Static Transmission Expansion Planning under an Improved Harmony Search Algorithm

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***Abstract*-- This paper proposes an improved harmony search (HS) algorithm for the solution of the static transmission expansion planning (TEP) problem with security constraints. The modification of this method in comparison to the original harmony search algorithm includes the introduction of a variable bandwidth in the memory consideration and the pitch adjustment phase for the selection of the new harmony vector (NHV) in the improvisation step of the algorithm. In that way, if previous harmonies are considered for the NHV, the algorithm allows only the best harmonies of the harmony memory in respect of objective function value to participate in the improvisation of the NHV. The results from the application of the proposed method on IEEE 24-bus reliability test system demonstrate the potentials and the practicality of the proposed HS algorithm.**

***Index Terms*-- Harmony search, meta-heuristic algorithms, memory consideration, power systems, transmission expansion planning.**

I. NOMENCLATURE

c_{ij}	Cost of a line added to the *i-j* right of way ($).
γ_{ij}	Susceptance of the line between buses *i* and *j*.
n_{ij}	Number of new lines added to the *i-j* right of way.
n_{ij}^0	Initial number of lines between buses *i* and *j*.
$\bar{n}_{ij}$	Maximum number of lines that can be added to the *i–j* right of way.
f_{ij}	Active power flow in the *i-j* right of way (MW).
f_{ij}^{mn}	Active power flow in the *i-j* right of way when a line in the *m-n* right of way is out of service (MW).
$\bar{f}_{ij}$	Active power flow limit on the *i-j* right of way (MW).
θ_i	Phase angle in bus *i*.
θ_i^{mn}	Phase angle in bus *i* when a line in the *m-n* right of way is out of service.
S	Branch-node incidence matrix.
S^{mn}	Branch node incidence matrix when a line in the *m-n* right of way is out of service.
$\boldsymbol{g}$	Vector of active power generation with elements g_k (generation in bus *k*).
$\boldsymbol{g}^{mn}$	Vector of active power generation when a line in the *m-n* right of way is out of service with elements g_k^{mn} .
$\bar{g}$	Vector of maximum generator capacity.
$\boldsymbol{d}$	Vector of the predicted load.
$\boldsymbol{r}$	Vector of load curtailment with elements r_κ .
$\boldsymbol{r}^{mn}$	Vector of load curtailment when a line in the *m-n* right of way is out of service with elements r_k^{mn} .
H	Sensitivity coefficient matrix with elements h_{ij}^k .
H^{mn}	Sensitivity coefficient matrix with elements $h_{ij}^{k,mn}$ when a line in the *m-n* right of way is out of service.
p_f	Load penalty factor ($/MW).
Γ	Set of load buses.
Ω	Set of all existing and new right-of-ways.
Ψ	Set of selected contingencies.

II. INTRODUCTION

In regulated electricity markets, the transmission expansion planning (TEP) problem consists of minimizing the investment cost in new transmission lines to meet the power system requirements for a future demand and a future generation configuration without violating any operational constraints. In deregulated power systems, the expansion of the transmission system should also provide nondiscriminatory and competitive market conditions to all stakeholders. The problem is a large scale, non-linear, mixed integer optimization problem that has been addressed by mathematical as well as by heuristic optimization techniques [1]. Mathematical optimization models for TEP problem include linear programming, dynamic programming, nonlinear programming, mixed integer programming, branch and bound, Bender’s decomposition, and hierarchical decomposition [1]. Heuristic models for the solution of TEP problem include simulated annealing, greedy randomized adaptive search procedure, taboo search, genetic algorithms, differential evolution, and hybrid heuristic models [1].

The TEP problem has also been addressed by probabilistic and stochastic methods that consider random and nonrandom uncertainties in their problem formulation. Random uncertainties can be statistically represented and may include load development, generators’ operating costs and availability, renewables production, and availability of transmission system facilities. Investment decisions concerning the location of new installed conventional or renewable generation and the closure of old generation or

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transmission facilities are nonrandom uncertainties. Probabilistic methods for the solution of TEP problem include probabilistic reliability criteria [2], risk assessment method [3], and chance constrained programming [4].

TEP can be classified as static or dynamic according to the study period. For static planning, the developer searches for the suitable circuits that should be added in the current transmission system. If multiple years are considered and an optimal expansion along the whole planning horizon is searched, planning is classified as dynamic. Independent of the market conditions, the power system should always be operated in a way that no contingency triggers cascading outages or causes any form of instability [5]. Most security rules therefore call for the system to be able to withstand the loss of any single component, thus being "$N-1$ secure". In transmission expansion problems, the steady state security analysis aims at satisfying the nodal power balance with no violations of the transmission lines maximum flow under normal and contingency situations.

A meta-heuristic algorithm known as harmony search (HS) has been recently developed [6] and has been very successful in a wide variety of optimization problems [7]-[10]. The HS algorithm mimics the musicians' improvisation behavior. Music players try to find the perfect musically pleasing harmony by improvising or "pitching" around a previous harmony, which is analogous to local and global search schemes in optimization techniques. Compared to earlier meta-heuristic optimization algorithms, the HS algorithm imposes fewer mathematical requirements and uses a stochastic random search instead of a gradient search so that derivative information is not necessary. Nevertheless, its capabilities are quite sensitive to parameter setting and premature convergence has been identified in the performance of classical HS [11]. An improved version of HS is presented in [12] where parameters are automatically adjusted according to its self-consciousness.

In this paper the static TEP problem is solved with an improved HS algorithm incorporating N-1 security analysis. The objective of this paper is to demonstrate the performance of the improved HS in various TEP problem cases and to run a sensitivity analysis around its parameter settings. The DC power flow is employed for the network representation. The TEP problem is presented in Section III while the proposed HS algorithm for the solution of the TEP problem is presented in Section IV. The method is applied to IEEE 24-bus reliability test system and the results are analyzed in Section V. Conclusions are drawn in Section VI.

III. The TEP Problem

In a power system represented by the DC load flow model and when re-dispatching of generators is considered, the static deterministic TEP model with security constraints can be formulated as follows:

$$Min\left\{\sum_{(i,j)} c_{ij} n_{ij} + p_f \sum_{k} r_k + p_f \sum_{(m,n)} r_k^{mn}\right\} \quad (1)$$

subject to:

$$S^T f + g + r = d \quad (1.1)$$

$$f_{ij} - \gamma_{ij}(n_{ij}^0 + n_{ij})(\theta_i - \theta_j) = 0 \quad (1.2)$$

$$\left|f_{ij}\right| \le (n_{ij}^0 + n_{ij})\,\bar{f}_{ij} \quad (1.3)$$

$$0 \le g \le \bar{g} \quad (1.4)$$

$$0 \le r \le d \quad (1.5)$$

$$(S^{mn})^T f^{mn} + g^{mn} + r^{mn} = d \quad (1.6)$$

$$f_{ij}^{mn} - \gamma_{ij}\left(n_{ij}^0 + n_{ij}\right)\left(\theta_i^{mn} - \theta_j^{mn}\right) = 0 \ , \ ij \neq mn \quad (1.7)$$

$$f_{ij}^{mn} - \gamma_{ij}\left(n_{ij}^0 + n_{ij} - 1\right)\left(\theta_i^{mn} - \theta_j^{mn}\right) = 0 \ , \ ij = mn \quad (1.8)$$

$$\left|f_{ij}^{mn}\right| \le (n_{ij}^0 + n_{ij})\,\bar{f}_{ij} \quad , \ ij \neq mn \quad (1.9)$$

$$\left|f_{ij}^{mn}\right| \le (n_{ij}^0 + n_{ij} - 1)\,\bar{f}_{ij} \quad , \ ij = mn \quad (1.10)$$

$$0 \le g^{mn} \le \bar{g} \quad (1.11)$$

$$0 \le r^{mn} \le d \quad (1.12)$$

$$0 \le n_{ij} \le \bar{n}_{ij} \quad (1.13)$$

$$n_{ij} \text{ is integer} \quad (1.14)$$

$$(i,j) \in \Omega \, , \ k \in \Gamma \ , \ (m,n) \in \Psi \quad (1.15)$$

In the above TEP formulation, the objective is to find an optimal transmission structure and a consequent generation dispatch to meet the peak load demand with minimum investment and loss of load cost, while satisfying operational and economic limitations for normal and N-1 contingency situation. Equation (1.1) stands for the power nodal balance equation; (1.2) is the DC power flow model, while (1.3) to (1.5) specify the operational limits of the system. Parameters with superscript *mn* denote the modified variables when a line on the *m-n* right of way is outaged. For each contingency a new branch node incidence matrix is created and the number of lines in the examined right of way is reduced by one. The security constrained TEP problem is solved for all credible contingencies *mn* included in set Ψ. Constraint (1.13) defines the range of the investment variables.

If the dispatch of the generators is set to a specific value for normal and all the contingency situations, then vector **g** is considered known and TEP formulation is:

$$Min \sum_{(i,j)} c_{ij} n_{ij} + p_f \sum_{(i,j)} \left(\left|f_{ij}\right| - \left(n_{ij}^0 + n_{ij}\right) \cdot \overline{f_{ij}} \right)$$
$$+ p_f \sum_{(m,n)} \left[\sum_{\substack{(i,j) \neq \\ (m,n)}} \left(\left|f_{ij}^{mn}\right| - \left(n_{ij}^0 + n_{ij}\right) \cdot \overline{f_{ij}} \right) \right.$$
$$\left. + \sum_{\substack{(i,j) = \\ (m,n)}} \left(\left|f_{ij}^{mn}\right| - \left(n_{ij}^0 + n_{ij} - 1\right) \cdot \overline{f_{ij}} \right) \right] \quad (2)$$

$$f = H \cdot (g - d) \quad (2.1)$$

$$f^{mn} = H^{mn} \cdot (g - d) \quad (2.2)$$

$$0 \le n_{ij} \le \bar{n}_{ij} \quad (2.3)$$

$$n_{ij} \ \textit{is integer} \quad (2.4)$$

$$(i,j) \in \Omega \, , \ (m,n) \in \Psi \quad (2.5)$$

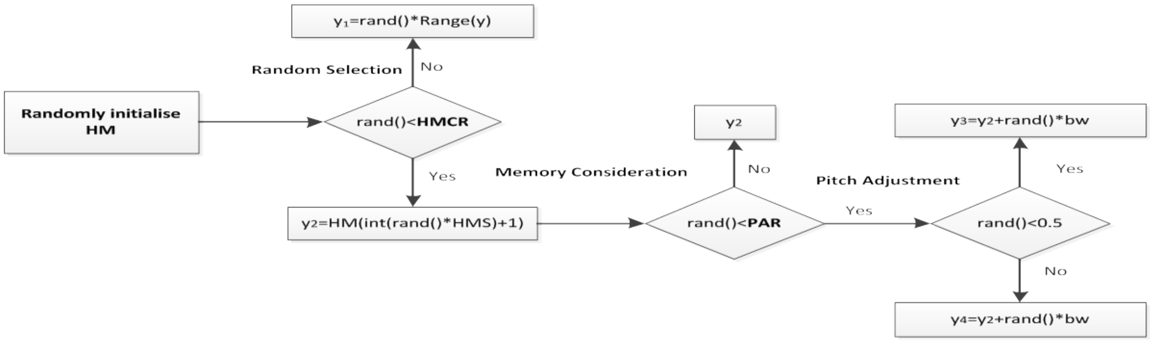

Fig.1. The new harmony vector (NHV) improvisation process

Sensitivity coefficient matrices H *and* H^{mn} show the sensitivity of the active power flow in branch *ij* regarding the injected power in node *k* when all lines are in service or a line in the *m-n* right of way is out of service respectively.

The TEP problem without security constraints is solved by removing all variables with superscript *mn* from (1) and (2).

IV. Improved HS Algorithm for Solving the TEP Problem

The HS algorithm is a meta-heuristic algorithm based on an analogy with music improvisation process of searching a perfect harmony as determined by aesthetic standard. First the original HS is described and then the improved HS algorithm for solving the TEP problem is presented.

A. Harmony search algorithm

The general steps of the procedure of harmony search are as follows [6]:

1) Create and randomly initialize a harmony memory (HM) with size HMS with respect to the variables limits. Each one of the HMS rows of the HM contains a potential solution vector of the optimization problem.
2) Improvise a new harmony vector NHV (solution vector) from the HM.
3) Update the HM. If the new harmony vector (NHV) is better than the worst harmony in the HM, replace this harmony with the NHV.
4) Repeat steps 2 and 3 until the stopping criterion is met.

The chore of the HS algorithm is mainly the improvisation of the new harmonies. As shown in Fig.1 the NHV *y* can be the outcome of a random selection, memory consideration or pitch adjustment. The parameter HMCR (Harmony Memory Consideration Rate), which varies between 0 and 1, controls the balance between random selection and memory consideration for the NHV. If the randomly generated probability is less than HMCR, the algorithm randomly selects a value from the possible range of the design variables. If it is greater than HMCR, it randomly picks one pitch from the HM. Once the pitch has been selected, a randomly generated probability is compared to the pitch adjustment rate (PAR) and determines whether the pitch selected from the HM will be adjusted according to the variable distance bandwidth (bw).

It is obvious that PAR and bw are very important parameters for the performance of the algorithm. Traditional HS uses fixed values for both PAR and bw. A small PAR value can considerably increase the number of iterations required to find the optimum solution but it can help the algorithm increase the diversity of solution vectors. A large PAR value may trigger undesirable pitch adjustments in the beginning of the algorithm but helps fine tuning of the solution vectors in the later stages. On the other hand, parameter bw has a considerable influence on the precision of solutions both in the early and the late stages of the algorithm.

B. Improved HS algorithm for TEP problem

In this paper a new step before the improvisation of a new harmony is added to the original HS algorithm and a variable bandwidth is being introduced in the harmony memory consideration and pitch adjustment phases. The algorithm for the solution of TEP problem is presented in Fig. 2 and described in the following paragraphs. For the parameter bw, the formulation proposed in [12] is used since this approach can progressively make finer adjustments to the harmony solution vectors.

Step 1. Initialize the optimization problem and HS algorithm parameters.

First the optimization problem is specified:

$$Min\ f(x) \tag{3.1}$$

subject to:

$$x_l \in X_l \quad , \ l = 1,2,\ldots,NL \tag{3.2}$$

where $f(x)$ is the objective function, x is the set of each decision variable and NL is the number of the decision variables. X_l is the set of the possible range of values for each design variable. For the TEP problem, the objective function $f(x)$ is (1) or (2), the design variables are the new added lines n_{ij} and NL is the size of Ω. The upper bound for each design variable is $\bar{n}_{ij}$. The HS algorithm parameters that are required to be specified in this step are: i) the size of the harmony memory (HMS), ii) the harmony memory consideration rate (HMCR), iii) the pitch adjusting rate (PAR) and iv) the number of improvisations (NI).

Step 2. Initialize the harmony memory (HM).

The harmony memory is initialized with randomly generated new installed lines with respect to the maximum number of lines that can be added per right of way:

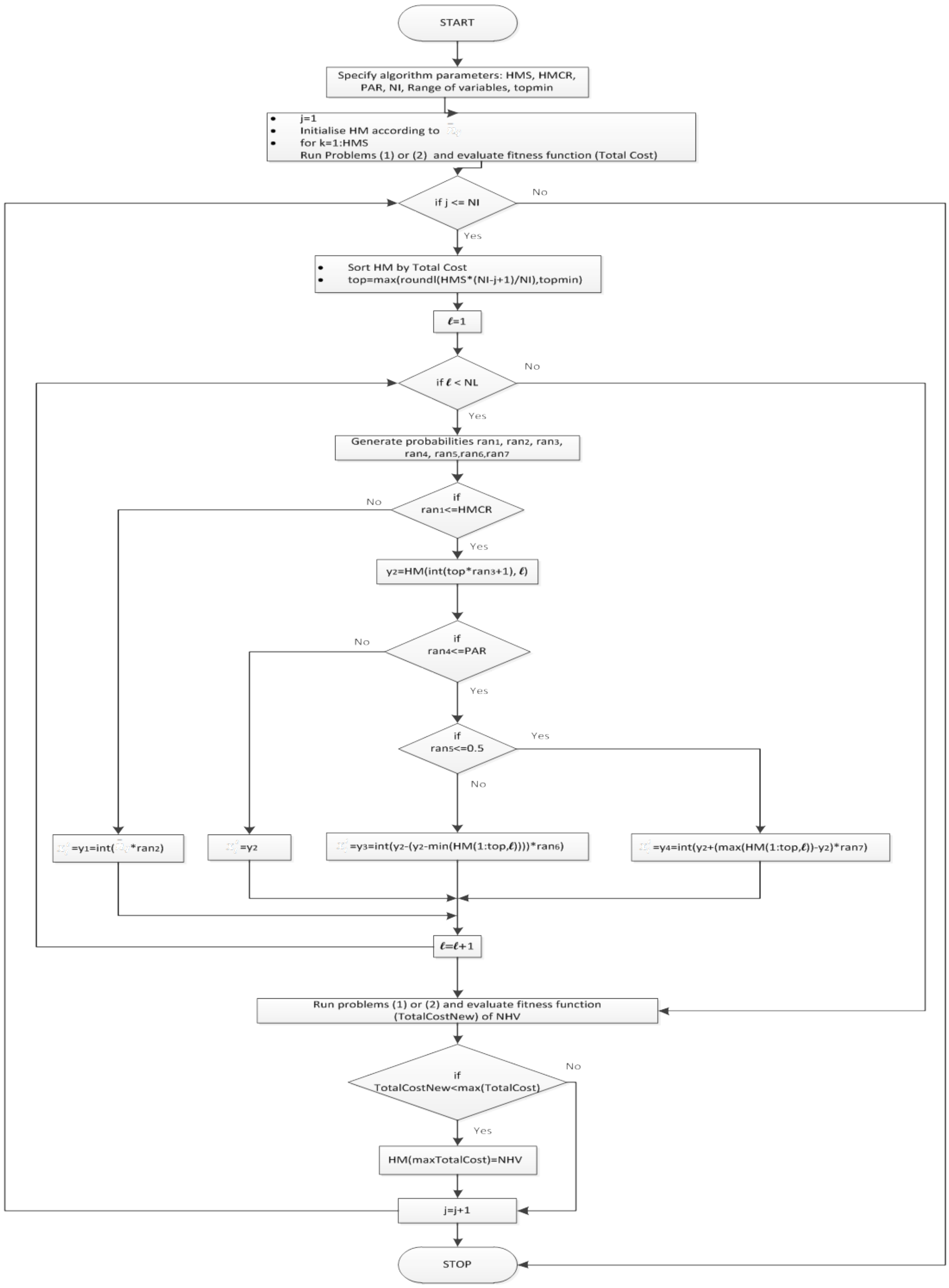

Fig.2. Flowchart of the improved HS algorithm for TEP problem

$$HM = \begin{pmatrix} x_1^1 & x_2^1 & \cdots & x_{NL-1}^1 & x_{NL}^1 \\ x_1^2 & x_2^2 & \cdots & x_{NL-1}^2 & x_{NL}^2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{NL-1}^{HMS-1} & x_{NL}^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{NL-1}^{HMS} & x_{NL}^{HMS} \end{pmatrix} \quad (4)$$

Step 3. Sort HM by f(x) values.

The harmonies in the HM (solution vectors) are evaluated by (1) or (2) and sorted in descending order so that the solutions with smaller objective function values occupy the first rows in the HM.

The value of the objective function of each HM vector is calculated by solving the linear problems (1) or (2) since the integer transmission investment decisions are provided from the HM solution vectors. For each HM vector, the cost of load curtailment for normal and all N-1 contingency configurations is added to its corresponding investment cost to form the total cost of the examined solution.

Step 4. Improvise a new harmony

A new harmony vector $NHV_k = \left(x_1^k, x_2^k, \ldots, x_{NL}^k\right)$ is generated based on three rules: (i) memory consideration, (ii) pitch adjustment and (iii) random selection.

For the memory consideration only the first *top* harmonies in the sorted HM will be used for the improvisation of the new harmony vector:

$$top = \max(\text{int}(HMS\,\frac{NI - j + 1}{NI}), topmin) \qquad j = 1,2,\ldots,NI \quad (5)$$

where *topmin* is the minimum value the variable *top* is allowed to have. This variable bandwidth allows the NHV to consider the values of the decision variables that are only at the first *top* harmonies of the sorted HM. In that way, the HS algorithm may use some of the previous best solutions for the improvisation step and decrease the number of improvisations (NI) needed to find the optimum solution since as NI increases the HS algorithm searches in a narrower bandwidth for the new value of each design variable of the NHV. To allow memory consideration until the final improvisation of the HS algorithm, *top* is bounded by *topmin*, which can be a percentage of HMS.

$$x_l^t = y_2 \leftarrow \begin{cases} x_l^t \in \{x_l^1, x_l^2, ..., x_l^{top}\} & \text{with probability HMCR} \\ x_l^t \in X_l & \text{with probability (1-HMCR)} \end{cases} \quad (6)$$

For instance, an HMCR=0.85 indicates that the HS algorithm will select randomly the decision variable's value for the NHV from the first *top* harmonies in the HM with 85% probability and from the initial value range of the design variable with 15% probability.

Once a value of a variable has been randomly picked from the HM consideration phase, the pitch adjustment rate (PAR) determines whether further adjustment is required:

$$\text{Pitch } y_2 \leftarrow \begin{cases} \text{Yes with probability PAR} \\ \text{No with probability (1-PAR)} \end{cases} \quad (7)$$

Probability PAR is adjusted in every iteration according to the following equation:

$$PAR = PAR_{\min} + \frac{j \cdot (PAR_{\max} - PAR_{\min})}{NI} \quad j=1,2,\dots,NI \quad (8)$$

If the randomly generated number is less than (1-PAR) then the algorithm proceeds with the next step of the HS. If pitch adjustment decision is Yes, the decision variable is further adjusted by the following equations [12]:

$$x_l^t = y_3 = y_2 - (y_2 - \min(HM(1:top))) \cdot ran[0,1] \quad (9)$$

or

$$x_l^t = y_4 = y_2 + (\max(HM(1:top)) - y_2) \cdot ran[0,1] \quad (10)$$

In (8) and (9), only the first *top* harmonies of the HMS take part in the fine tuning of the solution vectors of the memory consideration phase.

Step 5. Update the harmony memory

The NHV is evaluated in terms of the objective function value by solving problems (1) and (2). The harmony which is characterized by the higher total cost in the HM is compared to NHV total cost and if it is higher it is replaced by the NHV.

Step 6. Repeat steps 3 to 5 until the maximum number of improvisations is reached.

V. Case Studies

The proposed algorithm is implemented in MATLAB 7 and tested on IEEE 24-bus reliability test system [13]. Problems (1) and (2) for re-dispatched and fixed generation respectively are solved for various HS parameters and the performance of the algorithm is evaluated. The load penalty factor p_f is assumed equal to 10^7\$/MW. Finally, up to three new lines can be added per right of way while the loads and generation capacity are assumed three times higher than their original values.

The solutions of the algorithm for TEP with and without security constraints are presented in Table I. The investment cost per new line as well as the generation data for the four fixed generation scenarios G_1-G_4 can be found in [14] while G_0 is the re-dispatched generation scenario. The values of the HS algorithm parameters used are: HMS=75, HMCR=0.99, *topmin*=0.3·HMS, PAR_{min}=0.01, PAR_{max}=0.99 and NI=10000. All results include the best solution obtained after 30 runs of the algorithm.

TABLE I
TEP SCHEMES FOR IEEE 24-BUS TEST SYSTEM WITHOUT SECURITY CONSTRAINTS

Lines Added							
Line	From Bus	To Bus	Without security constraints				
			G_0	G_1	G_2	G_3	G_4
3	1	5		1	1		
6	3	9					1
7	3	24		1	1		
10	6	10	1	1	1	1	1
11	7	8	2	2	1	2	2
14	9	11					1
17	10	12	1		1	1	1
19	11	14					1
23	14	16	1	1	1	1	1
26	15	24		1	1		
27	16	17		2	2	1	1
28	16	19		1			
29	17	18		1	2		
33	20	23				1	
Number of new lines			5	11	11	7	9
Total investment cost (M\$)			152	370	392	218	327

TABLE II
TEP SCHEMES FOR IEEE 24-BUS TEST SYSTEM WITH SECURITY CONSTRAINTS

Lines Added							
Line	From Bus	To Bus	With security constraints				
			G_0	G_1	G_2	G_3	G_4
3	1	5	1	1	1	2	1
4	2	4		1	1		1
6	3	9		2	1	2	
7	3	24	1		2	1	2
8	4	9	1			1	
10	6	10	2	2	2	2	2
11	7	8	2	3	2	3	3
14	9	11		1			
15	9	12				1	
16	10	11	1	1	2		1
17	10	12		1		1	1
18	11	13	1		1		
19	11	14		1			
20	12	13		1		1	1
23	14	16	1	2	2	1	1
24	15	16		1	1		
25	15	21		1	1	1	1
26	15	24	1		2		2
27	16	17	1	3	3	1	1
28	16	19		2	1	1	
29	17	18		2	2		
31	18	21		1			
33	20	23				1	1
34	21	22		1	1	1	1
39	14	23				1	1
Number of new lines			12	27	25	21	20
Total investment cost (M\$)			441	1033	1034	829	913

All final solutions include almost zero load curtailment and therefore cannot straightforward be compared to the solutions of other heuristic algorithms reported in [14].

In order to reveal the impact of control parameters in finding the optimum solution of the problem, HMCR, HMS and *topmin* are varied within their permissible range by keeping the rest parameters constant to the aforementioned values. In Tables III total investment cost for various HMS and HMCR values are presented for scenario G_1. From a sensitivity analysis of all the scenarios, it is concluded that a higher HMCR value generally improves the performance of the algorithm. However, HMS is more system dependent and should follow the level of complexity of the scenarios. As shown in Table IV, a medium value for the lower bound *topmin* enhances algorithm's performance since a higher value would need more improvisations to find the best solution and a lower one could trap the algorithm in a suboptimal solution. The relative error is calculated based on the difference between each of the 30 solutions and the best solution presented in Table III.

TABLE III
HS ALGORITHM PERFORMANCE FOR VARIOUS HMS AND HMCR VALUES

HMCR	0.7	0.8	0.9	0.95	0.99
TOTAL INVESTMENT COST (M$)	1774	1566	1105	1079	1033
HMS	30	50	75	100	150
TOTAL INVESTMENT COST (M$)	1101	1077	1033	1053	1068

TABLE IV
HS ALGORITHM PERFORMANCE FOR VARIOUS *topmin* AND NI VALUES

NI=5000					
topmin	0.1·HMS	0.3·HMS	0.5·HMS	0.7·HMS	1.0·HMS
TOTAL INVESTMENT COST (M$)	1071	1079	1178	1249	1577
RELATIVE ERROR	10.4%	22.6%	37.5%	47.5%	69.5%
NI=10000					
topmin	0.1·HMS	0.3·HMS	0.5·HMS	0.7·HMS	1.0·HMS
TOTAL INVESTMENT COST (M$)	1056	1033	1041	1075	1084
RELATIVE ERROR	7.2%	8.8%	9.4%	11.9%	22.2%
NI=15000					
topmin	0.1·HMS	0.3·HMS	0.5·HMS	0.7·HMS	1.0·HMS
TOTAL INVESTMENT COST (M$)	1053	1033	1053	1033	1056
RELATIVE ERROR	7.3%	9.5%	7.5%	8.1%	9.3%
NI=20000					
topmin	0.1·HMS	0.3·HMS	0.5·HMS	0.7·HMS	1.0·HMS
TOTAL INVESTMENT COST (M$)	1056	1041	1056	1071	1056
RELATIVE ERROR	7.4%	7.7%	7.3%	8.2%	8.3%

VI. CONCLUSIONS

In this paper, an improved HS algorithm has been investigated for the solution of the static transmission expansion problem with N-1 security constraints. A variable bandwidth for the improvisation of the new harmony vector was introduced while the method was tested on IEEE 24 bus reliability test system for both fixed and re-dispatched generation for various HS algorithm parameter values. The results show that the relative fast convergence of the algorithm to the optimum value makes this algorithm suitable for large scale optimization problems, like TEP.

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