous Series Compensator is also found. The results of the proposed method are also drawn using the Particle Swarm Optimization as the method of optimization. These results are compared with those obtained from Harmony Search Algorithm to show the effectiveness of the proposed method in this locating and sizing optimization problem. The proposed method is tested on modified IEEE Reliability Test System as a congested network, and the results are presented and in detail discussed to show the effectiveness of the method.

KEYWORDS: Available Transfer Capacity, Harmony Search, Particle Swarm Optimization, Static Synchronous Series Compensator.

I. INTRODUCTION

Available Transfer Capacity (ATC) is the measure of available capability in a power system network or available room in physical transmission network, beyond the base case loading. In deregulated power systems the network lines are heavily loaded and the ATC for further trades are restricted due to line flow and bus voltage limits.

These new structures of power systems have to deal with the problem of building new transmission lines due to increase in power transactions. Thus the bulky power networks should be expanded further to obtain a high operational efficiency and network security. In this situation, one of the possible alternatives is the use of Flexible AC Transmission System (FACTS) technologies.

FACTS is a progressive technology based solution to aid electric utilities fully utilize their transmission assets other than installing new apparatus to increase the network strength. Since the concept of FACTS with its present applications was introduced by N. G. Hingorani in 1988, different FACTS controllers have been developed each with specific applications [1]. FACTS devices can control the line reactance, bus voltage and line active and reactive power flows. They provide new control facilities, both in steady state power flow control and dynamic stability control.

The circuit reactance, voltage magnitude and phase angle are the control parameters of FACTS devices which are used to re-distribute line flows and regulate voltage profiles. FACTS devices can offer an effective and promising alternative to conventional methods of ATC enhancement.

The Convertor-based controllers have superior performance over the thyristor-based (first generation) controllers [1-2]. The Static Synchronous Series Compensator (SSSC) is one of the second generation FACTS devices which is used in controlling active and/or reactive power-flow through a transmission line. Having this ability SSSC can be used to effectively relive the congestion in the network and let the ATC to be higher.

Reference [3] proposed the use of TCSC and SVC to maximize ATC. The paper demonstrated the virtue of these devices to increase the ATC, but the model which is used for these FACTS devices are not suitable for planning problems, especially when the financial issues are taken into account.

Many methods have been developed to model different FACTS devices in load-flow studies [4–5]. Incorporation of FACTS devices in a load flow algorithm results in more complexity due to the new terms related to these devices. An appropriate model for SSSC is presented in the next section. This model in fact is driven from the Unified Power Flow Controller (UPFC) model which is used successfully in previous works to find the optimal location and size of these FACTS devices.

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Many algorithms are proposed for the calculation of ATC in the literatures. Ejebe [6] used a full AC power flow solution for ATC calculations. The program considered the reactive power flows, voltage limits and voltage collapse, as well as thermal loading effects.

Considering the fast growth in problems' dimensions and great appeal to fast optimization algorithms in recent years, random search algorithms are widely used instead of the overall search in problem space [7].

Geem et al. [8] developed the harmony search algorithm (HSA) as a method that was conceptualized using the musical process of searching for a perfect state of harmony. Compared to the earlier meta-heuristic optimization algorithms, HSA imposes fewer mathematical requirements that can be easily adopted for various types of engineering optimization problems [9]. The potential of HSA in solving complex power system problems are shown in [10]-[11].

Particle swarm optimization (PSO) is another heuristic optimization algorithm that can be and has been used successfully in locating problems. It is a stochastic global optimization approach and its main strength is in its simplicity and fast convergence [12]-[13]. The results of placing algorithm are also drawn using PSO algorithm. These results are compared to those obtained by HSA to show the ability of HSA to solve this optimization problem.

In this paper, we focus on applying the HSA, to find the location and size of the SSSC with the aim of ATC enhancement. This problem is a large-scale optimization with too many binary and continuous variables.

The rest of paper is organized as follows. An appropriate SSSC model is described in section II. Section III gives an overview of Harmony Search Algorithm. Proposed method is presented in section IV. The proposed method is applied on modified IEEE Reliability Test System, and the results are presented and in detail discussed in section V. The conclusion is drawn in Section VI.

II. SSSC Modeling and Formulation

The SSSC is composed of voltage source converter, diodes, a dc link capacitor, and controller connected to transmission line via a coupling transformer [14]. The SSSC can be easily modeled as a special case from UPFC when there is no control for voltage. Fig .1 depicts the equivalent circuit model of SSSC. This model was used in deriving the steady-state model for load flow and static analysis [15] which makes it proper for our study. Auxiliary bus between the existing buses of the system is a reference point of the power flow direction. The SSSC control parameters (voltage source magnitude and angle) limits are as follows:

$$\begin{Bmatrix} V_{SC}^{Min} \le V_{SC} \le V_{SC}^{Max} \\ 0 \le \varphi_{SC} \le 2\pi \end{Bmatrix} \quad (1)$$

Therefore in this paper, for load flow analysis and ATC enhancement, SSSC variables V_{SC} and φ_{SC}, are needed to be optimized.

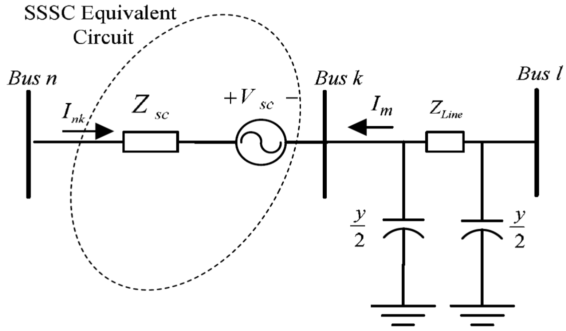

Fig. 1. SSSC static model.

(2) and (3) represent the derivation of the power flow equations of SSSC from bus *n* to bus *l*.

$$\begin{aligned} P_{nl} &= (V_n^2 + V_{SC}^2)g_{nl} + 2V_nV_{SC}g_{nl}cos(\varphi_{SC} - \delta_{nl}) \\ &\quad - V_nV_{SC}(g_{nl}\cos\varphi_{SC} + b_{nl}\sin\varphi_{SC}) \\ &\quad - V_nV_l(g_{nl}\cos\delta_{nl} + b_{nl}\sin\delta_{nl}) \\ Q_{nl} &= -V_nV_{SC}(g_{nl}\sin(\varphi_{SC} - \delta_{nl}) + b_{nl}\cos(\varphi_{SC} - \delta_{nl})) \\ &\quad - V_n^2 b_{ij} - V_nV_l(g_{nl}\sin\delta_{nl} - b_{nl}\cos\delta_{nl}) \end{aligned} \quad (2)$$

$$\begin{aligned} P_{\ln} &= V_n^2 g_{nl} - V_lV_{SC}(g_{nl}cos\varphi_{SC} - b_{nl}\sin\varphi_{SC}) \\ &\quad - V_nV_l(g_{nl}\cos\delta_{nl} - b_{nl}\sin\delta_{nl}) \\ Q_{\ln} &= -V_l^2 b_{nl} - V_lV_{SC}(g_{nl}\sin\varphi_{SC} - b_{nl}\cos\varphi_{SC}) \\ &\quad + V_nV_l(g_{nl}\sin\delta_{nl} + b_{nl}\cos\delta_{nl}) \end{aligned} \quad (3)$$

According to the above relationships, the power injection model of network line with SSSC is implemented in the optimization problem.

III. Harmony Search Algorithm

The harmony search algorithm was derived by adopting the idea that the existing meta-heuristic algorithms are found in the paradigm of natural phenomena. The algorithm was recently developed in an analogy with music improvisation process where music players improvise the pitches of their instruments to obtain better harmony [7]. The pitch of each musical instrument determines the aesthetic quality, just as the objective function value is determined by the set of values assigned to each decision variable [8]. Steps of optimization procedure of HSA are as follows [10], [11]:

Step 1. Initialize the optimization problem and algorithm parameters.
Step 2. Initialize the harmony memory (HM).
Step 3. Improvise a new harmony from the HM.
Step 4. Update the HM.
Step 5. Repeat steps 3 and 4 until the termination criterion is satisfied.

III.1. Initialization of the Optimization Problem and Algorithm Parameters

In this step the optimization problem is specified as follows:

Minimize $f(x)$

Subject to $x_i \in X_i$, i= 1, 2, . . . , N

where $f(x)$ is the objective function; x is a candidate solution consisting of N decision variables (x_i); X_i is the set of possible range of values for each decision variable, that is, ${}_L x_i \le X_i \le {}_U x_i$ for continuous decision variables where ${}_L x_i$ and ${}_U x_i$ are the lower and upper bounds for each decision variable, respectively; and N is the number of decision variables. In addition, HSA parameters that are required to solve the desired optimization problem are specified in this step. These parameters are the harmony memory size (HMS) or the number of solution vectors, harmony memory considering rate (HMCR), pitch adjusting rate (PAR), and termination criterion (maximum number of searches). HMCR and PAR are parameters that are used to improve the solution vector; both are defined in step 3.

III.2. Initialization of the Harmony Memory

In this step, the harmony memory (HM) matrix, shown in Eq. (4), is filled with as many randomly generated solution vectors as HMS and sorted by the values of the objective function, $f(x)$.

$$HM=\begin{bmatrix} x^1 \\ x^2 \\ . \\ . \\ x^{HMS} \end{bmatrix} \qquad (4)$$

III.3. Improvising New Harmony from the Harmony Memory

A new harmony vector, $x' = (x'_1, x'_2, ..., x'_N)$, is generated from the HM based on memory considerations, pitch adjustments, and randomization. For instance, the value of the first decision variable (x'_1) for the new vector can be chosen from any value in the specified HM range $(x_1^1 \sim x_1^{HMS})$. Values of the other decision variables (x'_i) can be chosen in the same manner. There is a possibility that the new value can be chosen using the HMCR parameter, which varies between 0 and 1 as follows:

$$x'_i \leftarrow \begin{cases} x'_i \in \{x_i^1, x_i^2, ..., x_i^{HMS}\} & \textit{with probability HMCR} \\ x'_i \in X_i & \textit{with probability (1-HMCR)} \end{cases}$$

The HMCR sets the rate of choosing one value from the historic values stored in the HM, and (1-HMCR) sets the rate of randomly choosing one feasible value not limited to those stored in the HM. For example, a HMCR of 0.9 indicates that the HSA will choose the decision variable value from historically stored values in the HM with the 90% probability or from the entire possible range with the 10% probability. Each component of the new harmony vector, $x' = (x'_1, x'_2, ..., x'_N)$, is examined to determine whether it should be pitch-adjusted. This procedure uses the PAR parameter that sets the rate of adjustment for the pitch chosen from the HM as follows:

Pitch adjusting decision for $x_i' \leftarrow \begin{cases} \text{Yes with probability PAR} \\ \text{No with probability (1-PAR)} \end{cases}$

A *PAR* of 0.3 indicates that the algorithm will choose a neighboring value with 30% × HMCR probability. If the pitch adjustment decision for x_i' is *Yes*, the pitch-adjusted value of x_i' will be $x_i' + \alpha$ where α is the value of $bw \times u(-1,1)$, *bw* is an arbitrary distance bandwidth for the continuous design variable, and *u* is a uniform distribution between −1 and 1.

III.4. Updating the Harmony Memory

In this stage, if the new harmony vector is better than the worst harmony vector in the HM in terms of the objective function value, the existing worst harmony is replaced by the new harmony. The HM is then sorted by the objective function value.

III.5. Termination Criterion

The computations are terminated when the termination criterion (maximum number of improvisations) is satisfied. Otherwise, steps 3 (improvising new harmony from the HM) and 4 (updating the HM) are repeated.

IV. Proposed Method

Main goal of this study is to find the optimal location and parameter settings of SSSC as a second-generation FACTS device in order to improve the ATC and network strength, which allows more power transactions. The proposed method is explained in three subsections. The first one discusses the ATC calculation method considering line flow limits, voltage limits and reactive power constraints. The second subsection describes a novel method to find the high potential lines as the candidate of the SSSC placing to restrict the search space. The Last subsection shows the implementation of the HSA to solve the aforementioned optimization problem.

IV.1.ATC Calculation

Bus voltage magnitude and transmission line/transformer thermal rating restrict the ATC between two buses of the system. Both criteria have been widely used in the literature and are the basis for a good approximation of the ATC.

The proposed method uses the inverse jacobian matrix to find an approximation of the change in bus voltage magnitude and transmission line flows. The equations (5) show the a linear approximation for ΔP_{line} and ΔV_{bus}. PF is the vector of bus power factors, (5) and (6) can be rewritten as (7) and (8) respectively.

$$\Delta P_{line} = diag(B_{line})L(JI_{11}\Delta P + JI_{12}\Delta Q) \quad (5)$$

$$\Delta|V| = JI_{21}\Delta P + JI_{22}\Delta Q \quad (6)$$

where $diag(...)$ refers to a diagonal matrix of the entries that appear in the argument.

$$\Delta P_{line} = diag(B_{line})L \times (JI_{11} + JI_{12}.diag(\cot[\cos^{-1}(PF)]))\Delta P \quad (7)$$

$$\Delta|V| = (JI_{21}\Delta P + JI_{22}.diag(\cot[\cos^{-1}(PF)]))\Delta P \quad (8)$$

S is the sending end bus, and *R* is the receiving end bus, then ΔP becomes a vector with 1 in the *S*th row and -1 in the *R*th row.

ΔP_{S-R} is designed for the value of the permissible increase in power transfer between buses *S* and *R* due to line flows and bus voltage limits. (9) and (10) show the thermal limit of line flow and voltage limit of different buses. It should be noted that (9) shows Nl inequalities. Where, Nl is the number of network lines.

$$\Delta P_{S-R}.(\frac{dP_{line}}{dP_{SR}}) + P_{line} \le P^{Rating}$$
$$-P^{Rating} \le \Delta P_{S-R}.(\frac{dP_{line}}{dP_{SR}}) + P_{line} \quad (9)$$

$$\Delta P_{S-R}.(\frac{d|V|}{dP_{SR}}) + |V| \le |V|^{Max}$$
$$|V|^{Min} \le \Delta P_{S-R}.(\frac{d|V|}{dP_{SR}}) + |V| \quad (10)$$

A linear optimization program can solve the inequalities to maximize the value of ΔP_{S-R}. This value could be referred as the ATC between the sending bus (S) and the receiving bus (R) if the degree of nonlinearity was low, but this is not always the case. In order to increase the accuracy of the model, one can increase the power flow from bus S to bus R step by step and update the jacobian matrix at each step. This is the procedure which is applied here to find the value of ATC accurately.

IV.2.Selection Candidate lines

In this section a base case (without SSSC) ATC calculation is performed and the congested lines are found, then we should find the lines which have more effect on the reduction of power flow of congested lines. This is the first measure for selecting the candidate lines for SSSC placing. A sensitivity analysis is performed and the rate of reduction in power flow of congested lines to the change in lines impedances are define as the first selection measure (11).

$$SM1_i = \sum_{j \in Set\ of\ Congestedlines} \frac{dp_j^{line}}{dx_i} \qquad (11)$$

The candidate lines should also have enough capacity, so a second selection measure is defined as (12), and finally the total selection measure is given by (13).

$$SM2_i = \frac{p_i^{line}}{p_i^{line,max}} \qquad (12)$$

$$SM_i = SM1_i . SM2_i \qquad (13)$$

The lines are ranked in order of the value of their selection measures and the top-ranking lines are selected to meet a predefined number of candidates.

IV.3.Applying Harmony Search Algorithm

The objective of power systems operation and planning in the deregulated markets is to maximize the social welfare through minimizing investment costs on transmission network. Because of the high costs of investment of SSSC, there is considerable risk in its implementation, therefore the best locating and proper sizing is very important optimization problem.

Fig. 2 shows proposed optimization procedure based on HSA. In this process after initializing optimization problem and algorithm parameters, OPF is performed. Based upon results of OPF, candidate lines for placement of SSSC in the network are selected. All of the lines of the system can be considered as a potential location for placement of SSSC in the optimization procedure but since the candidate lines are potential locations for placement of SSSC and to reduce the solution space only several lines are considered in the proposed optimization procedure.

After initializing HM, OPF is performed for the new system with SSSC. Based upon results of OPF, ATC of the system is calculated using (5)-(9) for each harmony vector. Next, a new harmony is improvised from the HM. After these processes, based on the calculated ATC of harmony vectors, HM will be updated. Finally, the termination criterion is checked. Termination criterion is assumed to be the number of iterations in this study.

The same procedure is used for applying the PSO algorithm to this optimization problem.

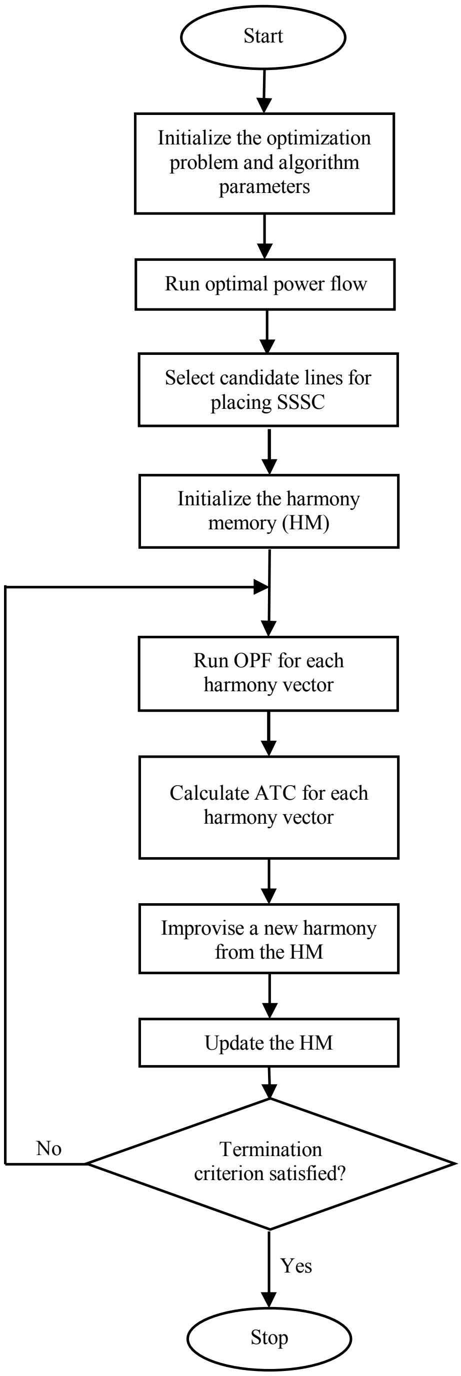

Fig. 2. Proposed optimization method procedure

V. Case Study

The proposed method is applied to the modified 24-bus IEEE Reliability Test System [16] comprises 26 generators and 17 loads and 38 transmission lines (Fig. 3). The data for the generators can be found in [17]. The load profile corresponds to a weekday of a winter week at 18:00 [12]. The only modification with respect to the network data listed in [17] consists in the reduction of the capacities of lines 11–13, 15–16 and 15–24 from 500 MVA to 175 MVA, 60 MVA, and 175 MVA, respectively.

Before proceeding to the simulation, careful selection of parameter settings is important to create a proficient result. Like other heuristic methods settings of the HSA are problem dependent [10]. The parameter sensitivity analysis is presented in Table I. This analysis features the HMCR and PAR set from 0 to 1. As shown in this table a HMCR of 1 or a PAR of 1 is not appropriate in the optimization problem. Based on the results, PAR and HMCR are chosen to be 0.35 and 0.6, respectively.

HAS and PSO parameters are presented in Table II. Loads and Units data are available in Tables III and IV, respectively. A base case OPF is run and the results are presented in Table V. Base case ATC is zero as no further power transfer is possible between the sending and receiving buses.

Among 10 branches that have been selected using equations (11)-(13) there are 3 transformers (9-11, 9-12 and 10-12), the other candidate branches are sown in Table VI.

This Table also shows the value of selection measure (discussed in section IV sub-section *B*) for each candidate line.

Table VI shows the candidate lines for SSSC placement (see equations (11)-(13)) as well as the optimum results of the proposed method. The improvement in ATC is also shown in Table V for installation of the SSSC at each line. The lines are ranked based on the value of this improvement. If the placement lines have same values of ATC improvement, we select the line which needs a smaller SSSC to increase the ATC, because this leads to a lower cost. To find the size of SSSC we multiply the line current to the series voltage compensation. The current in the candidate line is at its maximum level to improve the ATC as much as possible, so the size of SSSC can be readily calculated.

Table VII shows the system ATC when the problem is solved by the HSA and PSO. It can be observed that the best location for installation of SSSC is different for these two algorithms and HSA has found the better solution when we consider value of ATC as the objective function. It is interesting the three best locations are the same for both algorithms while the optimum size is not same. The results show that HSA can solve the problem more effectively.

TABLE I

HSA PARAMETERS SENSITIVITY ANALYSIS (100 RUNS)

HMCR	PAR							
	0.00		0.35		0.65		1.00	
	Best	Average	Best	Average	Best	Average	Best	Average
0	45	42.44	48	47.72	48	44.48	44	41.65
0.3	48	44.28	50	49.28	50	48.80	45	43.60
0.6	50	47.30	50	50	50	49.96	48	42.92
0.9	49	48.36	50	49.60	50	48.32	49	44.84
1	45	42.52	47	45.92	46	45.56	43	42.04

TABLE II

HS AND PSO ALGORITHMS' PARAMETERS

HS PARAMETERS			
HMS	HMCR	PAR	$ITER_{MAX}$
25	0.60	0.35	200

PSO PARAMETERS					
SWARM SIZE	C1	C2	W1	W2	$ITER_{MAX}$
30	1.70	1.70	0.90	0.40	200

TABLE III

LOAD DATA FOR CASE STUDY A IN (MW)

Bus No	*pd*	Bus No	*pd*
1	108	10	195
2	97	13	265
3	180	14	194
4	74	15	317
5	71	16	100
6	136	18	333
7	125	19	181
8	171	20	128
9	175		

TABLE IV

GENERATING UNITS' DATA FOR CASE STUDY A

Unit Type	*a* ($/(MWh)^2)	*b* ($/MWh)	*c* ($/h)	p_g^{max} (MW)	p_g^{min} (MW)
U12	0.08	38.9	56	2	12
U20	0.44	48.4	633	16	20
U76	0.01	11	145	15	76
U100	0.07	25.4	615	25	100
U155	0.01	9.3	220	54	155
U197	0.02	28.5	739	69	197
U350	0.01	8.6	440	140	350
U400	0	13.5	621	100	400

The size of SSSC is shown in table VII for each line. There are some interesting points in Table VII. First one is that the value of series voltage compensation is same for lines 36 and 37, this was not unexpected since these lines are located between same buses and their parameters are the same. The second point is that the value of series voltage compensation is not so high and with a relatively small SSSC the improvement in ATC is acceptable. Let us compare this voltage compensation with the voltage compensation achieved by a simple series capacitor in a simple example. Assume that a capacitor is selected to be installed in a line to increase the laudability as well as the line power flow. Its reactance is equal to -33% of line reactance and the voltage drop between two ends of the line is 2%. Then the value of series voltage compensation will be 1%. This simple example shows that the results of the proposed method are in an acceptable range for series voltage compensations.

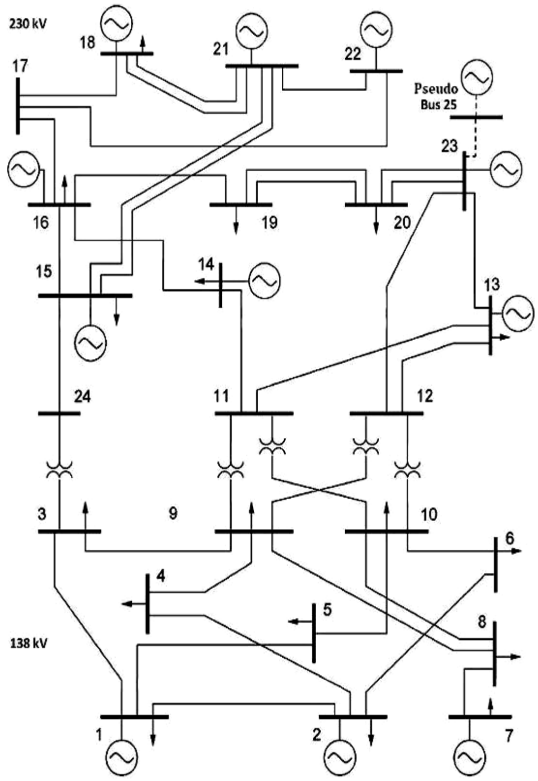

Fig. 3. IEEE RTS, case studies A and B.

TABLE V
OPF OUTPUTS FOR IEEE RTS CASE

BUS	Gen. Type	Unit Status	pg (MW)
1	U20	On	16.844
	U20	On	16.841
	U76	On	76
	U76	On	76
	Total		185.685
2	U20	Off	0
	U20	Off	0
	U76	On	76
	U76	On	76
	Total		152
7	U100	On	99.089
	U100	On	99.053
	U100	On	99.088
	Total		297.220
13	U197	On	139.763
	U197	On	139.772
	U197	On	139.768
	Total		419.323
15	U12	On	12

	U12	On	12
	U12	On	12
	U12	On	12
	U12	On	12
	U155	On	155
	Total		215
16	U155	On	155
18	U400	On	400
21	U400	On	400
23	U155	On	155
	U155	On	155
	U350	On	350
	Total		660

TABLE VI
CANDIDATE LINES AND SELECTION MEASURES

Branch #	From	To	*SM1*	*SM2*	SM
19	11	14	2.998	0.135	0.407
20	12	13	2.996	0.236	0.710
37	20	23	2.999	0.321	0.964
36	20	23	2.999	0.336	1.009
28	16	17	2.999	0.341	1.024
21	12	23	2.999	0.373	1.119
23	14	16	2.992	0.527	1.579

TABLE VII
COMPARISON OF THE BEST RESULTS BETWEEN HSA AND PSO

METHOD	Branch #	*ATC*	SSSC Size (MVA)
HSA	23	50	1.001
	19	50	2.601
	36	49	0.630
PSO	19	50	2.601
	23	49	1.148
	36	49	0.630

TABLE VIII
SSSC PARAMETERS IN CANDIDATE LINES BASED ON HSA

Branch #	From	To	V_{SC} (pu)	φ_{SC} (Rad)	*ATC*	SSSC Size (MVA)
23	14	16	0.0020	4.423	50	1.001
19	11	14	0.0052	4.631	50	2.601
36	20	23	0.0021	4.396	49	0.630
37	20	23	0.002	4.704	49	0.850
20	12	13	0.002	4.705	49	0.850
21	12	23	0.0051	4.489	49	2.500
28	16	17	0.0018	1.844	46	0.753

VI. Conclusion

The use of Static Synchronous Series Compensator (SSSC) in order to increase the Available Transfer Capacity (ATC) between desired network buses in order to improve the transmission system strength and reduce the transmission expansion cost has been proposed. The HS and PSO algorithms are applied to find the best installing location and size of SSSC in IEEE RTS. Some important points summarized at the end of case study section, show that the proposed method can effectively solve the SSSC placement problem.

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