HARMONY SEARCH ALGORITHM BASED 0-1 INTEGER PROGRAMMING FOR GENERATION MAINTENANCE SCHEDULING IN POWER SYSTEMS

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ABSTRACT

This paper presents a Harmony Search Algorithm to seek the optimal solution of the unit maintenance scheduling. For the maintenance scheduling, cost reduction is as important as reliability. The objective function of this algorithm considers the effect of economy as well as reliability. Various constraints such as spinning reserve, duration of maintenance crew are being taken into account. We apply the Harmony Search which is a music-inspired meta-heuristic algorithm on a power system with six generating units. We obtain one optimal solution. Numerical results reveal that the proposed algorithm can find better and faster solutions when compared to other heuristic or deterministic methods.

Keywords: *Harmony Search Algorithm, Integer Programming, Maintenance Scheduling, Optimization*

1. INTRODUCTION

The power station maintenance department exists to help the production function to maximize plant reliability, availability and efficiency by determining both short and long term maintenance requirements and by carrying out the work accordingly. This includes work to comply with statutory and mandatory requirements and investigations into plant problems. The department has to make the most economic use of its available resources; this is achieved, in part, by having a level of staff (engineering, supervisory, craft) to deal with the general day-to-day steady workload and by making alternative arrangements to cater for work load peaks [1].

To achieve the above goal, periodic servicing must take place and normally falls under the following items [1]:

1) Planned maintenance: overhaul, preventive maintenance
2) Unplanned maintenance: emergency maintenance

Preventive maintenance is expensive. It requires shop facilities, skilled labor, keeping records and stocking of replacement parts. However, the cost of downtime resulting from avoidable outages may amount to ten or more times the actual cost of repair. The high cost of downtime makes it imperative to economic operation that maintenance be scheduled into the operating schedule [1].

The maintenance scheduling problem is to determine the period for which generating units of an electric power utility should be taken off line for planned preventive maintenance over the course of a one or two year planning horizon, in order to minimize the total operating cost while system energy, reliability requirements and a number of other constraints are satisfied [2].

2. SOLUTION APPROACH

In the recent decade, many efforts which are categorized as follows have been done in the maintenance scheduling field:

1) Lagrangian relaxation [3]
2) Linear programming [4]
3) Mixed integer programming [5]
4) Decomposition methods [6]
5) Goal programming [7]
6) Tabu search [8]
7) Simulated annealing [9]
8) Genetic algorithm [10] –[13]
9) Fuzzy logic [14] – [17]
10) Neural networks [18]
11) Expert systems [19], [20]

12) Meta heuristic-based hybrid approaches [21]
13) Particle swarm optimization [22]
14) Ant colony optimization [23]
15) Deterministic approaches [24]

3. HARMONY SEARCH ALGORITHM

The harmony search algorithm (HSA) is a music-inspired evolutionary algorithm, mimicking the improvisation process of music players [25], [26]. The HS is simple in concept, few in parameters, and easy in implementation, with theoretical background of stochastic derivative [26]. The algorithm was originally developed for discrete optimization and later expanded for continuous optimization [27]. It has been successfully applied to various benchmark and real-world problems including traveling salesman problem, parameter optimization of river flood model, design of pipeline network, and design of truss structures. The steps in the procedure of harmony search are shown in Figure 1. They are as follows [28]:

Step 1: Initialize the problem and algorithm parameters
Step 2: Initialize the harmony memory
Step 3: Improvise a new harmony
Step 4: Update the harmony memory
Step 5: Check the stopping criterion

These steps are described in the next five subsections:

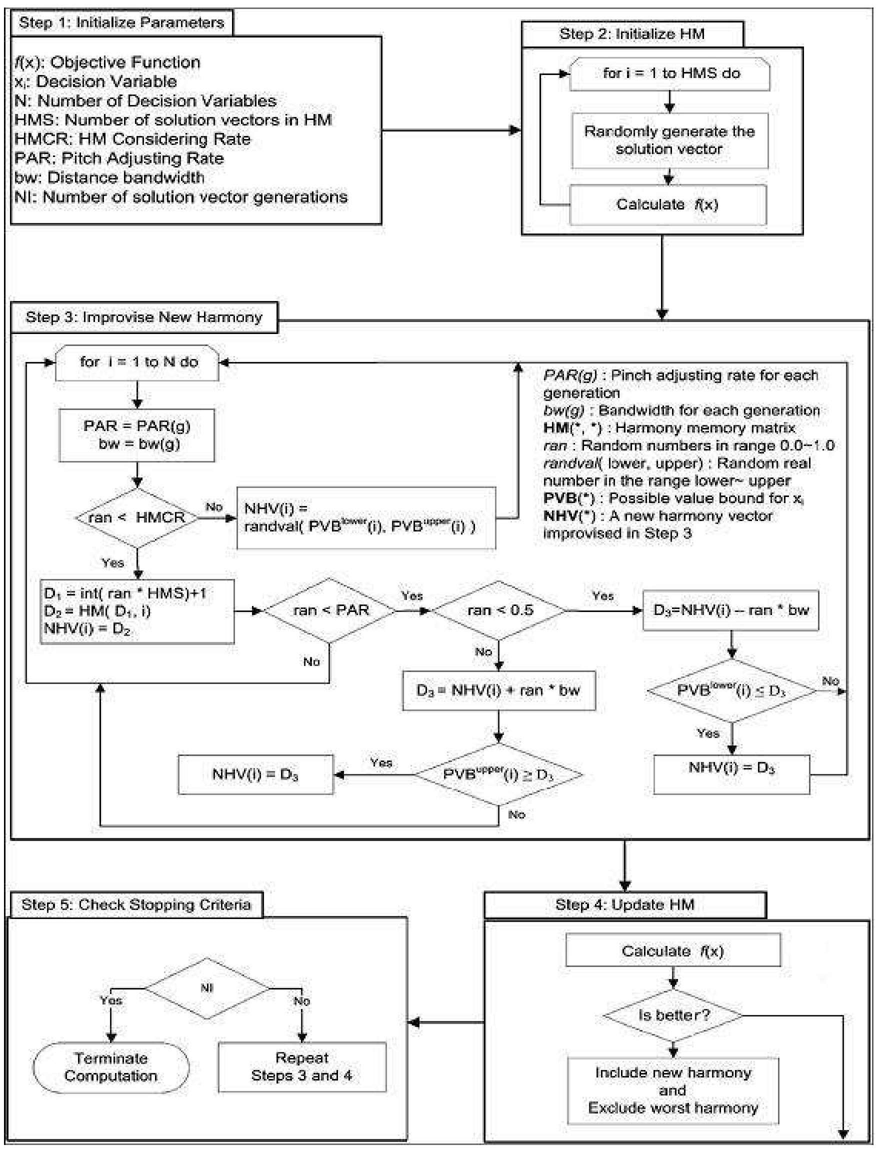

Figure 1. Optimization procedure of the harmony search algorithm [25]

3.1. Initialize the problem and algorithm parameters

In Step 1, the optimization problem is specified as follows:

$$\begin{aligned} &\text{Minimize} && f(\vec{x}) \\ &\text{Subject to} && g_i(\vec{x}) \geq 0 \qquad i = 1,2,\ldots,M. \\ & && h_j(\vec{x}) = 0 \qquad j = 1,2,\ldots,P. \\ & && {}_L x_k \leq x_k \leq {}_U x_k \qquad k = 1,2,\ldots,N. \end{aligned} \tag{1}$$

Where $f(\vec{x})$ is the objective function, M is the number of inequality constraints and P is the number of equality constraints. x is the set of each decision variable x_i ; N is the number of decision variables. The lower and upper bounds for each decision variable are ${}_L x_i$ and ${}_U x_i$ respectively. The HSA parameters are also specified in this step. These are the harmony memory size (HMS), or the number of solution vectors in the harmony memory, harmony memory considering rate (HMCR), pitch adjusting rate (PAR), and the number of improvisations (NI), or stopping criterion. The harmony memory (HM) is a memory location where all the solution vectors (sets of decision variables) are stored. The HM is similar to the genetic pool in the genetic algorithms (GAs) [28].

Here, HMCR and PAR are parameters that are used to improve the solution vector. Both are defined in Step 3.

3.2. Initialize the harmony memory

In Step 2, the HM matrix is filled with as many randomly generated solution vectors as the HMS:

$$\text{HM} = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \cdots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{\text{HMS}-1} & x_2^{\text{HMS}-1} & \cdots & x_{N-1}^{\text{HMS}-1} & x_N^{\text{HMS}-1} \\ x_1^{\text{HMS}} & x_2^{\text{HMS}} & \cdots & x_{N-1}^{\text{HMS}} & x_N^{\text{HMS}} \end{bmatrix}. \tag{2}$$

Infeasible solutions that violate the constraints have a chance to be included in the HM with hope of forcing the search towards the feasible solution area. Static penalty functions are used to calculate the penalty cost for an infeasible solution. The total cost for each solution vector is evaluated using:

$$fitness(\vec{x}) = f(\vec{x}) + \sum_{i=1}^{M} \alpha_i \times \min\left|[0, g_i(\vec{x})]\right| + \sum_{j=1}^{P} \beta_j \times \left|\min[0, h_j(\vec{x})]\right|. \tag{3}$$

Where α_i and β_j are the penalty coefficients. Generally, it is difficult to find a specific rule to determine the values of the penalty coefficients and normally these parameters remain problem-dependent.

3.3. Improvise a new harmony

A new harmony vector $\vec{x}' = (x_1', x_2', \ldots, x_N')$ is generated based on three rules:

1) Memory consideration
2) Pitch adjustment
3) Random selection

Generating a new harmony is called "improvisation" [28]. In the memory consideration, the value of the first decision variable (x_1') for the new vector is chosen from any of the values in the specified HM range $(x_1' - x_1^{\text{HMS}})$. Values of the other decision variables $(x_2', x_3', \ldots, x_N')$ are chosen in the same manner. The HMCR, which varies between 0 and 1, is the rate of choosing one value from the historical values stored in the HM, while (1-HMCR) is the rate of randomly selecting one value from the possible range of values, as shown in (4).

$$\begin{aligned} &\text{if}\,(rand\ () < \text{HMCR}\ ) \\ &\quad x_i' \leftarrow x_i' \in \{x_i^1, x_i^2, \cdots, x_i^{\text{HMS}}\} \\ &\text{else} \\ &\quad x_i' \leftarrow x_i' \in X_i \\ &\text{end}. \end{aligned} \tag{4}$$

Where *rand ()*: is a uniform random number between 0 and 1 and X_i is the set of the possible range of values for each decision variable, that is ${}_L x_i \leq X_i \leq {}_U x_i$.

For example, a HMCR of 0.85 indicates that the HSA will choose the decision variable value from historically stored values in the HM with an 85% probability. Every component obtained by the memory consideration is examined to determine whether it should be pitch adjusted. This operation uses the PAR parameter, which is the rate of pitch adjustment as follows:

$$\begin{array}{l} \text{if}\,(rand\,() < \text{PAR}\,) \\ \quad x'_i \leftarrow x'_i \pm rand\,() * \text{bw} \\ \text{else} \\ \quad x'_i \leftarrow x'_i \\ \text{end}\,. \end{array} \tag{5}$$

Where bw, is an arbitrary distance bandwidth. To improve the performance of the HSA and eliminate the drawbacks associated with fixed values of PAR and bw.

Reference [29] proposed an improved harmony search (IHS) algorithm that uses variable PAR and bw in improvisation step. In their method PAR and bw change dynamically with generation number as expressed below:

$$\text{PAR(gn)} = \text{PAR}_{\min} + \frac{(\text{PAR}_{\max} - \text{PAR}_{\min})}{\text{NI}} \times \text{gn}. \tag{6}$$

Where PAR (gn) is the pitch adjusting rate for each generation, $\text{PAR}_{\min}$ is the minimum pitch adjusting rate, $\text{PAR}_{\max}$ is the maximum pitch adjusting rate and gn is the generation number.

$$\begin{array}{l} \text{bw(gn)} = \text{bw}_{\max} \exp(\,c.\text{gn}\,). \\ c = \dfrac{Ln\left(\dfrac{\text{bw}_{\min}}{\text{bw}_{\max}}\right)}{\text{NI}}. \end{array} \tag{7}$$

Where bw(gn) is the bandwidth for each generation, $\text{bw}_{\min}$ is the minimum bandwidth and $\text{bw}_{\max}$ is the maximum bandwidth. Recently other variants of harmony search have been proposed. Reference [30] proposed a new variant of harmony search, called the global best harmony search (GHS), in which concepts from swarm intelligence are borrowed to enhance the performance of HSA such that the new harmony can mimic the best harmony in the HM. Reference [31] proposed a new stochastic derivative for discrete variables based on a harmony search algorithm to optimize problems with discrete variables and problems in which the mathematical derivative of the function cannot be analytically obtained.

3.4. Update harmony memory

If the new harmony vector, $\vec{x}' = (x'_1, x'_2, \ldots, x'_N)$, has better fitness function than the worst harmony in the HM, the new harmony is included in the HM and the existing worst harmony is excluded from the HM.

3.5. Check stopping criterion

The HSA is terminated when the stopping criterion (e.g., maximum number of improvisations) has been met. Otherwise, Steps 3 and 4 are repeated.

4. THE INTEGER PROGRAMMING PROBLEM

Many power systems areas (e.g., short-term hydro scheduling [32], optimal reconfiguration and capacitor allocation [33], reactive power market clearing [34], transmission network expansion planning [35], etc.) require the variables to be integers. These problems are called Integer Programming problems. Optimization methods developed for real search spaces can be used to solve Integer Programming problems by rounding off the real optimal values to the nearest integers. Maintenance scheduling problem is kind of 0-1 Integer Programming. Importance of HSA is in solving the problems of nonlinear optimization in the space of real numbers and has numerous applications in the problems related to engineering optimization. The authors of this paper, in order to expand the above mentioned matter in 0-1 integer programming, consider the real numbers of the problem, which at the beginning of HS algorithm are chosen randomly in the interval [0, 1]. While doing algorithm, randomly, some values are added to them or subtracted from them, but again the new values in the interval [0, 1] will remain. For solving the problem, values equal to or higher than 0.5 are rounded to 1 and values less than 0.5 are rounded to 0.

5. MAINTENANCE SCHEDULING MODEL

In this paper, we use Leou’s model with two objective functions [1], [16]. The binary nature of the maintenance scheduling problem makes it very reasonable to use integer programming optimization method. This method is computationally acceptable even for problems with a large number of variables and constraints. In this paper, the beginning time of maintenance is adopted as the state variable. The maintenance scheduling problem can be set up as a 0-1 integer programming whose general form is: find the n-vector x^* which minimizes the cost function.

$$z = c^T x \tag{8}$$

s.t.

$$Ax \leq b \tag{9}$$

Where $x_i = 0$ or 1, $i = 1,2,..., n$.

A feasible solution is a solution x which satisfies the constraints. A feasible n-vector x^* is optimal if and only if solution $c^T x^* \leq c^T x$ for all feasible x. Each x_i is associated with beginning maintenance on some unit j during some week k if and only if $x_i = 1$. for each problem tables relating i, j, and k are developed. Consider a group of six units that must be maintained during a ten week period. The machine input data are shown in Table 1.

Table 1. Machines input data for six unit system

Unit No.	Allowed period	Capacity (MW)	Maintenance crew	Outage duration
1	1-4	200	10	3
2	3-6	300	15	4
3	5-7	300	15	4
4	6-9	300	15	4
5	12-14	500	20	4
6	14-16	500	20	4

From Table 1, it can be seen that only four units (unit 1 to 4) should be maintained during the ten week period. The variables associated with each unit that should be maintained are given in Table 2.

In this table i, j, and k respectively shows "Associated unknown", "Unit No." and "Maintenance starts in week". For instance, if $x_6 = 1.$, maintenance on unit 2 begins on the fourth week.

5.1. Objective function

The deferring maintenance of units may cause damage on the machines. In order to improve the reliability of the power system and save the maintenance expense of the damaged machines, the objective function adopted in this paper, was to maintain the units as earlier as possible. Take the six-unit system. Only four units should be maintained during the following ten week period. The objective functions can be expressed as the following forms:

$$c_1 = [\ 1\ 2\ 3\ 4\ 1\ 2\ 3\ 4\ 1\ 2\ 3\ 1\ 2\ 3\ 4\ ] \tag{10}$$

$$c_2 = [\ 0\ 1\ 2\ 3\ 0\ 1\ 2\ 3\ 0\ 1\ 2\ 0\ 1\ 2\ 3\ ] \tag{11}$$

According to (8), values in the c_1 vector [1] and c_2 vector [16], [17] are the coefficients of objective functions and express the maintenance cost of each one of unit generators.

For each unit there is a cost of 1 associated with the beginning of the maintenance during the first allowed week. There is a cost of 2 imposed for beginning maintenance in the second week. The schedule that minimizes this cost function is the "earliest possible" maintenance schedule.

5.2. Constraints

5.2.1. Spinning reserve

In order to maintain the electric power supply normally, there must have a lot of spinning reserve to compensate for the outage of the generating units. The spinning reserve constraint can be expressed as below:

$$\text{Capacity for maintenance} + \text{load capacity} \\ . + \text{spinning reserve} \leq \text{generating capacity} \tag{12}$$

5.2.2 Maintenance crew

For each period, numbers of the people, who to perform maintenance schedule, cannot exceed the available crew. Assume the number of people available for maintenance is P. The maintenance crew should satisfy the following constraint for each period.

$$\text{Numbers of people are performing maintenance} \leq P \tag{13}$$

Table 2. State variables for six unit system during ten week period

x_i	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}
(j,k)	(1,1)	(1,2)	(1,3)	(1,4)	(2,3)	(2,4)	(2,5)	(2,6)	(3,5)	(3,6)	(3,7)	(4,6)	(4,7)	(4,8)	(4,9)

5.3. Duration of maintenance

In order to let the units operate in good condition, the units should be maintained after a period of operation.

CASE STUDY

6.1. Input data

In this section, test results of the six-unit test system mentioned previously is reported. As indicated in Table 1, the six-unit system can generate 2100 MW, and the number of people available for maintenance is 50. During the maintenance period (ten week interval), only four units (unit 1 to unit 4) need to perform maintenance. The machines input data are shown in Table 1.

Figure 2 shows the load curve of the system. The spinning reserve is 400 MW.

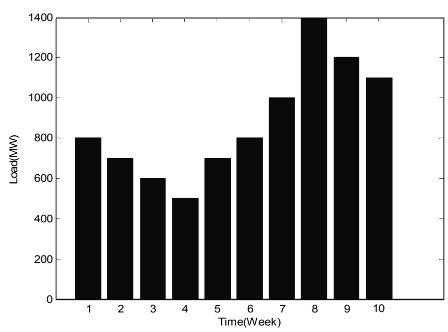

Figure 2. Load curve of the six unit system

Integrate with these input data, the model is shown as follows:

Min

$$Z = x_1 + 2x_2 + 3x_3 + 4x_4 + x_5 + 2x_6 + 3x_7 + 4x_8$$
$$+ x_9 + 2x_{10} + 3x_{11} + x_{12} + 2x_{13} + 3x_{14} + 4x_{15}$$

s.t.

$$x_1 + x_2 + x_3 + x_4 = 1$$
$$x_5 + x_6 + x_7 + x_8 = 1$$
$$x_9 + x_{10} + x_{11} = 1$$
$$x_{12} + x_{13} + x_{14} + x_{15} = 1$$
$$200x_1 + 800 + 400 \le 2100$$
$$200x_1 + 200x_2 + 700 + 400 \le 2100$$
$$200x_1 + 200x_2 + 200x_3 + 300x_5 + 600 + 400 \le 2100$$
$$200x_2 + 200x_3 + 300x_5 + 200x_4 + 300x_6 + 500 + 400 \le 2100$$
$$200x_3 + 300x_5 + 200x_4 + 300x_6 + 300x_7 + 300x_9 + 700 + 400 \le 2100$$
$$300x_5 + 200x_4 + 300x_6 + 300x_7 + 300x_9 + 300x_8 + 300x_{10}$$
$$. + 300x_{12} + 800 + 400 \le 2100$$
$$300x_6 + 300x_7 + 300x_9 + 300x_8 + 300x_{10} + 300x_{12}$$
$$. + 300x_{11} + 300x_{13} + 1000 + 400 \le 2100$$
$$300x_7 + 300x_9 + 300x_8 + 300x_{10} + 300x_{12} + 300x_{11}$$
$$. + 300x_{13} + 300x_{14} + 1400 + 400 \le 2100$$
$$300x_8 + 300x_{10} + 300x_{12} + 300x_{11} + 300x_{13} + 300x_{14}$$
$$. + 300x_{15} + 1200 + 400 \le 2100$$
$$300x_{11} + 300x_{13} + 300x_{14} + 300x_{15} + 1100 + 400 \le 2100$$
$$10x_1 \le 50$$
$$10x_1 + 10x_2 \le 50$$
$$10x_1 + 10x_2 + 10x_3 + 15x_5 \le 50$$
$$10x_2 + 10x_3 + 15x_5 + 10x_4 + 15x_6 \le 50$$
$$10x_3 + 15x_5 + 10x_4 + 15x_6 + 15x_7 + 15x_9 \le 50$$
$$15x_5 + 10x_4 + 15x_6 + 15x_7 + 15x_9 + 15x_8 + 15x_{10} + 15x_{12} \le 50$$
$$15x_6 + 15x_7 + 15x_9 + 15x_8 + 15x_{10} + 15x_{12} + 15x_{11} + 15x_{13} \le 50 \quad (14)$$
$$15x_7 + 15x_9 + 15x_8 + 15x_{10} + 15x_{12} + 15x_{11} + 15x_{13} + 15x_{14} \le 50$$
$$15x_8 + 15x_{10} + 15x_{12} + 15x_{11} + 15x_{13} + 15x_{14} + 15x_{15} \le 50$$
$$15x_{11} + 15x_{13} + 15x_{14} + 15x_{15} \le 50$$

1st to 4th constraints of (14) indicate the beginning maintenance constraint for unit 1 to unit 4. 5th to 14th constraints of (14) represent the spinning reserve constraints. From the machine input data of Table 1, in period 1 and period 2 only unit 1 is possible to perform the maintenance. The 6th constraint contains two items, which are $200x_1$ and $200x_2$. $200x_2$ describes the possibility of unit 1 start maintaining in period 2. 200 is the capacity of unit 1. Since the outage duration of unit 1 lasting 3 periods, hence $200x_1$ is included in the 6th constraint. For the same consideration, the spinning reserve constraint of period 3 is included in the 7th constraint. In addition to consideration of spinning reserve constraints, the available people to perform maintenance are also important. 15th to 24th constraints of (14) describe the consideration of crew constraints. In this case, the available people to perform maintenance are 50 people. In period 1, from the machine data shown in Table 1, only unit 1 is possible in maintenance. The crew constraint of period 1 is shown in the 15th constraint. Numbers of people needed to perform maintenance for unit 1 are ten people. In period 2, also only unit 1 is possible for maintenance, but unit 1 may start to maintain between period 1 and period 4. Therefore, in period 2, the crew constraint is demonstrated in the 16th constraint. Following the same rule, we build the crew constraints for all periods. According Figure 1, HSA is based on two loops. Firs loop (improvisation), is the main improvement loop. Second loop is the value giving loop of the objective function parameters. The second loop is placed in into the first loop. Therefore, computational time and complexity is $O(kn^2)$. n is the numbers of the first loop and k is a coefficient that is related to the number of constraints which are added to the objective function by penalty coefficients. The number of equality constraints (P) is defined as the number of generator units which are maintained and the number of inequality constraints (M) is made of the constraints related to spinning reserve and maintenance crew and that is twice the number of the weeks of maintenance of generator units, so the total of constraints is equal to:

$$\begin{aligned} P + M = {} & \text{The number of generators being maintained} + \\ & .2 \times (\text{The number of weeks} \\ & \quad .\text{in which maintenance is done}) \end{aligned} \tag{16}$$

With the increase of n, the $O(kn^2)$ will be almost equal to $O(n^2)$. It means that changes in the number of constraints which depends on P+M has less effect in the computational time and complexity. Equality constraints can be removed. For example, in the first four constraints, we can write x_1, x_5, x_9 and x_{12} according to rest of x_i s and place them in the inequality constraints. Therefore, we can generate minimal number of constrains in order not to miss the all possibilities. In (3), α_i and β_j respectively are 1 and 400. The HMS (The population size) of the harmony matrix is 20.

6.2. Output result

Programming commands used in this simulation are taken from VB.Net software. The problem formulated with c_1 vector is solved Using HSA. Regarding six generators, we will observe if HMCR=0.7 and PAR=0.2, the harmony matrix goes towards optimal solution. The optimal solution is obtained by Iteration of 30,000. The favorable value of solution is obtained while most of harmonies (rows) go towards a certain value. By shifting the value of HMCR and PAR, harmony matrix solutions will change in point of convergence velocity and accuracy. The result will be, if HMCR value is close to one and PAR value is close to zero, the convergence velocity improves. Of course, it should be kept in mind that more Iteration will lead to more accurate solutions. Figure 3 and Figure 4, show harmony matrix with Z and fitness function for two different numbers of Iteration.

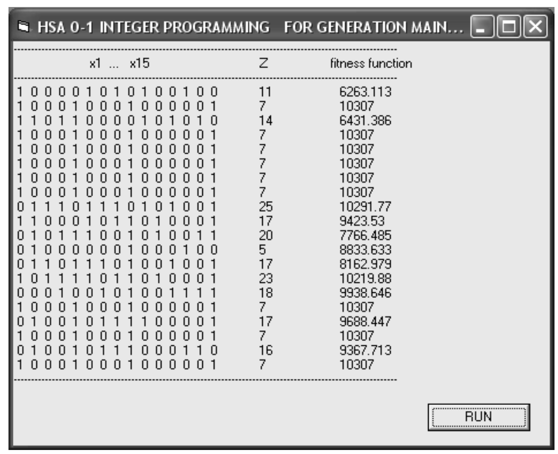

Figure 3. The harmony matrix (HMCR=0.7, PAR=0.2, Iteration= 20,000)

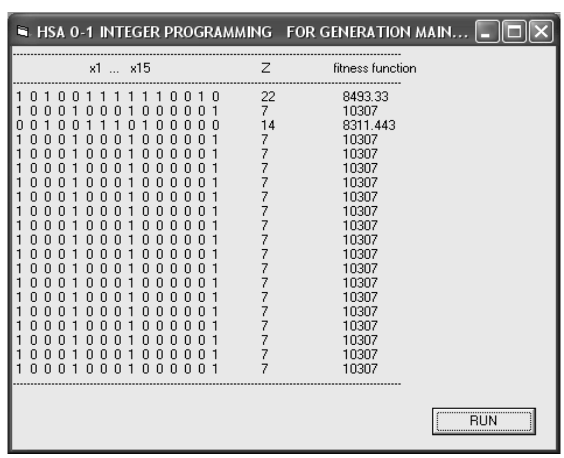

Figure 4. The harmony matrix (optimal solution (HMCR=0.7, PAR=0.2, Iteration= 30,000))

The obtained value of Z=7 calculated by HSA is equal to Z obtained through [1] while HSA is easier to implement and more accurate with greater velocity (see Table 3).

Again, in the same manner as above, the formulated problem is solved with c_2 vector. The obtained results are shown in Table 3 and Figure 5.

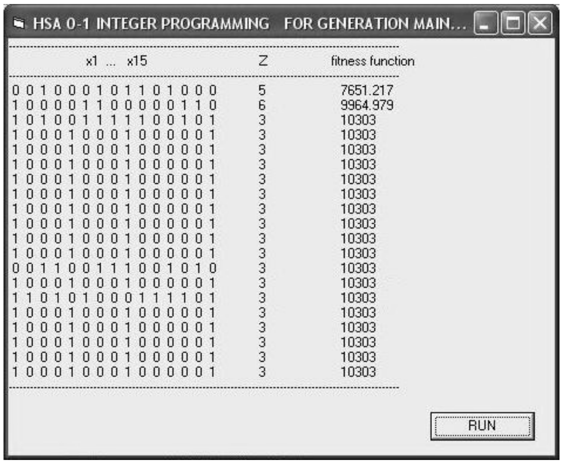

Figure 5. The harmony matrix (optimal solution (HMCR=0.8, PAR=0.2, Iteration= 70,000))

Compared with Leou's method (Fuzzy 0-1 Integer Programming) that calculates Z in 9 and 5 values [1], [15], HSA is more proper and simpler. Also, in comparison to implicit enumeration that calculates Z in 7 and 3 values [1], HSA is faster.

6. CONCLUSION

In this paper, 0-1 Integer Programming based on the Harmony Search Algorithm (HSA) for finding an optimal generation maintenance schedule is presented. The purpose of objective function is to make units maintain as earlier as possible. Constraints are spinning reserve, crew and duration of maintenance. Using the above method in a six unit system, we find one optimal solution among harmony matrix. Comparing the optimal schedule with other optimization methods indicates that ours is better than theirs.

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Table 3. Optimal solution

	Objective function with c_1 vector			Objective function with c_2 vector		
x	Fuzzy 0-1 Integer Programming	Implicit enumeration	**HSA**	Fuzzy 0-1 Integer Programming	Implicit enumeration	**HSA**
x_1	0	1	**1**	0	1	**1**
x_2	0	0	**0**	0	0	**0**
x_3	1	0	**0**	1	0	**0**
x_4	0	0	**0**	0	0	**0**
x_5	1	1	**1**	1	1	**1**
x_6	0	0	**0**	0	0	**0**
x_7	0	0	**0**	0	0	**0**
x_8	0	0	**0**	0	0	**0**
x_9	1	1	**1**	1	1	**1**
x_{10}	0	0	**0**	0	0	**0**
x_{11}	0	0	**0**	0	0	**0**
x_{12}	0	0	**0**	0	0	**0**
x_{13}	0	0	**0**	0	0	**0**
x_{14}	0	0	**0**	0	0	**0**
x_{15}	1	1	**1**	1	1	**1**
Z	9	7	**7**	5	3	**3**

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