Indian Journal of Fundamental and Applied Life Sciences ISSN: 2231– 6345 (Online)
An Open Access, Online International Journal Available at www.cibtech.org/sp.ed/jls/2015/01/jls.htm
2015 Vol.5 (S1), pp. 4534-4544/Jalili and Bayramzadeh

Research Article

HYBRID HSA WITH FUZZY MECHANISM FOR SOLVING GENERATION EXPANSION PLANNING PROBLEM

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ABSTRACT

In this paper a generation expansion planning in restructured power systems is presented based on Harmony Search Algorithm (HSA) and Fuzzy Mechanism (FM) for decoupling generation expansion planning from transmission expansion planning. Also for reducing complexity of the problem the benders decomposition is applied in this paper which divide the main problem in to two sub-problems as; maximize profits of each GENCO (PBGEP) and the security problem wants to satisfy security network constraints (SCGEP). Accordingly, calculate value of each GENCO’s profit and total profit are considered as an optimization problem by proposed algorithm. The effectiveness of the proposed technique is applied over modified IEEE 30-bus system. The presented results demonstrate the efficiency the proposed technique.

Keywords: *Customer Shopping Experience, On-line Loyalty, Saman Bank*

INTRODUCTION

The main objective of power system planning in regulated power systems is to meet the request of loads, while maintaining power system reliability. In this surrounding uncertainty is low. Transmission expansion planning is centralized and coordinated with generation expansion planning. Planners have availability to the required information for planning. Therefore, designer can design the least cost transmission plan based on the certain reliability criteria (Fang and Hill, 2003).

Composite power system expansion planning with open access to the transmission system has become a hot issue in the electricity energy industry in recent years (Hongwei *et al*., 1996; Sobhani and Ghadimi, 2013; Farhadi *et al*., 2013). Electric market access has moved the industry from conventional monopolistic electricity markets to competitive markets (Farhadi *et al*., 2013; Hashemi, 2012). In a competitive market, the price of the delivered energy and the quality of energy supply including voltage quality and reliability of service are the main factors for business success. A key factor in today’s competitive environment is the orientation toward customer’s needs and willingness to pay for quality (Farhadi *et al*., 2013).

Composite system expansion planning addresses the problem of broadening and strengthening an existing generation and transmission network to optimally serve a growing electricity market while satisfying a set of economic and technical constraints (Hashemi, 2012; Ghadimi *et al*., 2012). The problem is to minimize the cost subject to a reliability level constraint. Various techniques including branch and bound, sensitivity resolution, Bender decomposition, Simulated Annealing (SA), Genetic Algorithms (GA), Tabu Search (TS), and Greedy Randomized Adaptive Search Procedure (GRASP) have been used to study the problem (Sobhani *et al*., 2011; Hagh *et al*., 2011).

In this paper Generation Expansion Planning (GEP) is discussed. GEP is one of the strategic planning for every country. In traditional environment, the purpose of GEP was to minimize system cost (investment & operation costs) while satisfy system load. Restructuring in power systems change many previous concept and redefine these. In restructured environment each GENCO wants to maximize its profit while ISO surveys system reliability and security (Hongwei *et al*., 1996). So, moreover size, place, type and construction time of new units, market price and profit of each GENCO have been considered. Therefore, GEP is a mixed-integer nonlinear problem with several constraints (Aghdam, 2011). Solving this problem is very difficult. In addition, relation between GEP and Transmission Expansion Planning (TEP), is other difficulty for planners (Ghadimi *et al*., 2011).

Also, several optimization algorithms such as decomposition method (Ghadimi *et al*., 2012), genetic algorithm (Sobhani *et al*., 2011; Hagh *et al*., 2011) artificial neural networks (Aghdam, 2011) etc. have been applied to solve the complicated problem; benders decomposition method will match GEP framework very well. In this paper the benders decomposition is used for decoupling main problem to two sub-problems. For this purpose, the HSA is proposed in this paper to search and find best location of wind power. HSA is a recently developed powerful evolutionary algorithm, inspired by the improvisation process of musicians, for solving single or multi-objective optimization problems. The features and the advantages of this technique, such as escaping from local optima snares, global optimization, appropriate robustness, simple mechanism and quick convergence ability, would make this proposed technique as a promising optimization approach.

The effectiveness of the proposed technique is applied over modified IEEE 30-bus system and analyzes output results. The presented results demonstrate the robustness of the proposed technique.

Model Description

The remaining assumptions are considered in this paper:

- The forecasted load duration curve for a planning year is divided into multiple load blocks. As depicted in Figure 1, we use three load blocks of peak, medium, and base.
- The marginal cost of the most expensive committed unit, which satisfies the network security, will be the pseudo market clearing price (MCP). A security constrained unit commitment (SCUC) algorithm is used here for the simulation of MCP.

Figure 2 shows decomposition scheme for solving GEP in restructured power systems.

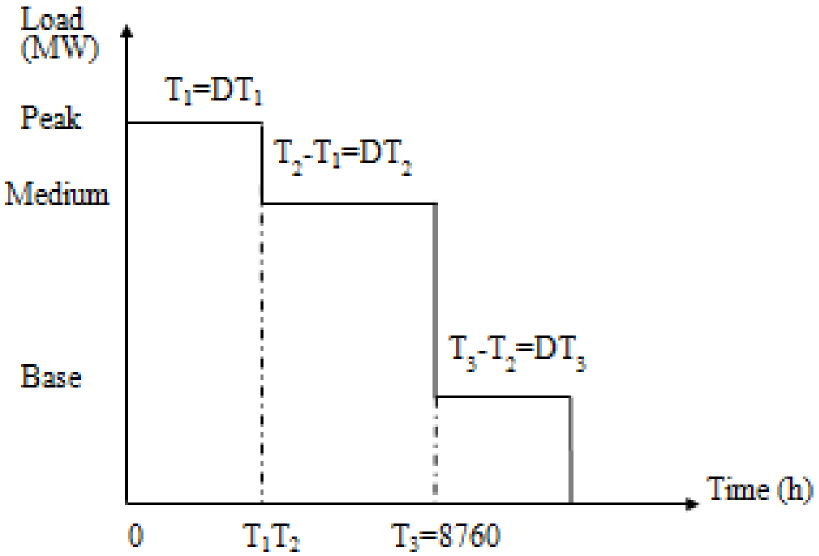


Figure 1: Load duration curve for a planning year

A. *Priced-Based Generation Expansion Planning*

After determining expansion value of each GENCOs with considering future load, each GENCO should start t’s planning process to maximize its profit. Profit in this paper defined as different between revenue from cost. Before GENCOs begin to plan. They should have generator data. this data that is for existing units and candidate units, included: unit type(gas, coil, etc), unit size, limit on the added unit per type, unit life, construction time, fixed cost of each unit (investment cost and fixed operation & maintenance costs), variable cost of each unit (operation costs), for of each unit, co2 emission of each GENCO. PBGEP is formulated as follows:

$$\min Y = -E\{\sum_{t=1}^{T}\sum_{b=1}^{B} DT_{bt} *[\sum_{i=1}^{NG}(R_{bt} * P_{G,ibt} - OC_{ibt} * P_{G,ibt}) -$$

$$\sum_{j=1}^{ND} CC_{jbt} * P_{C,jbt}]\} - \sum_{t}^{T}\sum_{i}^{CG} CI_{it} * (X_{it} - X_{i(t-1)})$$
$$-\left(\sum_{t}^{T}\sum_{i}^{CG}[FOM_i * X_{it}] - \sum_{t}^{T}\sum_{i}^{EG}[FOM_i * 1]\right) \quad (1)$$

$$\sum_{j=1}^{CG} CI_{it} * (X_{it} - X_{i(t-1)}) \le CI_t, t = (1,2,...,T) \quad (2)$$

$$\sum_{j=1}^{CG} cap_{it} * (X_{it} - X_{i(t-1)}) \le ULAC_t, t = (1,2,...,T) \quad (3)$$

$$\sum_{j=1}^{CG} (X_{it} - X_{i(t-1)}) \le ULAC_t, t = (1,2,...,T) \quad (4)$$

$$X_{it} = 0, if\,; t < CT_i, (i = 1,2,..., PG)(t = 1,2,...,T) \quad (5)$$

$$\sum_{i=1}^{EG} cap * E_{it} + \sum_{i=1}^{CG} cap_i * (X_{it} - X_{i(t-1)}) \ge P_{D,bt} + P_{R,bt} \quad (6)$$

(*b*=*peak load block*) (*t*=*1,2,…,T*)

$$X_{A1t} + X_{B1t} \le 1 \quad (7)$$

$$X_{A1t} = X_{A2t} = ... = X_{Amt} (t = T) \quad (8)$$

$$X_{A1t} = X_{A2t} = ... = X_{Ant} (t = T) \quad (9)$$

(A_1, A_2, …,$A_m \in A$ combination)

(B_1, B_2, …,$B_m \in B$ combination)

Outputs of this section are type, size and timing for the adding of new units that are as inputs of the next section.

B. ***Security-Constrained Generation Expansion Planning***

This section includes four sub-problems itself as follows:

1. *HSA Sub-problem*

In this sub-problem, ISO check planning bids of each GENCO to make sure that these are in acceptable level. If plans of each GENCOs are in the confine of *HSA* output, ISO pass those plans and run next sub-problem. Otherwise, ISO should send a security signal to GENCOs for improving their plans. This process will be repeated until reach ISO desired plans.

2. *Feasibility Sub-problem*

Feasibility sub-problem formulated as follow,

$$DT_{bt} * \sum_{j=1}^{ND} P_{C,jbt} \le \kappa_{bt} \quad (10)$$

$$E\{DT_{bt} * \sum_{j=1}^{ND} P_{C,jbt}\} \le \varepsilon_{bt} \quad (11)$$

$$\min E\{DT_{bt} * \sum_{j=1}^{ND} P_{C,jbt}\} \quad (12)$$

$$\sum_{i=1}^{NG} P_{C,jbt}(\varphi) + \sum_{j=1}^{ND} P_{C,jbt}(\varphi) = P_{L,bt}(\varphi) \tag{13}$$

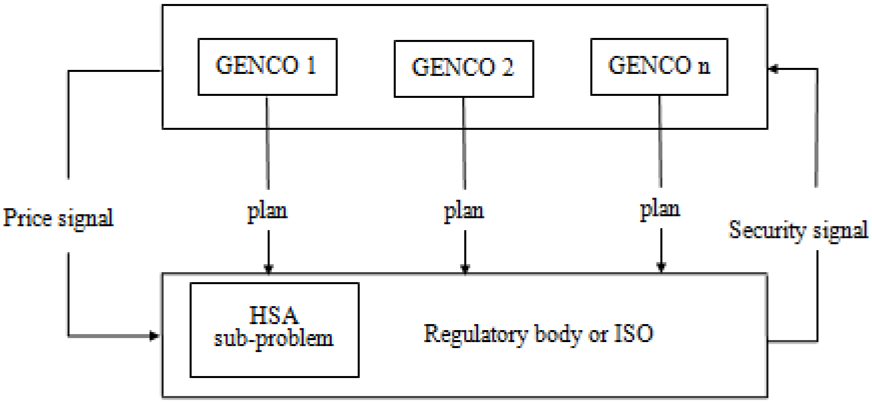


Figure 2: Generation expansion planning framework

$$P_{L,kbt}(\varphi) = D_{km}(\kappa) * [P_{G,ibt}(\varphi) + P_{C,ibt}(\varphi) - P_{D,jbt}(\varphi)], i, j \in m \tag{14}$$

$$0 \le P_{C,jbt}(\varphi) \le P_{D,jbt}(\varphi) \tag{15}$$

For existing units,

$$P_{Gi,\min} * E_{it} \le P_{G,jbt}(\varphi) \le P_{Gi,\max} * (E_{it}) \tag{16}$$

For candidate units,

$$P_{Gi,\min} * X_{it} \le P_{G,jbt}(\varphi) \le P_{Gi,\max} * (X_{it})$$

$$\left| P_{L,kbt}(\varphi) \right| \le PL_{k,\max} \tag{17}$$

If constraints (11) or (12) are not satisfied, corresponding benders cut will be generated as follow:

- If $DTbt * \Sigma^{ND}{}_{j=1} PC,jbt \le \kappa bt$ is not satisfied, the Bender cut is:

$$E\{DT_{bt} * \sum_{j=1}^{ND} P_{C,jbt}\} + \sum_{i=1}^{CG} \lambda_{ibt}^{n} P_{Gi,\max}(X_{it} - X_{it}^{n}) \le \varepsilon_{bt} \tag{18}$$

These n=1, 2, 3, . . . ,N−1 Bender cuts from the previous iterations are added to the master problem of resource planning to get the nth trial investment plan. The process will be repeated until a feasible plan is found for meeting the ISO’s requirement on system reliability.

3. Security-constrained Unit Commitment (SCUC) Sub-problem

Before solving the operation sub-problem, we calculate the electricity MCP over the planning horizon. We assume the MCP is the marginal cost of the most expensive unit among committed units based on the network security (Ghadimi and Ghadimi, 2011). SCUC is formulated as follows, the violations persist, the corresponding Bender cut will be generated as follows:

$$\min F = \sum_{j=1}^{NG} OC_{jbt} * P_{G,ibt} \tag{19}$$

$$\sum_{i=1}^{NG} P_{G,ibt}(\varphi) + \sum_{j=1}^{ND} P_{C,jbt}(\varphi) = P_{L,bt}(\varphi) \tag{20}$$

$$\sum_{i=1}^{NG} P_{Gi,\max} * I_{it} \ge P_{L,bt} + P_{R,bt} \tag{21}$$

$$P_{L,kbt}(\varphi) = D_{km}(\varphi) * [P_{C,jbt}(\varphi) + P_{C,jbt}(\varphi) - P_{D,jbt}(\varphi)], j \in m \tag{22}$$

$$\sum_{i=1}^{NG} P_{G,ibt} = P_{L,bt} \tag{23}$$

$$\sum_{t=1}^{T}\{\sum_{i=1}^{NG} P_{G,ibt}E_{ibt}\} \le \sigma_{bt} \tag{24}$$

$$0 \le P_{C,jbt}(\varphi) \le P_{D,jbt}(\varphi) \tag{25}$$

For existing and candidate units,

$$P_{Gi,\min} * I_{it} \le P_{G,ibt} \le P_{Gi,\max} * I_{it} \tag{26}$$

$$E\{DT_{bt} * \sum_{j=1}^{ND} P_{C,jbt}\} \le \varepsilon_{bt} \tag{27}$$

$$DT_{bt} * \sum_{j=1}^{ND} P_{C,jbt} \le \kappa_{bt} \tag{28}$$

The violations persist, the corresponding Bender cut will be generated as follows:

- If $DT_{bt} * \sum_{j=1}^{ND} P_{C,jbt} \le \kappa_{bt}$ cannot be satisfied, the Bender cut is:

$$E\{DT_{bt} * \sum_{j=1}^{ND} P_{C,jbt}\} + \sum_{i=1}^{CG} \mu_{ibt}^{n} P_{Gi,\max}(I_{it} - I_{it}^{n}) \le \varepsilon_{bt} \tag{29}$$

- If $E\{DT_{bt} * \sum_{j=1}^{ND} P_{C,jbt}\} \le \varepsilon_{bt}$ cannot be satisfied, the Bender cut is:

$$E\{DT_{bt} * \sum_{j=1}^{ND} P_{C,jbt}\} + \sum_{i=1}^{CG} \mu_{ibt}^{n} P_{Gi,\max}(I_{it} - I_{it}^{n}) \le \varepsilon_{bt} \tag{30}$$

Then the master problem of SCUC is solved iteratively to provide a least-cost generation schedule, while supplying the load demand.

4. Optimal operation sub-problem

After meeting the desired system reliability level and calculating the MCP, the optimal operation sub-problem for every planning scenario, year, and load block is formulated as follows:

$$\min W_{st} = -E\{\sum_{t=1}^{T}\sum_{b=1}^{B} DT_{bt} * [\sum_{i=1}^{NG} R_{bt} * P_{G,ibt} - OC_{ibt} * P_{G,ibt}) - \sum_{k=1}^{NL} TC_{k} * |P_{L,kbt}| - \sum_{j=1}^{ND}(CC_{jbt} * P_{C,jbt})]\} \tag{31}$$

For existing units which are committed,

$$P_{Gi,\min} \le P_{G,ibt}(\varphi) \le P_{Gi,\max} \tag{32}$$

For candidate units which are committed,

$$P_{Gi,\min} * X_{it} \le P_{G,ibt}(\varphi) \le P_{Gi,\max} * X_{it}$$

$$|P_{L,kbt}(\varphi)| \le PL_{k,\max} \tag{33}$$

The optimal operation cut associated with the nth trial solution is:

$$Z \le \sum_{t}\sum_{b}\{W_{bt}^{n} + [\sum_{i=1}^{CG} CI_{it} * (X_{it} - X_{i(t-1)}) + \Pi_{ibt}^{n} P_{Gi,\max}(X_{it} - X_{it}^{n})]\} \tag{34}$$

I. ***Proposed Algorithm***

A. *Review of Harmony Search Algorithm*

The brief procedure steps of harmony search for solving optimization problems are described in five steps as:

This procedure can be described as Figure 2.

Step 1: Arrange objective function and Equality & Inequality constraints in the following form:

$$\begin{aligned}&Minmize:\{f(x), x \in X\}\\&s.t\\&g(x) \geq 0\\&h(x) = 0\end{aligned} \tag{35}$$

where, *f(x)* is the objective function. X_i is the feasible set. x_i is the randomly selected parameter. *g(x)* is the inequality constraint. *h(x)* is the equality constraint (Mohammad *et al.*, 2013).

Step 2: Initialize Harmony Memory (HM)

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 \\ x_1^1 & x_2^2 & \cdots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \frac{\Delta y}{\Delta x} \tag{36}$$

Step 3: Harmony memory initialization

The New Harmony Improvisation is applied in this step and consists of two stages of HMCR and PAR in literature as;

Step 3.1:.1 Harmony Consider Rated (HMCR)

$$x_i' \leftarrow \left\{ \begin{matrix} x_i' \in \left\{x_i^1, x_i^2, ..., x_i^{HMS}\right\}(HMCR) \\ x_i' \in X_i\,(1-HMCR) \end{matrix} \right\} \tag{37}$$

Where x_i' is new value of x_i and *HMCR* is probability of choosing x_i' which PR means the probability function.

Step 3.2: pitch adjust rate (PAR)

$$x_i' \leftarrow \left\{ \begin{matrix} Yes, \Pr(PAR) \\ No, \Pr(1-PAR) \end{matrix} \right\} \tag{38}$$

Where, PAR is probability to shift x_i

$$x_i' \leftarrow x_i' \pm rand() \times bw \tag{39}$$

Where b*w* is range of x_i, rand is random number during 0-1.

Step 4: Update HM and check the stopping criterion Find value of f (x_i') from substitute x_i' [13].

Step 5: To check the stopping criterion, set the NI (Number of iteration) before begins to run the simulation; HS can stop calculation instantaneously when NI is reached.

B. ***Fuzzy Mechanism***

Upon having the Pareto-optimal set of non-dominated solution, the proposed approach presents one solution to the decision maker as the best compromise solutions. Due to imprecise nature of the decision maker's judgment, the ith objective function is represented by a membership function μi defined as (Mohammadhosein, 2013):

$$\mu_i(p_{gi}) = \frac{f_i^{\max} - f_i(p_{gi})}{f_i^{\max} - f_i^{\min}} \tag{40}$$

Where, f_i^{max} and f_i^{min} are the maximum and minimum values of ith objective, respectively.

$$FDM_i(p_{gi}) = \begin{cases} 0 & \mu_i(p_{gi}) \leq 0 \\ \mu_i(p_{gi}) & 0 < \mu_i(p_{gi}) < 1 \\ 1 & \mu_i(p_{gi}) \geq 1 \end{cases} \tag{41}$$

For each non-dominated solution k, the normalized membership function FDM^k is:

$$FDM^{k} = \left[\frac{\sum_{i=1}^{2} FDM_{i}^{k}(p_{gi})}{\sum_{j=1}^{M} \sum_{i=1}^{2} FDM_{i}^{j}} \right] \qquad (42)$$

The best compromise solution of congestion management problem is the one having the maximum value of FDM^k as fuzzy decision making function where M is the total number of non-dominated solutions ((Mohammad *et al*., 2013), Then, all the solutions are arranged in descending order according to their membership function values which will guide the decision makers with a priority list of non-dominated solutions in view of the current operating conditions. Figure 3 shows the membership structure μ_c for the fuzzy logical variable signifying total fuel cost $f_i(P_{gi})$.

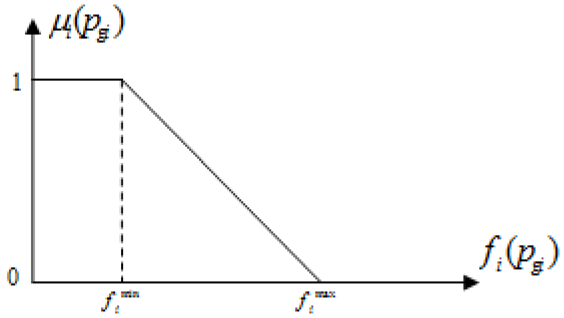


Figure 3: Membership function of fuzzy fuel cost

Case Study

The IEEE 30-bus system depicted in Figure 4 has 44-lines, 21-demand sides and 5-GENCOs with seven existing units and 22 Candidate units. The data for generators, forecasted peak demand with a load growth rate of 5%, available investment over a 15 year planning horizon, as well as the possible sites and types of candidate units and other information about the system are given in (HyungRoh *et al*., 2007) The initial construction cost represents the cost of construction at year 1. We assume that the construction cost will increase by 3% per year based on inflation.

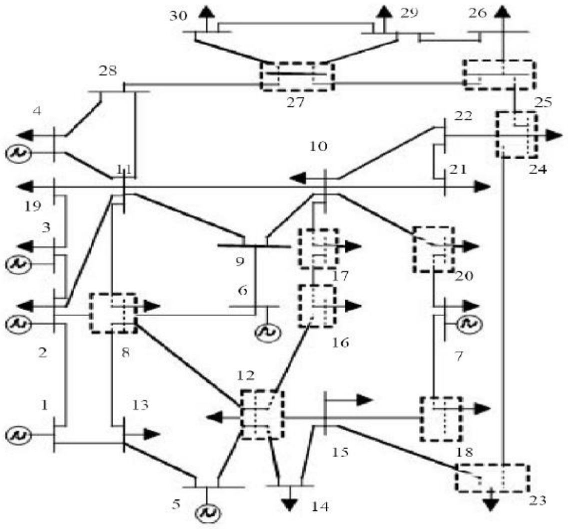
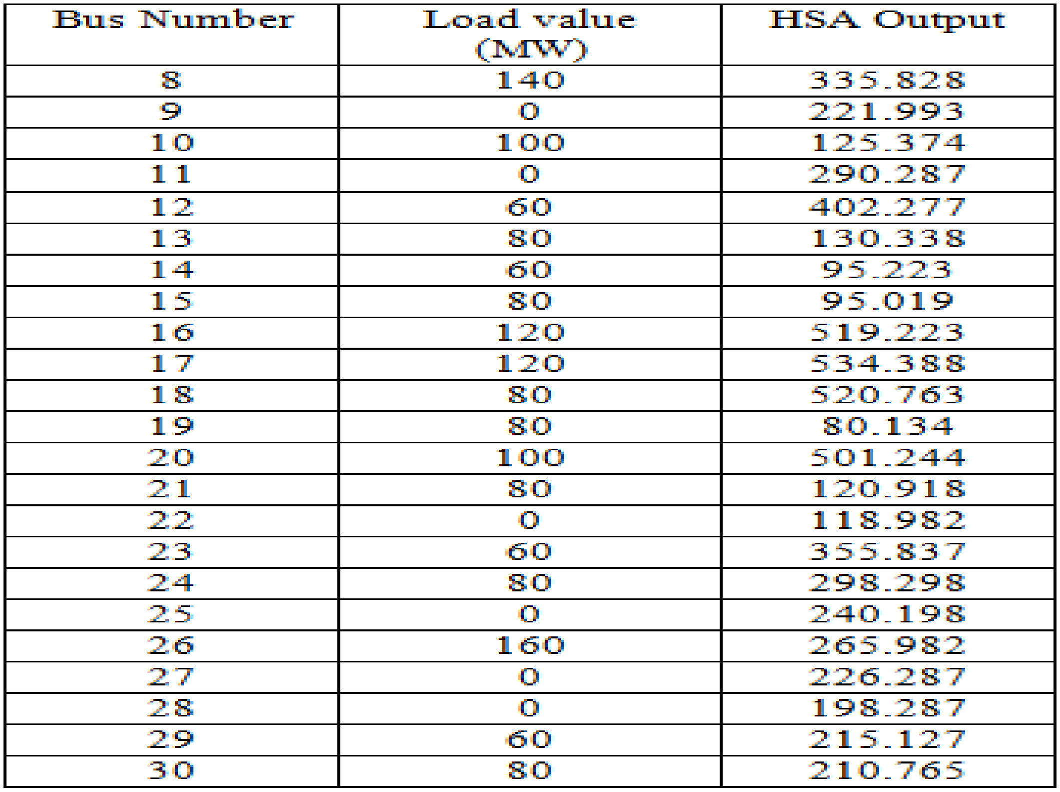


Figure 4: IEEE 30-bus test system

Table I: Outputs of hsa algorithm - contribution of each generator to load

Load bus number	Load value (MW)	Contribution of generator to load (MW)						
		G_1	G_2	G_3	G_4	G_5	G_6	G_7
8	140	17.112	30.661	18.123	38.822	16.177	14.240	4.865
10	160	2.443	13.212	12.443	30.984	20.181	30.363	50.374
12	100	2.554	8.272	4.387	10.345	45.653	5.234	23.555
13	120	30.098	8.382	11.345	25.534	17.347	6.716	20.578
14	60	3.873	23.234	3.556	7.663	16.837	3.882	0.955
15	80	1.234	4.211	3.532	7.908	25.548	5.374	32.193
16	60	1.654	4.234	3.098	7.097	20.759	5.474	17.684
17	80	1.567	4.098	3.786	15.345	15.393	12.098	27.713
18	120	1.453	5.235	5.984	5.345	15.938	1.445	84.600
19	120	1.521	2.554	102.013	8.124	0.553	0.565	4.670
20	80	0.563	3.012	1.345	2.887	3.255	2.456	66.482
21	80	0.563	1.334	5.574	15.181	12.987	12.187	32.174
23	100	2.112	5.445	6.994	15.383	25.985	7.038	37.043
24	80	2.445	7.432	5.093	15.987	10.543	12.984	25.516
26	160	5.873	15.332	18.736	63.987	15.983	14.938	25.151
29	60	1.644	4.987	7.377	25.276	5.543	4.224	10.949
30	80	2.590	8.353	9.883	35.094	5.098	5.987	12.995
Total generation (MW)		79.299	149.988	223.269	330.962	273.78	145.205	477.497

Table II: Outputs of HAS algorithm for the all of buses



Bus Number	Load value (MW)	HSA Output
8	140	335.828
9	0	221.993
10	100	125.374
11	0	290.287
12	60	402.277
13	80	130.338
14	60	95.223
15	80	95.019
16	120	519.223
17	120	534.388
18	80	520.763
19	80	80.134
20	100	501.244
21	80	120.918
22	0	118.982
23	60	355.837
24	80	298.298
25	0	240.198
26	160	265.982
27	0	226.287
28	0	198.287
29	60	215.127
30	80	210.765

In this study, the existing units are 4 years old each, have a useful life of 20 years, and will be out of service after 16 years. The forecasted reserve for a planning year is 500 MW (the largest unit available).

The ISO will use this figure in maximizing the social welfare and minimizing the cost of supplying the load.

Table III: Outputs of GEP algorithm - New units over the 15-year horizon

Planning Year	New unit added in each planning year
1	-
2	21,20
3	-
4	17
5	-
6	20
7	-
8	26
9	-
10	-
11	-
12	10
13	-
14	-
15	-

Table IV: Outputs of GEP algorithm - Value of each GENCO's profit and total profit

Genco1's profit	Genco2's profit	Genco3's profit	Genco4's profit	Genco5's profit	Total Profit
260.812	840.117	416.287	0	120.762	1637.978

At first, we calculate DLG matrix by HSA. Where, the achieved results are presented in Table 1. The Table1 shows contribution of each generator to satisfy considered load. The values for all the newly added generations are computed and compared as shown in Table 2. Accordingly, GENCOs with considering these data and other necessary data for planning run PBGEP problem to reach best plan that maximize its profit and submit it to ISO. Then, ISO with running SCGEP will accept or reject GENCO's proposed plans. Results of running this algorithm on supposed system are shown in Table 3. Table 4 shows value of each GENCO's profit and total profit. With comparing these results and outputs of HSA, shows that selected units at planning horizon are in acceptable level.

CONCLUSION

This paper presents a generation expansion planning in restructured power systems is presented based on HSA and fuzzy mechanism for decoupling generation expansion planning from transmission expansion planning. HSA is a recently developed powerful evolutionary algorithm, inspired by the improvisation process of musicians, for solving single or multi-objective optimization problems. Accordingly, calculate value of each GENCO's profit and total profit are considered as an optimization problem by proposed method. The effectiveness of the proposed technique is applied over modified IEEE 30-bus system. The presented results demonstrate the efficiency the proposed technique. With comparing these results and outputs of proposed method, shows that selected units at planning horizon are in acceptable level. In other word, with investing on this unit we ensure that can satisfy load without any congestion in transmission lines.

Nomenclatures

Indices:

I Existing or candidate unit
j Load point

k	Transmission line
m	Bus
n	Trial
b	Load block
t	Planning year
φ	Scenario

Parameters:

B	Number of load blocks
$Capi$	Capacity of unit i
CTi	Required construction time for candidate unit i
Cit	Capital investment in year t
$CIit$	Capital investment for candidate unit i in year t
$CCjbt$	Curtailment cost coefficient for load j at load block$b$ in year t
CG	Number of candidate units
CS	Set of candidate sites
Dkm	Sensitivity of line k flow to generation at bus m
$DTbt$	Duration of load block b in year t
EG	Number of existing units
$FOMi$	Fixed O&M cost of unit i
TCk	Transmission charge of line k
ND	Number of load points
NG	Number of committed units
NL	Number of transmission lines
$OCibt$	Operating cost unit i among committed units atload block b in year t
$Eibt$	CO2 emission of unit i among committed units atload block b in year t
PL,bt	required system load *at* load block b in year t
PD,jbt	Forecasted load point j at load block b in year t
PD,bt	Forecasted system load at load block b in year t
$PGi,$	min Lower limit of generation of unit i
$PGi,$	max Upper limit of generation of unit i
$PLk,$	max Capacity of line k
T	Planning horizon
$ULAUt$	Upper limit for the # of units added in year t
$ULACt$	Upper limit for generating capacity added inyear t
δbt	Acceptable limit of co2 emission at load block $b$in year t
κbt	Acceptable level of curtailment at load block $b$in year t
εbt	Acceptable level of EENS
Δ	Convergence threshold

Variables:

Eit	State variable associated with existing unit i inyear t; 1: on service, 0: out of service
$Iibt$	Commitment of unit i at load block b in year t; 1:committed, 0: decommitted/out of service
Rbt	Electricity sale price at load block b in year t
PC, jbt	Curtailment of load j at load block b in year t
PG,ibt	Dispatched capacity of committed unit i at loadblock b in year t
PL,kbt	Line k flow at load block b in year t
Xit	State variable associated with candidate unit i inyear t; 1: selected, 0: rejected. $(Xi\,(t-1)\ \_\ Xi\,t\,)$

Dual variables:

λ^{n}_{ibt}	Marginal decrease in unserved energy with a 1MWincrease in candidate unit i at load block b in year $t$associated with the nth trial plan.

μ^{n}_{ibt} Marginal decrease in unserved energy with a 1MW increase in commitment unit *i* at load block *b* in year*t* associated with the *n*th trial plan.

π^{n}_{ibt} Marginal increase in profit with a 1 MWincrease in candidate unit *i* at load block *b* in year *t*associated with the *n*th trial plan.

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