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Yusuf Yare

Ganesh K. Venayagamoorthy
*Missouri University of Science and Technology*

Ahmed Yousuf Saber

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# Economic Dispatch of a Differential Evolution Based Generator Maintenance Scheduling of a Power System

Y. Yare, *Student Member, IEEE*, G. K. Venayagamoorthy, *Senior Member, IEEE,* and
A. Y. Saber, *Member, IEEE*

***Abstract*— This paper presents generator maintenance scheduling (GMS) and economic dispatch (ED) of the Indonesian power system based on minimization of an economic cost function for the economical and reliable operation of a power system, while satisfying crew/manpower, maintenance window, load demand, generation limits and spinning reserve constraints. Differential evolution (DE), an evolutionary computation technique and an optimization algorithm that utilizes the differential information to guide its further search, is known to effectively solve large scale optimization problems and has been widely applied in power system. In this paper, the DE approach is proposed for solving the GMS problem and the resulting optimal maintenance schedules are used by the Lambda-iteration (LI) method to calculate the ED for the 19 generating units supplying power to two major industrial parks located in Bintan and Batam in Indonesian. The simulation results show great prospect for application in control centers by solving GMS and ED problems of many utilities which seek to minimize running costs. The results obtained offer an effective alternative for solving the GMS and ED problems.**

***Index Terms*—Differential evolution, economic cost function, economic dispatch, generator maintenance scheduling, Indonesian power system, maintenance cost, operation cost.**

## NOMENCLATURE

| | |
|---|---|
| $a_i$ | Fuel cost coefficient for running unit $i$ |
| $AM_t$ | Available manpower at period $t$ |
| $b_i$ | Fuel cost coefficient for running unit $i$ |
| $c_i$ | Fuel cost coefficient for running unit $i$ |
| $C_R$ | Crossover constant |
| $d_{jk}$ | Maintenance start indicator |
| $d$ | Population dimension |
| $D_j$ | Maintenance downtime for unit $j$ in maintenance |
| DE | Differential evolution |
| DE-LI | Differential evolution and Lambda-iteration |
| $e_i$ | Earliest period for maintenance of unit $i$ to begin |
| ED | Economic dispatch |
| F | Scaling factor for mutation |
| $fit$ | Fitness |
| GMS | Generator maintenance scheduling |
| $i$ | Index of running generating units |
| $j$ | Index of generating units in maintenance |
| $I$ | Set of generating unit indices |
| $l_j$ | Latest period for maintenance of unit $j$ to end |
| LI | Lambda-iteration |
| $L_t$ | Anticipated load demand for period $t$ |
| $M_{jk}$ | Manpower needed by unit $j$ at week $k$ |
| $np$ | Number of population in a generation |
| $N_c$ | Total number of constraints |
| $N_m$ | Total number of generating units in maintenance |
| $N_r$ | Total number of running generating units |
| $U^o$ | Initial random population |
| $U_1$, $U_2$ and $U_3$ | Randomly selected parents population vectors |
| $U_3'$ | Offspring vector |
| $U_i$ | Primary array vector |
| $P_{it}$ | Generating capacity of unit $i$ in period $t$ |
| $P_t$ | Trial vector |
| $rand$ | Random number with uniform distribution in the range of [0, 1] |
| $R_t$ | Spinning reserve in period $t$ |
| $t$ | Index of period |
| $T$ | Set of indices of periods in planning horizon |
| $\lvert V_C \rvert$ | Amount of constraint violation |
| $V_j$ | Maintenance cost per week |
| $\omega_C$ | Weighting coefficient for constraint violation |

## I. INTRODUCTION

MAINTENANCE scheduling of generating units is performed in order to supply electricity with a high reliability level while minimizing the total operating and maintenance costs. Modern power system is experiencing increased demand for electricity with related expansions in system size, which has resulted in higher number of generators and lower reserve margins making the generator maintenance scheduling (GMS) problem more complicated. The aim of maintenance scheduling is to determine the optimized timing and duration for scheduled planned maintenance overhauls for generating units while maintaining

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Y. Yare, G. K. Venayagamoorthy and A. Y. Saber are with the Real-Time and Intelligent Systems Laboratory, Department of Electrical and Computer Engineering, Missouri University of Science and Technology, Rolla, MO 65409-0249 USA (e-mail: yyqh3@mst.edu, gkumar@ieee.org & aysaber@ieee.org).

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high system reliability, reducing production cost, prolonging generator life time subject to some unit and system constraints [1], [2].

One of the options available to the utilities in order to maintain a high level of reliability and economy of the power system is economic dispatch (ED). ED allocates the total power demand among the online generating units in order to minimize the cost of generation while satisfying important system constraints. Some factors that influence ED of the system are operating efficiency of generating units, fuel and operating costs, and transmission losses. The ED problems are in general non-convex optimization problems with many local minima. Numerous classical techniques such as LaGrange based methods, linear programming (LP), non-linear programming (NLP) and quadratic programming (QP) methods have been reported in the literature [3].

Most of power system optimization problems including GMS and ED have complex and nonlinear characteristics with stringent equality and inequality constraints to be satisfied. Different optimization techniques applied so far to solving these problems can be classified according to the type of the search space and/or the objective function [1]-[9]. Depending on the problem formulation, the objective function could be minimization of the unit maintenance costs or some predefined reliability risks subject to some constraints resulting in nonlinear optimization as proposed in [4]-[7]. Solving such nonlinear optimization problems for most cases may not be feasible because their numerical solutions require extensive computational efforts, which increase exponentially with the problem complexities. Even though deterministic optimization problems are formulated with known parameters, real world problems almost invariably include some unknown parameters.

In order to obtain approximate solution of a complex GMS, new concepts have emerged in recent years [7]-[10]. They include applications of probabilistic approach [7], simulated annealing [8], decomposition technique [9] and genetic algorithm (GA) [10]. The application of GA to GMS presented in [10] have been compared with, and confirmed to be superior to other conventional algorithms such as heuristic approaches and branch-and-bound (B&B) in the quality of solutions.

GMS using DE for the minimization of reliability cost function of leveling reserve generation over an entire period of 52 weeks maintenance window for the Nigerian power system have been reported in [11], while in this paper the ED of DE based GMS which aims at the minimization of an economic cost function of the Indonesian power system is presented.

This paper presents the differential evolution (DE) algorithm that is simple and efficient for global optimization [12].

The primary contributions of this paper are:

- Application of DE algorithm in minimizing an economic cost function that aims at optimizing the overall costs of operating and maintaining generating units
- Application of DE to solving the GMS problem for the Indonesian power system, with results suggesting the possibility of having the potential for on line applications in the Indonesian control centers
- Solving the ED problem of running (or online) generating units while excluding units scheduled for maintenance

## II. PROBLEM FORMULATION

Basically, there are two main categories of objective functions in GMS, namely, based on reliability and economic cost [2]. The economic cost function is been considered in this paper. The costs that need to be minimized for this optimal maintenance scheduling of generators are the operation and maintenance costs, while penalty cost is added to the objective function for violation of any of the constraints [13].

The economic dispatch (ED) problem is to find the optimal combination of power generations that minimizes the total generation cost while satisfying some equality and inequality constraints. In maintenance scheduling with ED, the main challenge is to efficiently and optimally schedule generating units for maintenance while the running units handle fluctuating, uncertain and peak loads over the entire maintenance period.

Suppose $T_j \subset T$ is the set of periods when maintenance of unit $j$ may start, $T_j = \{t \in T : e_j \le t \le l_j - D_j + 1\}$ for each $j$.

Define

$$d_{jk} = \begin{cases} 0 & \text{if unit } j \text{ starts maintenance at week } k \\ 1 & \text{otherwise} \end{cases} \tag{1}$$

to be the maintenance start indicator for unit $j$ in period $t$. Let $S_{jt}$ be the set of start time periods $k$ such that if the maintenance of unit $j$ starts at period $k$ that unit will be in maintenance at period $t$, $S_{jt} = \{k \in T_j : t - D_j + 1 \le k \le t\}$.

The objective here is to minimize the economic cost function given by (2), consisting of both the operation and maintenance costs. The operation cost of a thermal unit is expressed as second order function of each unit output $P_{it}$, while the maintenance cost is represented by fixed maintenance cost per week $V_j$ times the maintenance downtime $D_j$ of each unit on maintenance. Since the equation for the operation cost of the generating units are expressed on a per hour basis, a multiplier of 168 is used to get the total cost for operation in one week.

Therefore, the objective function is

$$Min\left\{ \sum_{t=1}^{T} \sum_{i=1}^{N_r} 168(a_i + b_i P_{it} + c_i P_{it}{}^2) + \sum_{j=1}^{N_m} V_j D_j \right\} \tag{2}$$

subject to the following constraints:

- Crew/manpower constraint

This defines the manpower availability for maintenance work. The number of people to perform maintenance work cannot exceed the available crew within each period.

$$\sum_{j\in N_m}\sum_{k\in S_{jt}} M_{jk}(1-d_{jk})\le AM_t\ , \quad \text{for all } t\in T \tag{3}$$

- Maintenance window constraint

  This defines the possible times and duration of maintenance for each generating unit. It specifies the starting of maintenance at the beginning of an interval and finishing at the end of the same interval.

$$\sum_{k\in S_{jt}} (1-d_{jk})=D_j\ , \quad \text{for all } j\in N_m \tag{4}$$

- Load constraint

  The generated power from all the running units must satisfy the load demand and the system losses. However, the network loss is not considered in this paper for simplicity.

$$\sum_{i=1}^{N_r} P_{it}=L_t\ , \quad \text{for all } t\in T \tag{5}$$

- Generation limits constraints

  Each generating unit must not exceed lower and upper generation limits.

$$P_{i\,\min}\le P_i\le P_{i\,\max} \tag{6}$$

- Spinning reserve constraint

  Sufficient spinning reserve is required from all running units to maximize and maintain system reliability.

$$\sum_{i=1}^{N_r} P_{it}^{\max}-L_t\ge R_t\ , \quad \text{for all } t\in T \tag{7}$$

Penalty cost given by (8) is added to the objective function in (2) if the schedule cannot satisfy the constraints given by (3) and (4). The penalty value for each constraint violation is proportional to the amount by which the constraint is violated.

$$PC=\sum_{c=1}^{N_c}\omega_c\left|V_c\right| \tag{8}$$

## III. DIFFERENTIAL EVOLUTION BASED APPROACH

### *A. Differential Evolution*

Differential evolution is an optimization algorithm that solves real-valued problems based on the principles of natural evolution [11], [14]. DE uses a population of given size composed of floating point encoded individuals that evolve over generations to reach an optimal solution. It was introduced by Storn and Price in 1995 as heuristic optimization method which can be used to minimize nonlinear and non-differentiable continuous space functions with real-valued parameters. It has been extended to handle mixed integer discrete continuous optimization problem [15]. Design principles in DE are [11], [14]:

- Simple structure, ease of use and robustness.
- Operating on floating point with high precision.
- Effective for integer, discrete and mixed parameter optimization.
- Handling non-differentiable, noisy and/or time dependent objective functions.
- Effective for nonlinear constraint optimization problems with penalty functions, etc.

Like the other evolutionary (EA) family, DE also relies on initial random population generation, which is then improved using selection, mutation, and crossover repeated through generations until the convergence criterion is met.

Although the canonical form of differential evolution solves optimization problems over continuous spaces, minor adjustments to the code allow DE to solve mixed integer optimization problems [15]. This is achieved with the use of operator that rounds the variable to the nearest integer value, when the value lies between two integers.

An initial population composed of vectors $U_i^o$, $i = 1,2,\ldots np$, is randomly generated within the parameter space. The adaptive scheme used by the DE ensures that the mutation increments are automatically scaled to the correct magnitude. For reproduction, DE uses a tournament selection where the offspring vectors compete against one of their parents. The parallel version of DE maintains two arrays, each of which holds a population of *np*, *d* - dimensional, real value vectors. The primary array holds the current population vector, while the secondary array accumulates vectors that are selected for the next generation. In each generation, *np* competitions are held to determine the composition of the next generation. Every pair of randomly chosen vectors $U_1$ and $U_2$ defines a vector differential: ($U_1$ - $U_2$). Their weighted differential is used to perturb another randomly chosen vector $U_3$ according to (9) given by:

$$U_3^{'}=U_3+F*(U_1-U_2) \tag{9}$$

Typically ($0 \le F \le 1.0$) and $F$ of 0.5 is taken in this study. It controls the speed and robustness of the search; a lower value increases the rate of convergence but also the risk of being stuck at the local optimum. The crossover is a complimentary process for DE. It aims at reinforcing the prior successes by generating the offspring vectors. In every generation, each primary array vector $U_i$, is targeted for crossover with a vector like $U_3'$ to produce a trial vector $U_t$ according to (10).

$$U_t = \begin{cases} U_3^{'} & \text{if } rand < C_R \\ U_i & \text{otherwise} \end{cases} \tag{10}$$

Typically ($0 \le C_R \le 1.0$) and $C_R$ of 0.8 is taken in this study. The newly created vector will be evaluated by the objective function and the corresponding value is compared with the target vector. The best fit vector is kept for the next generation as given by (11). The best parameter vector is evaluated for every generation in order to track the progress made throughout the minimization process; thus making the DE elitist method.

$$U_i(t+1) = \begin{cases} U_i(t) & \text{if } fit(U_i(t)) \le fit(offspring\ (t)) \\ offspring & \text{otherwise} \end{cases} \tag{11}$$

The best parameter vector evaluated for every generation produce the optimum cost and is used to generate the optimal maintenance schedule that must satisfy constraints (3), (4) and (5).

A detailed flowchart for the ED of a DE based GMS of a power system is illustrated in Fig. 1.

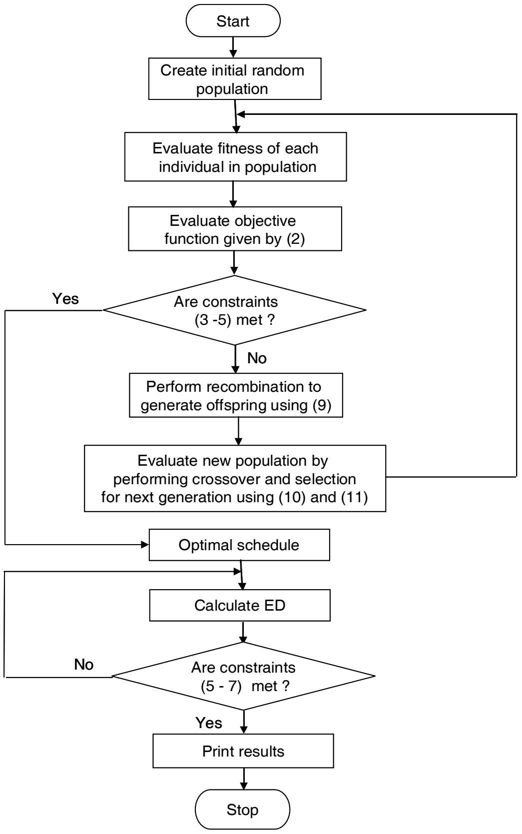

Fig. 1. Flowchart for the ED of DE based GMS

### *B. Economic Dispatch*

The load demand is distributed among the running units in ED. The generation output of each unit should lie between the minimum and maximum power limits for good ED [16]. While minimizing the total generation cost, the total generation from running units should be equal to the total system demand plus the transmission network loss. However, the network loss is not considered in this paper for simplicity. The ED consists of finding the optimum operating policy and distribution of power among the running units while satisfying constraints (5 - 7) [16], [17]. The weekly maintenance schedule for the 19 generating units generated by the DE algorithm is used by the Lambda-iteration (LI) method, referred to by the authors as DE-LI, to calculate the ED of the running units while satisfying constraints (5 - 7), as shown in Fig. 1, the economic dispatch schedules are then printed and ready for dispatching in control centers or for further power system analysis such as use on the real time implementation platform for various forms low frequency oscillations and network disturbance studies.

## IV. CASE STUDIES ON INDONESIAN POWER SYSTEM

The test data for this paper is taken from a real power system consisting of 19 generating units from two industrial parks located in Bintan and Batam in Indonesia [12]. A planning horizon of 25 weeks is considered in this GMS problem.

Table I presents the fuel cost coefficients and the output power ratings of the 19 generating units. Using the data in Table I, the production cost of the running units can be evaluated based on the economic dispatch schedule of running units, after obtaining the maintenance schedule from the minimization of the objective function in (2) subject to the constraints (3 - 7). Maintenance downtime (*D*) in weeks and the weekly maintenance cost (*V*) for each generating unit which participate in maintenance are also shown in Table I. These data are used in calculating the total maintenance cost.

TABLE I
GENERATING UNITS RATING, MAINTENANCE DOWNTIME AND WEEKLY MAINTENANCE COST

| Unit | Generating units maximum output power *P* (MW) | Fuel cost coefficients | | | Maintenance downtime *D* (weeks) | Weekly maintenance cost *V* ($/week) |
|---|---|---|---|---|---|---|
| | | a | b | c | | |
| 1 | 6.1 | 52.6 | 5.4 | 0.0038 | 4 | 750 |
| 2 | 6.1 | 52.6 | 5.4 | 0.0038 | 1 | 750 |
| 3 | 6.1 | 52.6 | 5.4 | 0.0038 | 1 | 750 |
| 4 | 6.1 | 52.6 | 5.4 | 0.0038 | 1 | 750 |
| 5 | 6.1 | 52.6 | 5.4 | 0.0038 | 1 | 750 |
| 6 | 6.1 | 52.6 | 5.4 | 0.0038 | 3 | 750 |
| 7 | 6.1 | 52.6 | 5.4 | 0.0038 | 4 | 750 |
| 8 | 6.1 | 53.7 | 5.4 | 0.0046 | 3 | 750 |
| 9 | 6.1 | 51.5 | 5.4 | 0.005 | 3 | 750 |
| 10 | 6.4 | 51.5 | 5.4 | 0.005 | 3 | 850 |
| 11 | 6.4 | 52.5 | 5.4 | 0.0057 | 2 | 850 |
| 12 | 6.4 | 52.5 | 5.41 | 0.0057 | 1 | 820 |
| 13 | 8 | 76.5 | 5.36 | 0.0346 | 1 | 1500 |
| 14 | 8 | 76.5 | 5.4 | 0.0346 | 2 | 1500 |
| 15 | 2.1 | 55.4 | 5.33 | 0.0076 | 3 | 600 |
| 16 | 2.1 | 55.4 | 5.41 | 0.0076 | 2 | 600 |
| 17 | 2.1 | 55.4 | 5.41 | 0.0076 | 1 | 600 |
| 18 | 2.1 | 55.4 | 5.42 | 0.0076 | 3 | 600 |
| 19 | 6.1 | 59.3 | 5.4 | 0.0079 | 1 | 900 |

.

Table II shows the forecast of load demand, spinning reserve requirement and available crew/manpower for the maintenance horizon of 25 weeks. Overall average load demand forecast is 70.22MW. There is 15MW of spinning reserve requirement on every maintenance week. Also the maximum manpower available to carry out weekly maintenance work is limited to the manpower data presented in Table II.

TABLE II
LOAD DEMAND FORECAST, SPINNING RESERVE REQUIREMENT AND AVAILABLE MANPOWER FOR 25 WEEKS

| Maintenance period *t* (weeks) | Load demand *L* (MW) | Maximum installed capacity (MW) | Spinning reserve *R* (MW) | Net reserve (MW) | Available manpower *AM* |
|---|---|---|---|---|---|
| 1 | 70.2 | 104.6 | 15 | 19.4 | 12 |
| 2 | 69.1 | 104.6 | 15 | 20.5 | 12 |
| 3 | 69.3 | 104.6 | 15 | 20.3 | 12 |
| 4 | 66.4 | 104.6 | 15 | 23.2 | 12 |
| 5 | 70.5 | 104.6 | 15 | 19.1 | 12 |
| 6 | 73.4 | 104.6 | 15 | 16.2 | 10 |
| 7 | 67.5 | 104.6 | 15 | 22.1 | 12 |
| 8 | 68.9 | 104.6 | 15 | 20.7 | 8 |
| 9 | 70.1 | 104.6 | 15 | 19.5 | 8 |
| 10 | 70.4 | 104.6 | 15 | 19.2 | 12 |
| 11 | 68.7 | 104.6 | 15 | 20.9 | 12 |
| 12 | 67.6 | 104.6 | 15 | 22 | 12 |
| 13 | 70.3 | 104.6 | 15 | 19.3 | 12 |
| 14 | 71.4 | 104.6 | 15 | 18.2 | 10 |
| 15 | 67.9 | 104.6 | 15 | 21.7 | 12 |
| 16 | 70.8 | 104.6 | 15 | 18.8 | 8 |
| 17 | 72.1 | 104.6 | 15 | 17.5 | 10 |
| 18 | 72.3 | 104.6 | 15 | 17.3 | 12 |
| 19 | 70.7 | 104.6 | 15 | 18.9 | 12 |
| 20 | 66.9 | 104.6 | 15 | 22.7 | 12 |
| 21 | 71.1 | 104.6 | 15 | 17.9 | 12 |
| 22 | 76 | 104.6 | 15 | 13.6 | 12 |
| 23 | 71.7 | 104.6 | 15 | 17.9 | 10 |
| 24 | 70.6 | 104.6 | 15 | 19 | 8 |
| 25 | 71.6 | 104.6 | 15 | 18 | 8 |

*Results*

Table III shows typical maintenance schedules generated by DE algorithm for the 19 generating units over period of 25 weeks, while Table A of the Appendix summarizes the units scheduled for maintenance on weekly basis over the maintenance horizon of 25 weeks.

TABLE III
GENERATING UNITS SCHEDULED FOR MAINTENANCE BY DE OVER 25 WEEKS MAINTENANCE PERIOD

| Maintenance period (weeks) | Generating unit's index of scheduled maintenance | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 4 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |
| 5 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |
| 6 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |
| 7 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 8 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 9 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 |
| 10 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| 11 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| 12 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 13 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 14 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 15 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 16 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 17 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 18 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 19 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 20 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 21 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 22 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 23 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 24 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 25 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

Status: 1 – Running units, 0 – Units down on maintenance

The economic dispatch schedule of each of the running 19 generating units (that is online units) is presented in Table B of the Appendix. The table shows the amount of power economically dispatched to meet the load demand presented in Table II while satisfying constraints (5 - 7).

Table IV shows the operation and maintenance costs obtained from the ED produced by DE-LI over 25 weeks maintenance period. The total weekly maintenance cost is obtained using the fixed maintenance cost data presented in Table II. The maintenance cost is calculated by multiplying the fixed maintenance cost per week *V* times the maintenance downtime *D* of each unit in maintenance. The total operation costs for the 25 weeks period with the DE-LI stands at \$5,681,037.60, while the total maintenance cost is \$31,920.00. The operation cost is high for weeks 1, 3, 20 - 22 since no unit is scheduled for maintenance within these periods and low for weeks 6 and 10 - 11 since these periods are experiencing high levels of maintenance work. Conversely, the maintenance cost is high during weeks 6 and 10 - 11, while weeks 1, 3, 20 - 22 have no maintenance cost as there is no maintenance work been undertaken. These analogies agree with the results shown in Figs 2, 3 and 4 and Table A of the Appendix.

TABLE IV
OPERATION AND MAINTENANCE COSTS

| Maintenance period (weeks) | Operation cost ($) | Maintenance cost ($) | Total cost ($) |
|---|---|---|---|
| 1 | 242356.8 | 0 | 242356.8 |
| 2 | 232545.6 | 750 | 233295.6 |
| 3 | 241550.4 | 0 | 241550.4 |
| 4 | 211528.8 | 1950 | 213478.8 |
| 5 | 204338.4 | 2700 | 207038.4 |
| 6 | 194628 | 3520 | 198148 |
| 7 | 213192 | 2250 | 215442 |
| 8 | 232360.8 | 750 | 233110.8 |
| 9 | 202440 | 3700 | 206140 |
| 10 | 198996 | 4600 | 203596 |
| 11 | 222213.6 | 1950 | 224163.6 |
| 12 | 231168 | 750 | 231918 |
| 13 | 233637.6 | 750 | 234387.6 |
| 14 | 234813.6 | 750 | 235563.6 |
| 15 | 231621.6 | 750 | 232371.6 |
| 16 | 224968.8 | 1350 | 226318.8 |
| 17 | 225792 | 1350 | 227142 |
| 18 | 234981.6 | 750 | 235731.6 |
| 19 | 233520 | 750 | 234270 |
| 20 | 239349.6 | 0 | 239349.6 |
| 21 | 243180 | 0 | 243180 |
| 22 | 247665.6 | 0 | 247665.6 |
| 23 | 235099.2 | 850 | 235949.2 |
| 24 | 234091.2 | 850 | 234941.2 |
| 25 | 234998.4 | 850 | 235848.4 |
| Total cost for 25 weeks ($) | 5,681,037.60 | 31,920.00 | 5,712,957.60 |

Fig. 2 presents the plot of the operation cost over the entire maintenance period of 25 weeks. Figs. 3, 4 and 5 shows that there are heavier maintenance activities at weeks 6 and 10 -11 compared with any other week, resulting in reduced operation costs within these maintenance periods. The manpower required for these maintenance works has also gone up. Fig.3 also shows that at weeks 1, 3, 20 - 22 the operation costs are high compared with any other week. This is because all the generating units are running and none is out on maintenance, and the manpower requirement has dropped to zero as shown in Fig. 5. The generated schedule in Table A of the Appendix summarizes these facts and analogies. The plot of the operation cost shows a mean cost and standard deviation of $227,240.00±14697.00.

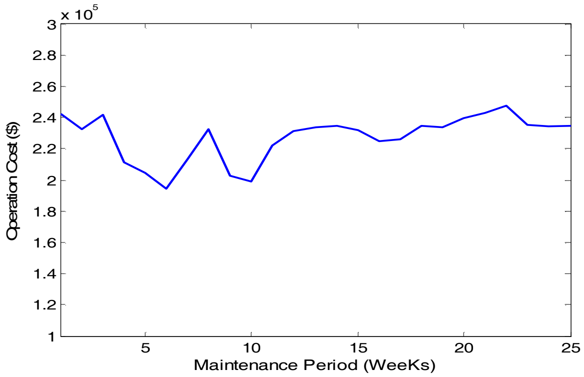

Fig. 2. Operation cost plot

Fig. 3 shows the plot of the maintenance cost. The weekly maintenance cost in $/week is provided as a fixed quantity for each of the 19 generating units as shown in Table I. These raw maintenance costs data are obtained based on the actual unit maintenance practices in Indonesia [13]. From Table I, units 13 and 14 have the highest maintenance cost per week mainly due to large capacity size machines, ageing, obsolete maintenance/repair or replacement parts of the units that must be purchased at expensive rates and the distance that the workmen must travel to get to the maintenance site, while units 15 – 18 have the least maintenance cost per week which may be attributable to these units been new with easily accessible and cheap maintenance parts and closeness of work site to the workmen. These units however, have different maintenance downtime window ranging from 1 week to 3 weeks. Based on the typical maintenance schedule shown in Table A of the Appendix and from Table IV, weeks 6 and 10 - 11 indicate periods with heavy maintenance work, resulting in large maintenance costs. The plot of the maintenance cost shows a mean cost and standard deviation of $1276.80±1237.50.

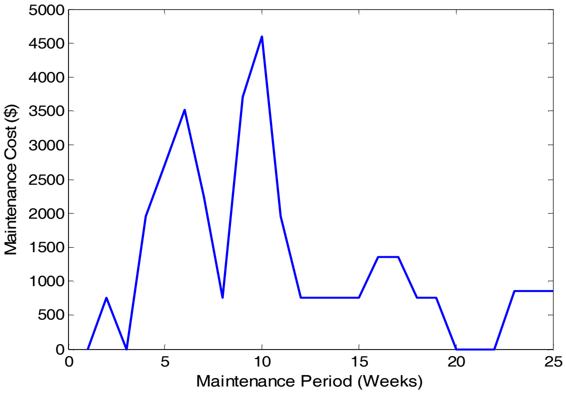

Fig. 3. Maintenance cost plot

Fig. 4 shows typical crew/manpower utilization over the maintenance period of 25 weeks produced by the DE algorithm. The DE algorithm is able to meet the crew constraint given by (3) and the limit on manpower availability presented in Table II. The crew plot has an average and standard deviation of 3±2.81. The plot shows that there is no maintenance on weeks 1, 3 and 20 - 22. Week 6 experienced the highest level of maintenance work requiring 8 crew members to maintain generating units 1,6,12, 15 and 18, with a combined installed capacity of 22.8MW, which is 21.79% of the overall total installed capacity of 104.6MW.

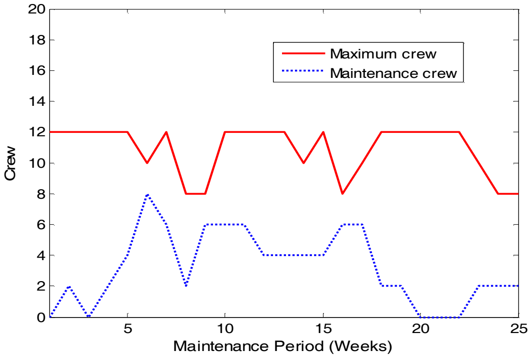

Fig. 4. Maintenance crew plots

Fig. 5 shows the plots of maximum installed capacity, load demand and economic dispatch generation in MW over 25 weeks maintenance period. The figure shows that the total economic dispatch generation from the operating units meets the total load demand, thus satisfying constraint (5). The total weekly economic dispatch generation and load demand plots have average and standard deviations of 70.16±2.14 MW and 70.22±2.14 MW respectively, representing an error margin of 0.085%. Typically, this small error margin is acceptable for most practical applications. The figure also shows sufficient spinning reserve over the entire 25 weeks maintenance period, thus satisfying constraint (7).

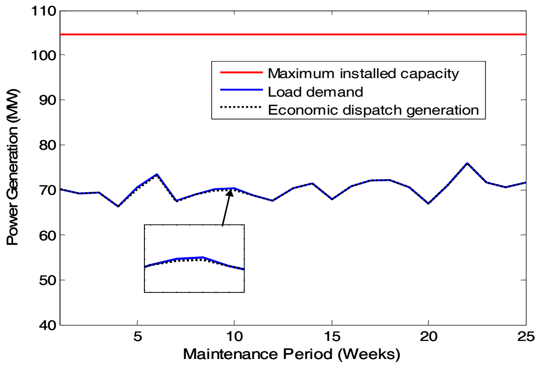

Fig. 5. ED generation and load demand plots

Fig. 6 shows the summary and at a glance chart of the total weekly economic dispatch generation, spinning and net reserves from the entire simulation. The figure shows the sufficiency of spinning reserve at each maintenance week. The net reserve is the extra MW available after the load demand and spinning reserve requirements are met. The net reserve largely depends on the total maximum installed capacity of 104.6 MW from the 19 generating units.

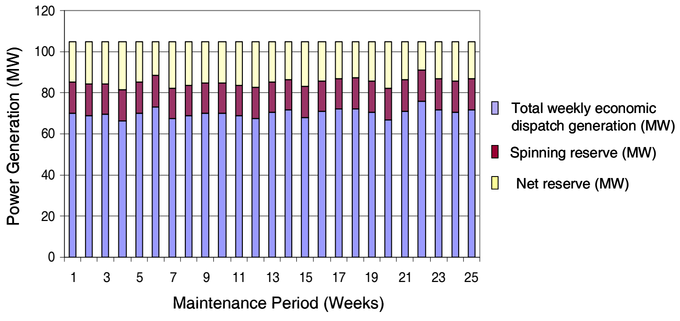

Fig. 6. Total weekly economic dispatch, spinning reserve and net reserve chart

Table V shows the operation cost comparison between DE and DE-LI based approaches for evaluation of ED using similar generator maintenance schedules produced by the DE algorithm. The DE-LI generation dispatch results in operation cost saving of $26,000.00 compared with DE based dispatch, representing a total cost saving of 0.47%. Their maintenance costs are however the same with no cost saving.

TABLE V
COST COMPARISON TABLE BETWEEN DE AND DE-LI BASED APPROACHES FOR ED

| Maintenance period (weeks) | Operation cost ($) | | Cost saving | |
|---|---|---|---|---|
| | DE | DE-LI | ($) | % |
| 1 | 236530 | 233540 | 2990 | 1.26 |
| 2 | 236530 | 233540 | 2990 | 1.26 |
| 3 | 224280 | 223900 | 380 | 0.17 |
| 4 | 236530 | 233540 | 2990 | 1.26 |
| 5 | 215870 | 214570 | 1300 | 0.6 |
| 6 | 196810 | 194610 | 2200 | 1.12 |
| 7 | 207530 | 202930 | 4600 | 2.22 |
| 8 | 210530 | 214410 | -3880 | -1.84 |
| 9 | 184200 | 192030 | -7830 | -4.25 |
| 10 | 156300 | 167410 | -11110 | -7.11 |
| 11 | 186000 | 183770 | 2230 | 1.2 |
| 12 | 199410 | 212850 | -13440 | -6.74 |
| 13 | 231490 | 233630 | -2140 | -0.92 |
| 14 | 232860 | 234820 | -1960 | -0.84 |
| 15 | 232860 | 231250 | 1610 | 0.69 |
| 16 | 232860 | 233900 | -1040 | -0.45 |
| 17 | 246530 | 234100 | 12430 | 5.04 |
| 18 | 236750 | 235460 | 1290 | 0.55 |
| 19 | 246530 | 232820 | 13710 | 5.56 |
| 20 | 246530 | 239350 | 7180 | 2.91 |
| 21 | 246530 | 243190 | 3340 | 1.35 |
| 22 | 246530 | 247660 | -1130 | -0.46 |
| 23 | 246530 | 243730 | 2800 | 1.14 |
| 24 | 246530 | 242730 | 3800 | 1.54 |
| 25 | 246530 | 243640 | 2890 | 1.17 |
| Total cost for 25 weeks ($) | 5,629,580.00 | 5,603,380.00 | 26,200.00 | 0.47 |

Table B of the Appendix shows the optimum economic dispatch policy that results in minimum operating costs for the economic operation of the 19 generating units supplying power to the two industrial parks located in Bintan and Batam in Indonesia.

## V. CONCLUSION

This paper illustrates the application of the DE algorithm in minimizing an economic cost function that optimizes the total cost of operating 19 generating units of two industrial parks located in Indonesia. The results show a prospect for incorporating additional system constraints and increasing the dimensionality of the problem. The results present an executable economic dispatch schedule that can easily be implemented in Indonesia’s control centers responsible for system operations, and illustrates optimum dispatch policy on how economically the Indonesian 19 generating units could be operated. Further work will examine implementation of these results in real time on the real-time digital simulator (RTDS) platform to investigate low frequency oscillations and real time system responses to various forms of power system network disturbances.

## APPENDIX

TABLE A
TYPICAL GENERATOR MAINTENANCE SCHEDULES OBTAINED BY DE AFTER 500 ITERATIONS AND 5000 TRIALS

| Maintenance period (weeks) | Generating units scheduled for maintenance | Economic dispatch generation (MW) | Spinning reserve (MW) | Net reserve (MW) |
|---|---|---|---|---|
| 1 | - | 70.2 | 15 | 19.4 |
| 2 | 2 | 69.1 | 15 | 20.5 |
| 3 | - | 69.3 | 15 | 20.3 |
| 4 | 3,15,18 | 66.4 | 15 | 23.2 |
| 5 | 4,6,15,18 | 70.2 | 15 | 19.4 |
| 6 | 1,6,12,15,18 | 73.19 | 15 | 16.41 |
| 7 | 1,5,6 | 67.23 | 15 | 22.37 |
| 8 | 1 | 68.9 | 15 | 20.7 |
| 9 | 1,11,14,17 | 69.79 | 15 | 19.81 |
| 10 | 7,11,13,14 | 69.89 | 15 | 19.71 |
| 11 | 7,19 | 68.7 | 15 | 20.9 |
| 12 | 7 | 67.5 | 15 | 22 |
| 13 | 7 | 70.3 | 15 | 19.3 |
| 14 | 9 | 71.4 | 15 | 18.2 |
| 15 | 9 | 67.9 | 15 | 21.7 |
| 16 | 9,16 | 70.8 | 15 | 18.8 |
| 17 | 8,16 | 72.1 | 15 | 17.5 |
| 18 | 8 | 72.3 | 15 | 17.3 |
| 19 | 8 | 70.7 | 15 | 18.9 |
| 20 | - | 66.9 | 15 | 22.7 |
| 21 | - | 71.1 | 15 | 18.5 |
| 22 | - | 76 | 15 | 13.6 |
| 23 | 10 | 71.7 | 15 | 17.9 |
| 24 | 10 | 70.6 | 15 | 19 |
| 25 | 10 | 71.6 | 15 | 18 |

TABLE B
GENERATED ECONOMIC DISPATCH SCHEDULE

| Maintenance period (weeks) | Generating units' economic dispatch schedule (MW) | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| 1 | 4.69 | 4.69 | 4.69 | 4.69 | 4.69 | 4.69 | 4.69 | 3.87 | 3.56 | 3.56 | 3.13 | 2.25 | 6.95 | 6.29 | 1.09 | 1.69 | 1.69 | 1.03 | 2.26 |
| 2 | 4.98 | OFF | 4.98 | 4.98 | 4.98 | 4.98 | 4.98 | 4.11 | 3.78 | 3.78 | 3.32 | 2.44 | 7.1 | 6.33 | 1.12 | 1.83 | 1.83 | 1.17 | 2.4 |
| 3 | 4.62 | 4.62 | 4.62 | 4.62 | 4.62 | 4.62 | 4.62 | 3.82 | 3.51 | 3.51 | 3.08 | 2.2 | 6.92 | 6.29 | 1.09 | 1.65 | 1.65 | 0.99 | 2.22 |
| 4 | 5.47 | 5.47 | OFF | 5.47 | 5.47 | 5.47 | 5.47 | 4.52 | 4.16 | 4.16 | 3.65 | 2.77 | 1.18 | 6.38 | OFF | 2.08 | 2.08 | OFF | 2.63 |
| 5 | 6.1 | 6.1 | 6.1 | OFF | 6.1 | OFF | 6.1 | 5.28 | 5.86 | 4.86 | 4.26 | 3.38 | 1.28 | 6.48 | OFF | 2.1 | 2.1 | OFF | 3.07 |
| 6 | OFF | 6.1 | 6.1 | 6.1 | 6.1 | OFF | 6.1 | 5.81 | 5.35 | 5.35 | 5.69 | OFF | 5.35 | 6.55 | OFF | 2.1 | 2.1 | OFF | 4.39 |
| 7 | OFF | 5.78 | 5.78 | 5.78 | OFF | OFF | 5.78 | 4.78 | 4.4 | 4.4 | 3.86 | 2.98 | 7.5 | 6.42 | 1.21 | 2.1 | 2.1 | 1.58 | 2.78 |
| 8 | OFF | 4.96 | 4.96 | 4.96 | 4.96 | 4.96 | 4.96 | 4.1 | 3.77 | 3.77 | 3.31 | 2.43 | 7.1 | 6.33 | 1.12 | 1.82 | 1.82 | 1.17 | 2.39 |
| 9 | OFF | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 5.04 | 4.64 | 4.64 | OFF | 3.19 | 7.66 | OFF | 1.25 | 2.1 | OFF | 1.74 | 2.94 |
| 10 | 6.03 | 6.03 | 6.03 | 6.03 | 6.03 | 6.03 | OFF | 4.98 | 4.58 | 4.58 | OFF | 5.66 | OFF | OFF | 2.1 | 2.1 | 2.1 | 1.7 | 5.9 |
| 11 | 5.15 | 5.15 | 5.15 | 5.15 | 5.15 | 5.15 | OFF | 4.25 | 3.91 | 3.91 | 3.93 | 2.05 | 6.35 | 7.18 | 1.14 | 1.92 | 1.92 | 1.26 | OFF |
| 12 | 4.86 | 4.86 | 4.86 | 4.86 | 4.86 | 4.86 | OFF | 4.01 | 3.69 | 3.69 | 3.24 | 2.36 | 7.03 | 6.31 | 1.11 | 1.77 | 1.77 | 1.11 | 2.34 |
| 13 | 5.08 | 5.08 | 5.08 | 5.08 | 5.08 | 5.08 | OFF | 4.19 | 3.86 | 3.86 | 3.38 | 2.51 | 7.14 | 6.34 | 1.14 | 1.88 | 1.88 | 1.22 | 2.44 |
| 14 | 5.07 | 5.07 | 5.07 | 5.07 | 5.07 | 5.07 | 5.07 | 4.19 | OFF | 3.85 | 3.38 | 2.5 | 7.14 | 6.34 | 1.13 | 1.88 | 1.88 | 1.22 | 2.44 |
| 15 | 4.79 | 4.79 | 4.79 | 4.79 | 4.79 | 4.79 | 4.79 | 3.96 | OFF | 3.64 | 3.19 | 2.32 | 7 | 6.31 | 1.1 | 1.74 | 1.74 | 1.08 | 2.3 |
| 16 | 5.17 | 5.17 | 5.17 | 5.17 | 5.17 | 5.17 | 5.17 | 4.27 | OFF | 3.93 | 3.45 | 2.57 | 7.19 | 6.35 | 1.15 | OFF | 1.93 | 1.27 | 2.49 |
| 17 | 5.31 | 5.31 | 5.31 | 5.31 | 5.31 | 5.31 | 5.31 | OFF | 4.03 | 4.03 | 3.54 | 2.66 | 7.26 | 6.36 | 1.16 | OFF | 1.99 | 1.34 | 2.55 |
| 18 | 4.93 | 4.93 | 4.93 | 4.93 | 4.93 | 4.93 | 4.93 | OFF | 4.07 | 3.75 | 3.75 | 3.69 | 6.32 | 7.07 | 2.01 | 1.12 | 1.81 | 1.81 | 2.37 |
| 19 | 4.81 | 4.81 | 4.81 | 4.81 | 4.81 | 4.81 | 4.81 | OFF | 3.97 | 3.65 | 3.65 | 3.51 | 6.31 | 7.01 | 2.03 | 1.01 | 1.75 | 1.75 | 2.31 |
| 20 | 4.44 | 4.44 | 4.44 | 4.44 | 4.44 | 4.44 | 4.44 | 3.67 | 3.38 | 3.38 | 2.96 | 2.08 | 6.83 | 6.27 | 1.07 | 1.56 | 1.56 | 0.91 | 2.14 |
| 21 | 4.76 | 4.76 | 4.76 | 4.76 | 4.76 | 4.76 | 4.76 | 3.93 | 3.62 | 3.62 | 3.17 | 2.29 | 6.98 | 6.3 | 1.1 | 1.72 | 1.72 | 1.06 | 2.29 |
| 22 | 5.12 | 5.12 | 5.12 | 5.12 | 5.12 | 5.12 | 5.12 | 4.23 | 3.89 | 3.89 | 3.42 | 2.54 | 7.17 | 6.34 | 1.14 | 1.9 | 1.9 | 1.25 | 2.46 |
| 23 | 5.09 | 5.09 | 5.09 | 5.09 | 5.09 | 5.09 | 5.09 | 4.21 | 3.87 | OFF | 3.39 | 2.52 | 7.15 | 6.34 | 1.14 | 1.89 | 1.89 | 1.23 | 2.45 |
| 24 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4.13 | 3.8 | OFF | 3.34 | 2.46 | 7.11 | 6.33 | 1.13 | 1.84 | 1.84 | 1.19 | 2.41 |
| 25 | 5.08 | 5.08 | 5.08 | 5.08 | 5.08 | 5.08 | 5.08 | 4.2 | 3.86 | OFF | 3.39 | 2.51 | 7.15 | 6.34 | 1.14 | 1.88 | 1.88 | 1.23 | 2.45 |

## REFERENCES

[1] M. K. C. Marwali and S. M. Shahidehpour, "Coordination between long – term and short – term generation scheduling with network constraints," *IEEE Transactions on Power Systems*, vol. 15, pp.1161-1167, August 2000.

[2] K. P. Dahal and N. Chakpitak, "Generator maintenance scheduling in power systems using metaheuristic-based hybrid approaches," *Electric Power Systems Research*, vol. 77, pp. 771-779, May 2007.

[3] B. H. Chowdhury and S. Rahman, "A review of recent advances in economic dispatch," *IEEE Transactions on Power Systems,* vol. 5, no. 4, pp. 1248-1259, November 1990.

[4] Z. A. Yamayee, "Maintenance scheduling: description, literature survey, and interface with overall operations scheduling," *IEEE Transactions on Power Apparatus and Systems*, PAS-101, pp. 2770-2779, 1982.

[5] H. Kim, Y. Hayashi and K. Nara, "An algorithm for thermal unit maintenance scheduling through combined GA, SA, and TS," *IEEE Transactions on Power Systems,* 12, (1), pp. 329-33, February 1997.

[6] R. C. Leou, "A flexible unit maintenance scheduling considering uncertainties," *IEEE Transactions on Power Systems,* 16, (3), pp. 553-559, August 2001.

[7] R. Billinton and A. Abdulwhab, "Short-term generating unit maintenance in a deregulated power system using a probabilistic approach," *IEE Proceedings - Generation, Transmission and Distribution*150, (4), pp. 463-468, July 2003.

[8] T. Satoh and K. Nara, "Maintenance scheduling by using simulated annealing method," *IEEE Transactions on Power Systems,* 6, pp. 850-857, 1991.

[9] J. Yellen, T. M. Al-khamis, S. Vermuri and L. Lemonidis, "A decomposition approach to unit maintenance scheduling," *IEEE Transactions on Power Systems* 7, pp. 726-733, 1992.

[10] H. T. Firma and L. F. L. Legey, "Generation expansion: an iterative genetic algorithm approach," *IEEE Transactions on Power Systems*, 17, (3), pp. 901-906, August 2002.

[11] Y. Yare and G. K. Venayagamoorthy, "A differential evolution approach to optimal generator maintenance scheduling of the Nigerian power system," *IEEE Power and Energy Society General Meeting – Conversion and Delivery of Electrical Energy in the 21st Century,* pp. 1-8, 20-24 July 2008.

[12] R. Storm and K. Price, "Differential evolution - a simple and efficient adaptive scheme for global optimization over continuous spaces," [Online*]. Journal of Global Optimization*, Dordrecht, vol. 11, pp. 341-359, June 1997.

[13] K. Y. Lee and M. A. El-Sharkawa, "Modern heuristic optimization techniques: theory and applications to power systems," IEEE Press, 445 Hoes Lane, Piscataway, New Jersey, pp. 354-359, 2008.

[14] G. A. Bakare, G. krost, G. K. Venayagamoorthy and U. O. Aliyu, "Differential evolution for reactive power optimization of Nigerian grid system," *IEEE Power Engineering Society General Meeting,* pp. 1-6, June 2007.

[15] Y. Lin, F. Wang, K. Hwang, "A hybrid method of evolutionary algorithms for mixed-integer nonlinear optimization problems," Proceeding 1999 Congress on Evolutionary Computation, vol. 3, pp. 2159-2166, July 1999.

[16] A. J. Wood and B. F. Wollenberg, *Power generation operation and control.* New York, NY: John Wiley and Sons, 2004.

[17] G. A. Bakare, U. O. Aliyu, G. K. Venayagamoorthy and Y. K. Shu'aibu, "Genetic algorithms based economic dispatch with application to coordination of Nigerian thermal power plants," *IEEE Power Engineering Society General Meeting*, vol. 1, pp. 551-556, 12-16 June 2005.