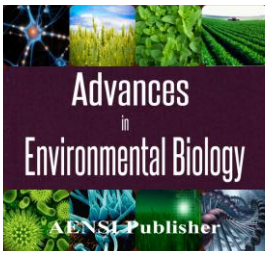
Advances in Environmental Biology, 8(12) July 2014, Pages: 1727-1734

AENSI Journals

Advances in Environmental Biology

ISSN-1995-0756 EISSN-1998-1066

Journal home page: http://www.aensiweb.com/AEB/



Stochastic Placement and Sizing of Static Synchronous Series Compensator in Restructured Power Systems

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ARTICLE INFO

Article history:
Received 25 May 2014
Received in revised form
26 July 2014
Accepted 22 October 2014
Available online 2 November 2014

Keywords:
Power System Loadability
Static Synchronous Series Compensator (SSSC)
Uncertainties
Monte-Carlo
Harmony Search Algorithm

ABSTRACT

Background: Enhancement of Available Transfer Capacity is an important issue in the electric power market. The Available Transfer Capacity (ATC) of a transmission network is the unutilized transfer capabilities of the network that can be used for the further transfer of power. **Objectives:** This paper presents the use of Flexible AC Transmission Systems (FACTS) for improving ATC in deregulated electric power system. The optimal location and parameter settings of Static Synchronous Series Compensator (SSSC) as a FACTS device have been investigated in this study. The use of SSSC is proposed in this paper to alleviate the congestion in transmission lines to maximize the ATC between desired network buses and compares two optimization methods to reach a more reliable algorithm for this problem. The uncertainties associated with transmission system equipment's availability is modeled using the scenario approach, Monte Carlo simulation is applied to generate scenarios; scenario reduction techniques are applied to reduce the size of the stochastic SSSC implementation problem. **Results:** 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. The obtained Results demonstrate the necessity of consideration of uncertainties associated with power system in planning of SSSC placement problem.

To Cite This Article: Ali Emamhosseini, Stochastic Placement and Sizing of Static Synchronous Series Compensator in Restructured Power Systems. ***Adv. Environ. Biol., 8(12),*** *1727-1734, 2014*

INTRODUCTION

In a power system the uncertainties associated with equipment's' unavailability affects the system operation and planning decisions. The risk of the actions decreases if these uncertainties are considered in decision making process.

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 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.

FACTS devices are used to increase the capacity over existing transmission lines by proper power flow control over designed lines [1]. The Convertor-based controllers have superior performance over the Thyristor-based (first generation) controllers [2]-[3]. The Static Synchronous Series Compensator (SSSC) is one of the second generation FACTS devices which are 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.

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Many methods have been studied in the literature to model different FACTS devices in the load-flow studies [4-5]. Reference [6] proposed the use of Thyristor Controlled Series Compensator (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.

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].

Neglecting uncertainties of the transmission system equipment's lead to a high risk and render the stochastic saving caused with TCSC placement non-optimal. In order to model these uncertainties a set of scenarios is created by the Monte Carlo simulation, each with an occurrence probability. TCSC placement and sizing study includes a large number of variables, so it requires a proper scenario reduction technique to decrease the computational burden of the large number of scenarios. In this paper both deterministic and stochastic approaches are applied for SSSC implementation.

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.

Sssc modeling and formulation:

In this section SSSC static model and it's formulation in optimal power flow problem is presented. The SSSC is composed of voltage source converter, diodes, a dc link capacitor, and controller connected to transmission line via a coupling transformer [12]. 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 [13] 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:

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

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

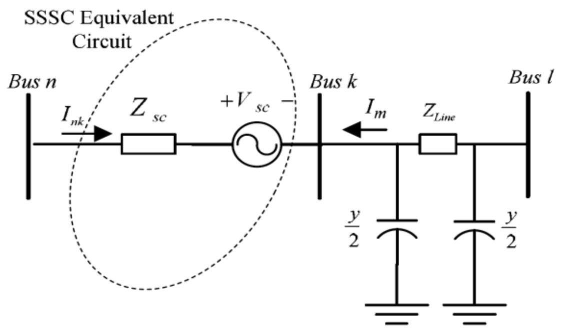

Fig. 1: SSSC static model.

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

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

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

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

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 [8]. 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 [9]. 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.

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, ${}_L x_i \leq X_i \leq {}_U x_i$ 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.

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, $f(x)$.

$$
\text{HM=}\begin{bmatrix} x^1 \\ x^2 \\ . \\ . \\ x^{HMS} \end{bmatrix} \tag{4}
$$

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:

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

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% $\times$ 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 × u(−1,1), bw is an arbitrary distance bandwidth for the continuous design variable, and u is a uniform distribution between −1 and 1.

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.

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.

Proposed Approach:

The Objective of this paper is to find the optimal location and parameter settings of SSSC as a FACTS device in order to improve the ATC and network strength, which allows more power transactions.

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 Jacobean 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, and 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. Equations (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.

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

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

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 Jacobean matrix at each step. This is the procedure which is applied here to find the value of ATC accurately.

Stochastic Analysis:

In order to model uncertainties associated with line outage and transmission system equipments unavailability risk-constrained approach is employed in this study. Scenario generation and reduction methods are discussed in the following.

Scenario Generation:

There are various approaches to generating scenarios for stochastic programming. Scenarios are commonly generated by sampling historical time series or statistical models such as time series or regression models [14]. In this paper, the Monte Carlo simulation method is employed to generate scenarios. Monte Carlo simulation is executed (i.e., a very large number) times to generate scenarios for transmission equipment's availability. Fig. 2 shows these states for system demand (as an example).

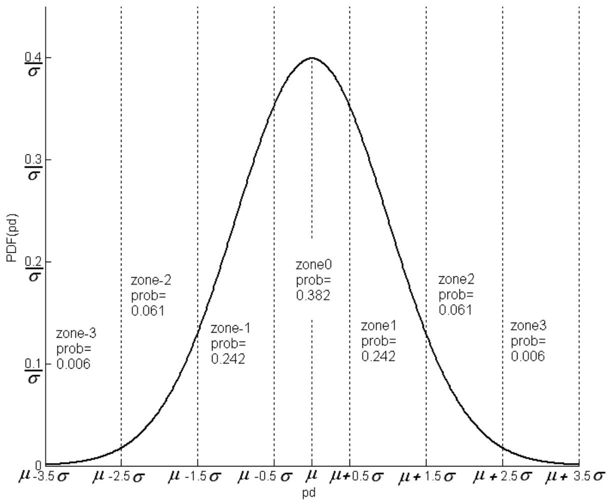

Fig. 2: Probability density function of system demand.

Scenario reduction:

Number of scenarios directly affects the computational requirements for solving scenario-based optimization models. So an effective scenario reduction method could be very essential for solving large-scale systems. The reduction technique is a scenario-based approximation with a smaller number of scenarios and a reasonably good approximation of original system [15]. Therefore, a subset of scenarios and a probability measure based on this subset that is the closest to the initial probability distribution in terms of probability metrics is determined. The scenario reduction technique that is used in this study control the goodness-of-fit of approximation by measuring a distance of probability distributions as a probability metric. Efficient algorithms developed from backward and fast forward methods determine optimal reduced measures. Simultaneous backward and fast forward reduction methods are explained in [16]. Let *ξs* (*s*=1,…,*N*) denote *N* different scenarios, each with a probability of *PRs*, and *Dists,s'* be the distance of scenario pair (*s,s'*). The simultaneous backward and fast forward reduction includes the following steps:

Step 1: Set S as the initial set of scenarios; DS is the set of scenarios to be deleted. The initial DS is null. Compute the distances of all scenario pairs: Dists,s' = Dist(ξs ,ξs'), s,s' =1,…,N;

Step 2: for each scenario k, Distk(r) = min Distk,s' , s', $k \in S$ *and s' ≠ k, r is the index of scenario that has the minimum distance with scenario k;*

*Step 3: compute DDk(r) = PRk * Distk(r),* $k \in S$ *. Choose d so that DDd = min (DDk),* $k \in S$ *;*

Step 4: S = S – {d}, DS = DS + {d}; PRr =PRr + PRd;
Step 5: repeat steps 2-4 until the number to be deleted meets the predefined number of scenarios.
Considering the stochastic analysis Equations (7) and (8) will be as follows:

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

$$\Delta|V|(sc) = (JI_{21}(sc)\Delta P(sc) + JI_{22}(sc).diag(\cot[\cos^{-1}(PF)]))\Delta P(sc) \quad (12)$$

Where, sc represent scenario number, $prob(sc)$ show occurrence probability of scenario *sc*.

Simulation Results:

The proposed method is applied to the modified 24-bus IEEE Reliability Test System [17] comprises 26 generators and 17 loads and 38 transmission lines. The data for the generators can be found in [18]. The load profile corresponds to a weekday of a winter week at 18:00. The only modification with respect to the network data listed in [18] 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. In this study initially 2,000 scenarios were generated and by applying the scenario reduction technique the number of scenarios reduces to 20.

Table 1: HSA Parameters.

HS Parameters			
HMS	HMCR	PAR	$ITER_{MAX}$
40	0.60	0.40	100

HSA parameters are presented in Table 1. Loads and Units data are available in Tables 2 and 3, respectively.

Table 2: 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 3: Generating Units' Data .

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

As mentioned earlier 20 scenarios are obtained after scenario reduction. These scenarios can effectively model the stochastic nature of power system associated with transmission system equipment's unavailability. The best three solutions based on the stochastic analysis are provided in Table 4. In order to find the SSSC location and size in stochastic approach HSA has been employed. As the results show Branch 19 (11-14) is the best location for application of SSSC.

Table 4: SSSC Parameters Based on Stochastic Approach.

Branch #	From	To	V_{SC} (pu)	φ_{SC} (Rad)	*ATC*	SSSC Size (MVA)
19	11	14	0.0050	4.631	48.23	2.573
23	14	16	0.0018	4.243	47.52	0.985
18	11	13	0.0037	3.394	47.38	0.851

Table 5 presents the best solution of deterministic and stochastic approaches that were presented in this study. The deterministic approach fails to find the proper size of SSSC, and can only provide the location of SSSC. Using HAS as an optimization tool to find the optimal size of SSSC for deterministic approach the optimal size and therefore the *ATC* is obtained and presented in Table 5. Therefore it demonstrates that deterministic approach does not render high quality solution. The solutions of deterministic and stochastic approaches are different and that is due to consideration of transmission system equipment's' unavailability in stochastic analysis.

Table 5: Comparison of Different Approaches.

Approach	Branch #	From	To	*ATC*
Deterministic	18	11	13	51.24
Stochastic	19	11	14	48.23

Conclusion:

The use of SSSC in order to increase the ATC between desired network buses has been proposed in order to improve the transmission system strength and reduce the transmission expansion cost.

Deterministic and stochastic approaches were employed to determine the optimal application of SSSC. The HSA was applied to find the best installing location and size of SSSC in IEEE RTS. The results demonstrated that deterministic approach fails in finding the high quality solution that provide proper size and location of SSSC. The results also show that consideration of stochastic nature of power system is very important in planning studies and neglecting them will render non-optimal solution.

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