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Harmony Search Method Based Parallel Contingency Analysis

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Abstract—**Power system security management is one of the key problems in power system analysis. Power system management center operators need to simulate contingencies as fast as possible and take the remedial actions in time. These contingency analyses comprise of the outages of the branches, transformers and other power system components. This paper solves branch outage problem using a bounded approach. Harmony search method is used to solve the local constrained optimization problem of the bounded approach. Several outage simulations using IEEE 14, 30, and 118 bus systems are performed and compared against AC power flow in terms of accuracy. In order to speed up the contingency simulation, the problem is also solved in a parallel environment. Speed up results of the IEEE 118 and 300 bus test systems are given.**

***Index Terms*--branch outage, contingency studies, harmony search method, intelligent methods, modeling, optimization.**

I. INTRODUCTION

POWER systems are composed of transmission lines, transformers, generators, etc. Outage of one of these components may cause significant disturbances in a system. Hence, electricity management system operators need to simulate the effects of possible component outages and take remedial actions in time. One of the fundamental analyses they should perform is the contingency analysis, which includes consecutive branch outage simulation of the system branches one by one and the calculation of post outage bus voltage magnitudes and reactive power flows.

The classical method used for branch outage simulation is the AC power flow analysis. Since, it requires the information of all branch admittance magnitudes its computational efficiency decreases as the power system under investigation gets larger and larger. Thus, it is not suitable for handling real time systems. Several other methods based on linearized approaches have been developed but they lack in handling especially the post outage bus voltage magnitudes and reactive power flow magnitudes in accuracy [1-3]. A recent paper formulates branch outage problem as a local constrained optimization problem [4]. A pair of fictitious reactive power sources is inserted to the terminals of the outaged branch and only the first order degree of the neighbors of the corresponding buses is included in the computation. That is why; this method is faster than the other mentioned methods.

Optimization problems can either be solved analytically or numerically. Numerical methods are gradient based methods such as; steepest descent method, conjugate gradient method, Lagrangian method etc. Non-gradient based methods are the ones such as particle swarm optimization method, differential evolution method, harmony search method, etc.

Gradient based methods use the information of the gradients of the variables; on the other hand non-gradient based methods do not need to use the information of the gradients of the variables. Non-gradient based methods initially create random solution candidates. By applying some operators like, crossover, mutation, selection, survival of the fittest, as the number of iterations increases new solution candidates which are generally better are found.

Up to now, branch outage problem is solved by using genetic algorithms [5], particle swarm optimization [6] method, differential evolution method [7] and harmony search method [7].

This study applies one of the recently developed non-gradient based optimization methods named; Harmony Search (HS) Method [8] to the local constrained optimization problem. Harmony search method mimics the musicians aim to find the best harmony in a music composition. Especially the Jazz musicians play notes based on their experiences, or randomly find a good harmony. In harmony search method, musical instruments correspond to decision variables, and harmony corresponds to solution vector. It consists of three basic steps. In the first step solution candidates are initialized randomly in the specified range of variables. The second step is called the improvisation, which improvises a new set of solution candidates with experience and randomness. Final step excludes the worst harmony in the old harmony and includes a new harmony if new harmony is better than the worst one. Until a specified stopping criterion is met the second and the third steps are repeated.

In this study, free power system package Matpower [9], and Matlab are used as computational tools. The proposed solution algorithm is tested with the IEEE standard test cases (IEEE 14, 30, and 118 bus systems). Several simulation results comparing the accuracy of the proposed method with respect to AC power flow are given. Since the contingency analysis requires the computation of post-outage magnitudes of all possible branch outages as fast as possible, the contingency

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analysis problem is solved in a parallel environment by using the Parallel Computing Toolbox of Matlab [10]. Speedup results for the tests using IEEE 118 and 300 bus systems are given.

The rest of the paper is organized as follows: In the second part, a branch outage model and a local optimization method for solving branch outages are defined. In the third part, the basics of the harmony search method are introduced. Next, algorithm for the application of the harmony search algorithm for the branch outage problem is given, and post-outage voltage magnitude results using HS based method and AC power flow method are presented and compared in terms of accuracy for several outages of IEEE 14, 30 and 118 bus systems. The part before conclusion gives HS based parallel contingency simulation algorithm and presents speedup results for IEEE 118 and 300 bus test systems.

II. BRANCH OUTAGE MODELING

The model in [4], performs an outage between two busses by adding two fictitious sources as shown in Fig 1.

Reactive power flowing through the line ij, transferred reactive power, and reactive power loss are represented by Q_{ij}, ${Q_{ij}}^T$, and Q_{Li} respectively. These reactive powers can be expressed in terms of system variables as follows.

$$Q_{ij} = -[V_i^2 - V_i V_j \cos\delta_{ji}]b_{ij} + V_i V_j g_{ij} \sin\delta_{ji} - V_i^2 \frac{b_{i0}}{2} \quad (1)$$

$${Q_{ij}}^T = -[V_i^2 - {V_j}^2]\frac{b_{ij}}{2} + V_i V_j g_{ij} \sin\delta_{ji} \quad (2)$$

$$Q_{Li} = -[V_i^2 + {V_j}^2 - 2V_i V_j \cos\delta_{ji}]\frac{b_{ij}}{2} - [V_i^2 + V_j^2]\frac{b_{i0}}{4} \quad (3)$$

where, V_i and δ_i represent bus voltage magnitude and bus voltage phase angle respectively.

The bounded network in which the computation for optimization takes place is shown in Fig. 1. Only load bus voltage magnitudes in this bounded region are taken into consideration during the computation process of the optimization problem.

The procedure for the existing method is as follows.

1- Select an outage of a branch, connected between busses i and j, and number it as k.

2- Calculate bus voltage phase angles using linearized MW flows (see [11] for details).

$$\delta_l = \delta_l - (X_{li} - X_{lj})\,\Delta P_k,\ l = 1,\ldots,NB \quad (4)$$

$$\Delta P_k = \frac{P_{ij}}{1 - \dfrac{(X_{ii} - X_{jj} - 2X_{ij})}{x_k}} \quad (5)$$

where, X represents the inverse of the bus susceptance matrix, P_{ij} is the preoutage active power flow through the line and x_k represents the reactance of the line at hand. If the voltage magnitudes are calculated then the calculation of the busses included in the bounded network would suffice

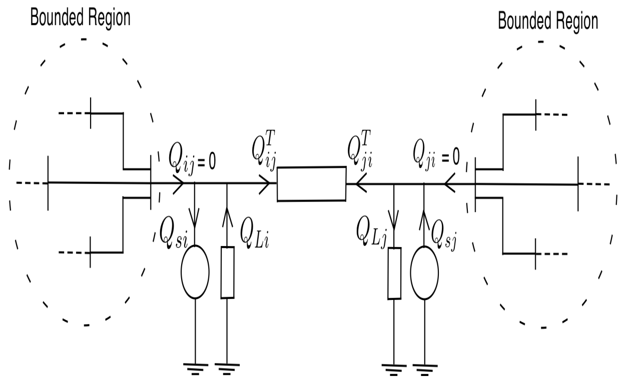

Fig. 1. Simulated outage between two busses, reactive power flows and corresponding bounded regions.

3- Calculate the reactive power transfer ${Q_{ij}}^T$ between the busses. This power includes the increment due to the change in bus voltage phase angles.

4- Minimize the reactive power mismatches of busses i and j. This process is mathematically equivalent to the following constrained optimization problem.

$$\min_{wrt\ Q_{si}} \left\| Q_i - (\widetilde{Q}_{ij}^T + Q_{Li}) + Q_{Di}\ \ Q_j - (- \widetilde{Q}_{ij}^T + \widetilde{Q}_{Li}) + Q_{Di} \right\| \quad (6)$$
$$\text{subject to } \mathrm{g_b(U)} = \varDelta Q_b - B_b \varDelta U_b$$

where, ||.|| is the Euclidean norm of a vector. Equation (6) is linear reactive power equation for load busses, $\varDelta Q$ is reactive power mismatch vector, V is bus voltage magnitude vector and B is bus susceptance matrix. It should be stated that only two elements of $\varDelta Q$ vector are nonzero, and they are represented as shown below.

$$[\varDelta Q] : [\varDelta Q]_i = -[\varDelta Q]_j = Q_{si} - Q_{ij}^T \quad (7)$$

On the other hand, subscript b is used to denote the bounded region where the optimization process is done.

For the case of a transformer with tap t, these values are given as follows.

$$[\varDelta Q]_k = \begin{cases} [\varDelta Q]_i = Q_{si} - Q_{ij}^T \\ [\varDelta Q]_j = \dfrac{tU_j}{-2U_i + tU_j}[\varDelta Q]_i \\ [\varDelta Q]_k = 0 \text{ for } k \neq i, j \end{cases} \quad (8)$$

III. HARMONY SEARCH METHOD

Harmony search is a recently developed heuristic method [8], [12]. It has been applied to the economic dispatch problem [13] in electrical power systems so far. Other heuristic methods such as simulated annealing, tabu search, particle swarm optimization are naturally inspired techniques. Harmony search is inspired from the observation that the aim of the music to find the best harmony.

Harmony search method flowchart is given in Fig. 2. The first step of the harmony search algorithm is the initialization process. Harmony memory size (HMS), harmony memory considering rate (HMCR), pitch adjusting rate (PAR) parameters are chosen and the calculation is initialized. After parameter initialization, the first harmony is generated by randomly created values in the specified range of variables.

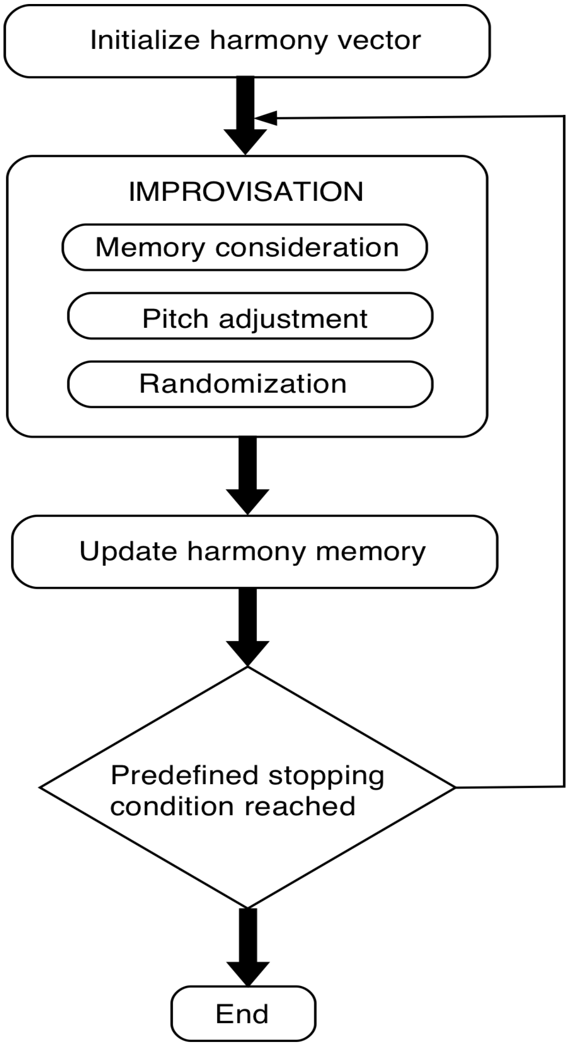

Fig. 2. Flowchart of the harmony search method.

HMS is typically set between 10 and 100 [14]. If HMS is chosen as 10, initial HM will have 10 (number of variables) elements. Initial HM is sorted with respect to objective function values.

$$HM = \begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^{HMS} \end{bmatrix} \tag{9}$$

At the second step, a new harmony vector $x' = (x_1', x_2', \cdots, x_N')$ is generated with respect to memory considerations, pitch adjustments, and randomization [8]. These steps are explained in the following paragraphs.

In memory consideration, the value of the first decision variable is randomly selected from the elements at the same column of HM. The other decision values are chosen in the same manner. The usage of the values existing in HM itself, limits the solutions to the past history values of HM. Therefore, HMCR is defined to provide selection of the values from the extended solution space. HCMR varies between 0 and 1. Extension of the solution space by using HMCR can be stated as follows.

$$x_i' = \begin{cases} x_i' \in \{x_1', x_2', \ldots, x_i^{HMS} & \text{with prob. } HMCR \\ x_i' \in X_i & \text{with prob. } 1 - HMCR \end{cases} \tag{10}$$

PAR parameter is used to determine whether a component of the new harmony vector $x' = (x_1', x_2', \cdots, x_N')$ be pitch-adjusted or not. This process is shown below.

$$\text{Pitch adjustment decision for } x_i' = \begin{cases} \text{YES with prob. } PAR \\ \text{NO with prob. } (1 - PAR) \end{cases} \tag{11}$$

The value $1 - PAR$ sets the rate of doing nothing. If the pitch adjustment decision for x_i' is yes, x_i' is changed as follows.

$$x_i' \leftarrow x_i' + rand * bw \tag{12}$$

where, $rand()$ is a random number between 0 and 1, and bw is an arbitrary distance bandwidth.

At the third step, after having applied memory consideration pitch adjustment and random selection to each variable of the new harmony vector, the objective function corresponding to new harmony vector is compared with the objective function of the worst harmony in HM. If this new value is better than the worst one in HM then the new harmony is replaced with the worst harmony in HM.

At the final step, the algorithm terminates if stopping criterion is met or the process is restarted from step 3.

A. Application of Harmony Search Method to Branch Outage Problem

The application of the harmony search algorithm for solving the local constrained optimization problem formulated for branch outage problem can be outlined as follows:

1- Run a base case load flow for pre-outage (initial) state and obtain initial bus voltage magnitudes in the bounded region.

2- Create HMS different solution candidate values Q_{si} randomly in a specified range. An example specified range can be between $Q_{si^{initial}} - \text{limit}$ and $Q_{si^{initial}} + \text{limit}$ where limit is user specified

3- Determine ΔQ vectors either by using (7) or by using (8) and update load bus voltage magnitudes after solving the second equation of (6).

4- Generate a new harmony vector Q'_{si} by using memory consideration, pitch adjustment and random selection.

5- Compute the objective functions. Compare the objective function of the new harmony members with the worst one in the harmony. If the new objective function is better than the worst one in HM, replace the worst memory with the new harmony.

6- If a predetermined stopping criterion is met stop, otherwise go to step 2.

B. Harmony Search Method Parallel Contingency Analysis

All branches, instead of the ones in which a branch is connected to a generator in both ends, and instead of the ones, outage of which form islanding, are considered in contingency analysis.

The algorithm starts with running a base case load flow. After having obtained initial voltage magnitudes and angles for using in all outage scenarios, a vector BR , that has indices of branches that will be outaged are obtained. Assuming that BR has n elements and the contingency analysis will be performed on m processors, following arithmetical operation is performed.

$$\text{No of elements} = \frac{n}{m} \tag{13}$$

Then, a new matrix $PROCS$, that has No of elements in each column and m rows is formed. Each No of elements of n elements of BR vector is inserted in each row of $PROCS$ matrix consecutively. If (13) has a remainder r , r number of elements of BR vector are distributed to each row of $PROCS$ matrix one by one in turn in order to achieve a good load balancing. This is shown in Fig. 3.

By using spmd (single program multiple data) property of Matlab Parallel Computing Toolbox, each row of the matrix $PROCS$ is given to harmony search based branch outage program as inputs. In other words each processor runs harmony search based branch outage subprogram, No of elements times or $\text{No of elements} + 1$ regarding to the corresponding row of $PROCS$ matrix.

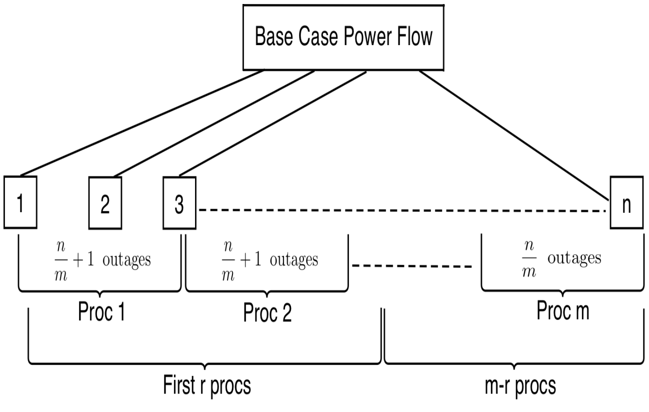

Fig. 3. Parallel Load Balancing

Tests performed for this study can be divided into two groups. First group consists of the simulated outage cases for different test cases. Second group is the parallel contingency testing using IEEE 118 and 300 test cases.

Harmony search based parallel contingency algorithm can be summarized as follows.

1- Run a base case load flow in order to obtain initial voltage magnitudes and angles.

2- By excluding the branch pairs that are connected to generators and the ones that form islanding; form a vector BR that has indexes of branches that will be outaged.

3- By dividing the number of elements of BR to m, obtain outages per processor as given in (13). If the remainder of this operation is not zero, than distribute remaining outages one by one to each processor in turn as described above.

4- For each processor, run a harmony search based branch solution algorithm.

IV. TEST RESULTS

Tests performed for this study can be divided into two groups. First group consists of the simulated outage cases for different test cases. Second group is the parallel contingency testing using IEEE 118 and 300 test cases.

A. Tests for Harmony Search Method Based Branch Outage Simulations

Harmony Search Method application to branch outage problem is tested on IEEE 14, 30, and 118 bus test systems. Matlab based open source software [9] is used as a tool.

Following tables give some results for the different outage simulations for IEEE test systems. In the tables V_{AC} represents the calculated post-outage voltage magnitude of a specific bus by using AC load flow, on the other hand V_{HS} symbolizes the calculated post-outage voltage magnitude of a specific bus by using HS method. $Err\,\%$ represents the percentage error of the specific bus voltage magnitude, and is computed as follows.

$$\%Err = 100\,\frac{abs\,(V_{AC} - V_{\mathrm{HS}})}{V_{AC}} \tag{14}$$

For IEEE 14 bus system, outage of line between buses 7-9 and transformer line 5-6 are simulated. Table I gives the results for these two different simulations. Maximum percentage error for the outage of line 7-9 is 0.59 and for the outage of line 5-6 is 0.88.

Table II gives the post bus voltage magnitudes and their corresponding percentage errors for the simulation of outages of line 4-6 and line 4-12 in IEEE 30 Bus system. Maximum percentage errors for these two cases are 0.52 and 0.61 respectively.

TABLE I
IEEE 14 BUS TEST CASE

	Outage of Line 7-9			Outage of Transformer 5-6		
Bus No	V_{AC}	V_{HS}	Err(%)	V_{AC}	V_{HS}	Err(%)
1	1.0600	1.0600	0.00	1.0600	1.0600	0.00
2	1.0450	1.0450	0.00	1.0450	1.0450	0.00
3	1.0100	1.0100	0.00	1.0100	1.0100	0.00
4	1.0169	1.0178	0.08	1.0181	1.0271	0.88
5	1.0174	1.0196	0.21	1.0272	1.0352	0.78
6	1.0700	1.0700	0.00	1.0700	1.0700	0.00
7	1.0671	1.0699	0.27	1.0656	1.0659	0.02
8	1.0900	1.0900	0.00	1.0900	1.0900	0.00
9	1.0291	1.0352	0.59	1.0682	1.0602	0.76
10	1.0282	1.0337	0.54	1.0614	1.0545	0.65
11	1.0446	1.0479	0.31	1.0623	1.0587	0.34
12	1.0535	1.0539	0.04	1.0543	1.0555	0.11
13	1.0459	1.0472	0.13	1.0525	1.0510	0.14
14	1.0179	1.0224	0.44	1.0422	1.0382	0.39

Table III gives the results for the outage of line 52-53 in IEEE 118 Bus system. Table IV gives the results for the outage of the transformer line between buses 30 and 17 in IEEE 118 bus system. Because of the limited space, table III comprises of the buses, which have percentage errors greater then 0.05% and similarly table IV comprises of the buses which have errors greater then 0.10%.

TABLE II
IEEE 30 BUS TEST CASE

	Outage of Line 4-6			Outage of Transformer 4-12		
Bus No	V_{AC}	V_{HS}	Err(%)	V_{AC}	V_{HS}	Err(%)
1	1.0500	1.0500	0.00	1.0500	1.0500	0.00
2	1.0500	1.0500	0.00	1.0500	1.0500	0.00
3	1.0233	1.0223	0.10	1.0419	1.0453	0.32
4	1.0165	1.0154	0.10	1.0396	1.0437	0.40
5	1.0500	1.0500	0.00	1.0500	1.0500	0.00
6	1.0399	1.0411	0.12	1.0381	1.0408	0.25
7	1.0364	1.0373	0.09	1.0355	1.0371	0.15
8	1.0500	1.0500	0.00	1.0500	1.0500	0.00
9	1.0507	1.0532	0.24	1.0498	1.0483	0.15
10	1.0449	1.0499	0.48	1.0462	1.0399	0.60
11	1.0500	1.0500	0.00	1.0500	1.0500	0.00
12	1.0526	1.0507	0.18	1.0252	1.0224	0.27
13	1.0500	1.0500	0.00	1.0500	1.0500	0.00
14	1.0392	1.0376	0.16	1.0131	1.0113	0.17
15	1.0339	1.0346	0.07	1.0150	1.0112	0.37
16	1.0397	1.0427	0.29	1.0288	1.0225	0.61
17	1.0387	1.0427	0.39	1.0348	1.0294	0.52
18	1.0253	1.0279	0.25	1.0136	1.0092	0.44
19	1.0235	1.0270	0.34	1.0161	1.0111	0.49
20	1.0280	1.0319	0.38	1.0229	1.0175	0.52
21	1.0329	1.0379	0.48	1.0334	1.0273	0.59
22	1.0336	1.0385	0.47	1.0338	1.0278	0.58
23	1.0260	1.0282	0.22	1.0133	1.0093	0.39
24	1.0243	1.0280	0.37	1.0198	1.0152	0.45
25	1.0285	1.0334	0.47	1.0306	1.0252	0.52
26	1.0110	1.0160	0.49	1.0132	1.0078	0.54
27	1.0400	1.0452	0.50	1.0457	1.0399	0.55
28	1.0376	1.0386	0.10	1.0357	1.0378	0.19
29	1.0205	1.0258	0.52	1.0264	1.0205	0.57
30	1.0092	1.0145	0.52	1.0152	1.0093	0.58

TABLE III
IEEE 118 BUS TEST CASE (OUTAGE OF BRANCH 52-53)

Bus	V_{AC}	V_{HS}	Error (%)
51	0.9719	0.9726	0.08
52	0.9654	0.9669	0.16
53	0.9356	0.9371	0.16
58	0.9619	0.9623	0.05

TABLE IV
IEEE 118 BUS TEST CASE (OUTAGE OF BRANCH 30-17)

Bus	V_{AC}	V_{HS}	Error (%)
13	0.9668	0.9683	0.16
20	0.9538	0.9569	0.33
21	0.9531	0.9577	0.49
22	0.9639	0.9690	0.53
23	0.9970	0.9995	0.24
30	1.0131	1.0182	0.51
33	0.9704	0.9719	0.16
38	0.9683	0.9726	0.45

B. Parallel Contingency Analysis Test Results

IEEE 118 and 300 Bus test systems are used for contingency analysis. Numbers of simulated outages are 126 for IEEE 118 Bus test system and 336 for IEEE 300 Bus system. Programs are run on a distributed cluster, with 37 nodes, each consisting of 2 CPU's having 3.40 GHz CPU, and 2 GB memory.

Fig. 4. shows wall clock time versus number of processors for the mentioned two test cases. Fig. 5. shows relative speed up versus number of processors. At most 32 processors are used in simulations, since it is observed that with the increment to bigger processors no gain in speedup is achieved.

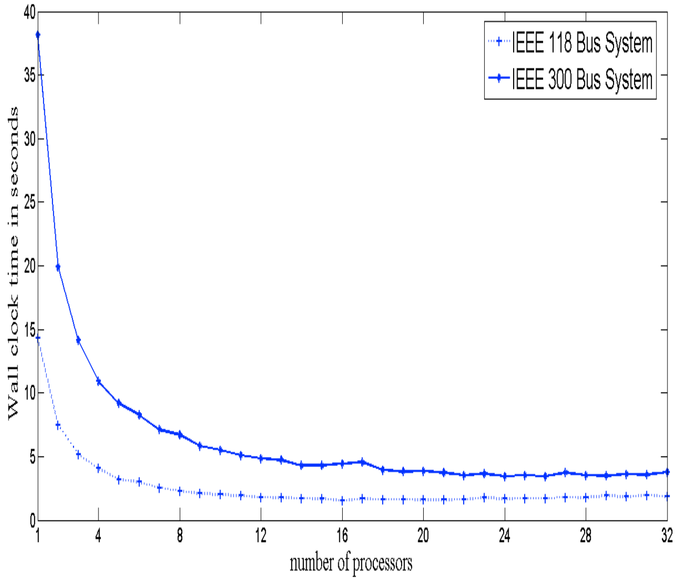

Fig. 4. Wall clock time versus number of processors for IEEE 118 and IEEE 300 Bus Test Systems

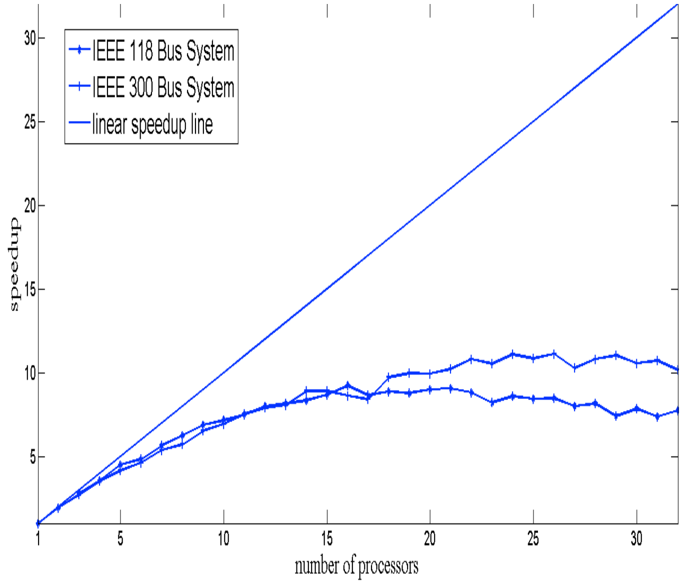

Fig. 5. Speedup versus number of processors for IEEE 118 and IEEE 300 Bus Test Systems

V. CONCLUSIONS

In this study, harmony search method is used for solving the local constrained optimization problem representing the branch outage phenomenon in an electric power system. Contingency analysis is also solved in parallel by using parallel computing toolbox of Matlab.

Simulation results have shown that the problem at hand can be solved with reasonable accuracies and contingency analysis problem can be easily parallelized. For IEEE-118 and IEEE-300 bus test systems for 32 processors relative speedup achieved are 9.21and 11.08 respectively. Parallelization has been performed in Matlab, which also could be a good alternative especially if multi-core personal computers are used in terms of cost and speed.

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VII. BIOGRAPHIES

Oguzhan Ceylan (M'09) was born in Ankara in Turkey on 1977. He graduated from Istanbul Technical University Electrical Engineering Department on 2000. He got his master degree from Computational Science and Engineering Department of the same university on 2003. He is a PhD student in computational science and engineering department since then. He is working as a research assistant at Istanbul Technical University Informatics Institute since 2000. His research interests include power system analysis, optimization, and intelligent methods in optimization.

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Aydogan Ozdemir (M'98) was born in Artvin, Turkey, in January 1957. He received the B.Sc., M.Sc., and Ph.D. degrees all in electrical engineering from Istanbul Technical University, Istanbul, Turkey, in 1980, 1982, and 1990, respectively. He is a Professor at Istanbul Technical University. His current research interests are in the area of electric power system with emphasis on reliability analysis, modern tools (neural networks, fuzzy logic, genetic algorithms, etc.) for power system modeling, analysis and control, and high-voltage engineering. Dr. Özdemir is a Member of the National Chamber of Turkish Electrical Engineering.