GMS Considering Uncertainty in Wind Power in a Wind-Hydrothermal Power System

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***Abstract*— An optimal preventive generator maintenance scheduling (GMS) in a smart grid environment comprising wind-hydrothermal energy resources is presented in this paper. GMS problem is solved with the aim of maximizing economic benefits subject to satisfying system constraints. This GMS formulation becomes a challenging problem because of the variability and intermittency of wind speed and the incorporation of uncertainty in wind generation. The objective is to perform preventive GMS in such a manner that the annual generation cost is minimized, the annual cost saving is increased while all operating constraints are satisfied in the presence of uncertainty in wind generation. Discrete modified particle swarm optimization (MPSO-D) algorithm is used to solve this problem. The results presented on a typical Nigerian power system show the potential and benefits obtainable from increasing wind power penetration.**

***Index Terms*—Cost saving, economic cost function, generator maintenance scheduling, smart grid, uncertainty in wind generation.**

NOMENCLATURE

A_w	Swept area of the wind turbine's blade
a_i, b_i & c_i	Fuel cost coefficients for unit i
AM_t	Available manpower at period t
β_{gb}	Global best strategic learning parameter for mutation
c_1 & c_2	Cognitive and social acceleration constants respectively
$C_{D,w}$ & $C_{E,w}$	Penalty cost coefficients (coeffs) for calling reserves to cover for deficit wind-generated power and for not using all available wind power respectively from wth wind plant
C_h & C_w	Cost functions for hth hydro unit and wth wind plant respectively
C_p	Performance coeff
d	Particle's dimension
d_{jk}	Maintenance start indicator and state of unit j in week k
D_{jt}	Maintenance downtime for unit j in period t
e_i & f_i	Fuel cost coeffs for unit i with valve-point effect
ep_j	Earliest period for maintenance of unit j to begin
F_T	Objective function
γ	Degree of uncertainty in wind generation
h	Index of hydro unit
i	Index of thermal unit
$Iter$ & $Iter_{max}$	Current and maximum iteration number respectively
j	Index of generating unit in maintenance
k	Discrete time step
K_{pb}	Penalty factor coeff for real power balance constraint
l	lth particle
l_j	Latest period for maintenance of unit j to end
M_{jk}	Manpower needed by unit j at week k
M_r	Mutation rate
N	Number of dimensions
N_c	Total number of constraints
N_H & N_T	Total number of running (or on-line) hydro and thermal units respectively
N_m	Total number of generating units in maintenance
N_W	Total number of wind-powered plants (or wind farms)
$P_{av,wt}$	Available wind power from the wth wind-powered plant (wind farm) in period t
P_{gd}	Swarm's best position for dimension d
P_{ht} & P_{it}	Scheduled generations from the hth hydro and ith thermal units respectively in period t
$P_i^{\min}$ & $P_i^{\max}$	Minimum and maximum power limits respectively for thermal unit i
P_{loss}	System loss
P_{lbd}	lth particle best position for dimension d
P_{ld}	Position vector of the particle l in dimension d
$P_{s,wt}$	Anticipated or scheduled wind power from the wth wind-powered plant (wind farm) in period t
$P_{s,wt}^{\min}$ & $P_{s,wt}^{\max}$	Minimum and maximum scheduled wind power respectively from the wth wind-powered plant in period t
P_t^D	Total real load demand for period t
P_w	Wind turbine output power
PC_{GMS}	GMS penalty cost
R	System reserve
ρ	Density of air
r, $rand$, $rand_1$ & $rand_2$	Random numbers with uniform distribution in the range of [0, 1]
$randn$	Gaussian distributed random number with a zero mean and a variance of 1

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t	Index of period
T	Set of indices of periods in planning horizon
U_{ht} & U_{it}	Scheduled maintenance state of hth hydro and ith thermal units respectively in time t
V_w	Wind speed
$\lvert V_C \rvert$	Amount of GMS constraint violation
V_{ld} & V_{max}	lth particle velocity in dimension d and maximum particle velocity respectively
V_{jt}	Unit's maintenance cost per week
w	Index of wind-powered plant (or wind farm)
ω_C	Weighting coeff for GMS constraint violation
w_{iner}, $w_{iner}^{\min}$ & $w_{iner}^{\max}$	Current, initial and final inertia weights respectively

I. INTRODUCTION

ELECTRIC utilities have always relied on maintenance programs to keep their equipment in good working conditions for as long as it is feasible. It is expected that effective maintenance policies can reduce the frequency of service interruptions and the many undesirable consequences of such interruptions. Maintenance clearly affects component and system reliability: if too little is done, this may result in an excessive number of costly failures and poor system performance and, therefore, reliability is degraded; done too often, reliability may improve but the cost of maintenance will sharply increase. The two expenditures must be balanced in a cost effective scheme [1]-[6].

Preventive generator maintenance scheduling (GMS) is an important task in power system and plays important role in the operation and planning activities of the electric power utility. Maintenance scheduling of generating units is performed in order to supply electricity with a high reliability level while minimizing the total generation and maintenance costs [5]. 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 GMS problem more complicated. The aim of GMS is to determine the optimized timing and duration for scheduled planned maintenance overhauls for generating units while maintaining high system reliability, reducing production cost, prolonging generator life time subject to some unit and system constraints [1]-[6].

Worldwide interest in reducing environmental pollution and the increasing concern over possible energy shortage has led to fruitful increasing interest in generation of renewable electrical energy. Wind power has become the fastest growing energy sources in the world and the leading source among various renewable energy sources in the power industry.

Wind turbines are usually placed in clusters (wind farms), with sizes ranging from a few MW up to several MW. Therefore, a large wind farm typically consists of hundreds of individual WTGs running simultaneously. The pooling of several large wind farms into clusters (in the GW range) will make new options feasible for an optimized integration of variable-output generation into electricity supply systems. Wind power fluctuates over time, mainly under the influence of meteorological fluctuations. The variations occur on all time scales: seconds, minutes, hours, days, months, seasons and years. Understanding these variations and their predictability is of key importance. New concepts for cluster management include the aggregation of geographically dispersed wind farms according to various criteria, for the purpose of an optimized network management, maintenance and generation scheduling. These clusters are operated and controlled like large conventional power plants [7]-[13].

A smart grid delivers electricity from suppliers to consumers using intelligent technology to save energy, reduce cost and increase reliability and transparency. According to the United States Department of Energy's Smart Grid System Report, a modern smart grid must [14]:

- Enables informed participation by customers
- Accommodate variety of generation and storage options
- Enables new products, services and markets
- Provides the power quality for the range of needs
- Optimizes asset utilization and operating efficiency
- Operates resiliently to disturbances, attacks and natural disasters

In enhancing the smart grid initiative, this paper applies a discrete modified particle swarm optimization (MPSO-D) algorithm that is suitable for large scale optimization [1] to solve this challenging GMS problem for a modern power system consisting of wind-hydrothermal energy resources. In addition, further challenges imposed on this GMS optimization problem are the variability, intermittency and uncertainty in wind energy generation factored into the problem formulation to effectively and practically represent integration issues of this modern power system as it concerns GMS.

The primary contributions of this paper are:

- Formulation of a challenging GMS optimization problem in a smart grid environment consisting of wind-hydrothermal energy resources
- Handling of variability and intermittency of wind energy resource with different degrees of uncertainty in generation
- Application of a modified discrete particle swarm optimization to solving the challenging GMS problem for wind-hydrothermal Nigerian power system
- Demonstration of the capability of this approach in increasing annual cost saving

II. PROBLEM FORMULATION

A wind turbine creates mechanical torque on a rotational shaft, while an electrical generator on the same rotating shaft is controlled to produce an opposing electromagnetic torque. In steady operation, the magnitude of the mechanical torque is converted to the real power given by (1) and is delivered to the grid [7]. Multiple wind turbines in the wind farm are required to generate aggregated MW for bulk delivery to the power grid system.

$$P_w = \frac{1}{2}\rho A_w C_p V_w^2 \tag{1}$$

In general, there are two main categories of objective functions in GMS, namely, based on reliability and economic cost [1], [5]. 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 generation and maintenance costs, while penalty cost is added to the objective function for violation of any of the constraints [1], [5].

Suppose $T_j \subset T$ is the set of periods when maintenance of unit j may start, $T_j = \left\{ t \in T : ep_j \leq t \leq l_j - D_j + 1 \right\}$ for each j. Define maintenance start indicator of unit j in period k represented by d_{jk} as 0 or 1 (0: if unit j starts maintenance at week k, 1: if unit j is on-line in week k). 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, $S_{jt} = \left\{ k \in T_j : t - D_{jt} + 1 \leq k \leq t \right\}$.

The generator costs are usually approximated using quadratic functions. However, it is more practical to consider the generator valve-point loading effects [5]-[6]. One way of representing this effect is to model the generator cost curve by piecewise quadratic cost functions [5]-[6]. A second approach is the Walter-Sheble model that uses a rectified sinusoidal function to represent the valve-point loading in the cost function [5]-[6]. The latter approach is been considered in this paper.

The objective function F_T given in (2) is for the minimization of the nonconvex economic cost function, consisting of the generation and maintenance costs and generator valve-point loading effects. The generation 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_{jt} times the downtime D_{jt} of each unit on maintenance. Since the equations for the generation cost of units are expressed on a per hour basis, a multiplier of 168 is used to get the total cost for generation in one week. F_1 represent the traditional sum of the fuel costs of the conventional thermal generators as given by (4), while F_2 represents the cost for generating hydro power as shown in (4). From (4-6), C_h and C_w are the direct costs for the power derived from the hydro units and wind farms (wind-powered plants) respectively. The existence and size of these terms will depend on the ownership of the hydro units and wind-powered plants. If the hydro generators and wind-powered plants are owned by the system operator (or utility owned, such as in vertically integrated power networks), these terms may not even exist if it accounts only for the incremental fuel cost, which is zero for the hydro and wind. The penalty cost $C_{E,w}$ for not using all available wind may be set to zero. The last term in (5) relates to the price that must be paid for overestimation of the available wind power. Without regard to ownership of the wind-powered plants, the model must account for the possibility that a reserve would need to be drawn on if all the available wind power is inadequate to cover the amount of the wind power schedule in a given time period.

The degree of uncertainty in wind generation γ is added to the objective function in (2) using (5-7). This degree of uncertainty lies within the limits ($0 \leq \gamma \leq 1$). γ=1 represents 100% uncertainty in available wind generation from the wind farm (no wind energy), while γ=0 signifies 0% uncertainty in available wind generation.

$$F_T = \sum_{t=1}^{T} \left\{ F_1 + F_2 + F_3 + F_4 \right\} + \sum_{t=1}^{T} \left\{ \sum_{j=1}^{N_m} V_{jt} D_{jt} \right\} \tag{2}$$

where,

$$F_1 = \sum_{i=1}^{N_T} U_{it} \left\{ 168\left(a_i + b_i P_{it} + c_i P_{it}^2\right) + \alpha \left| e_i \sin\left(f_i \left(P_{it}^{\min} - P_{it}\right)\right) \right| \right\} \tag{3}$$

$$F_2 = \sum_{h=1}^{N_H} U_{ht} \left\{ C_h \left(P_{ht} \right) \right\} \tag{4}$$

$$F_3 = \gamma \sum_{w=1}^{N_W} \left\{ C_w\left(P_{s,wt}\right) + C_{E,w}\left(P_{av,wt} - P_{s,wt}\right) + C_{D,w}\left(P_{s,wt} - P_{av,wt}\right) \right\} \tag{5}$$

$$If \begin{cases} P_{av,wt} > P_{s,w}\text{, } then\ C_{E,w} > 0\ and\ C_{D,w} = 0 \\ P_{av,wt} = P_{s,wt}\text{, } then\ C_{E,w} = 0\ and\ C_{D,w} = 0 \\ P_{av,wt} < P_{s,wt}\text{, } then\ C_{E,w} = 0\ and\ C_{D,w} > 0 \end{cases} \tag{6}$$

$$F_4 = K_{pb} \left(\sum_{i=1}^{N_T} U_{it} P_{it} + \sum_{h=1}^{N_H} U_{ht} P_{ht} + \gamma \sum_{w=1}^{N_W} P_{s,wt} - P_t^D - P_{loss} \right)^2 \tag{7}$$

where α =1 if valve-point loading is taken into account (for nonconvex fuel cost functions), otherwise α =0 (for convex fuel cost functions). U_{it} and U_{ht} take values of 0 or 1 (0: if the thermal or hydro unit is scheduled for maintenance, 1: if the thermal or hydro unit is running or on-line) depending on the generated schedule.

The objective function in (2) is minimized to satisfy the GMS constraints (8-13). The loading constraint in (10) is incorporated and enforced in the objective function (2) using (7).

- *Crew/manpower constraint*
  This defines the manpower availability for maintenance task. The number of people required to perform maintenance task cannot exceed the available crew within each period.

$$\sum_{j \in N_m} \sum_{k \in S_{jt}} M_{jk} (1 - d_{jk}) \leq AM_t \text{,} \qquad \text{for all } t \in T \tag{8}$$

- *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. With commencement of maintenance task, the maintenance start indicator d_{jk} is 0, and remains 0 for the entire duration of maintenance represented by D_{jt} as expressed by (9).

$$\sum_{j \in N_m} \sum_{k \in S_{jt}} (1 - d_{jk}) = D_{jt} \text{,} \qquad \text{for all } t \in T \tag{9}$$

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

$$\sum_{i=1}^{N_T} U_{it} P_{it} + \sum_{h=1}^{N_H} U_{ht} P_{ht} + \gamma \sum_{w=1}^{N_W} P_{s,wt} = P_t^D + P_{loss}, \quad \text{for all } t \in T \tag{10}$$

- *Thermal units generation limits constraints*
  Each thermal generating unit must not exceed lower and upper generation limits.

$$P_i^{\min} \le P_{it} \le P_i^{\max}, \quad \text{for all } t \in T \tag{11}$$

- *Wind farms (plants) generation limits constraints*
  Each wind farm's turbine must not exceed lower and upper generation limits.

$$P_{s,wt}^{\min} \le P_{s,wt} \le P_{s,wt}^{\max}, \quad \text{for all } t \in T \tag{12}$$

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

$$\sum_{i=1}^{N_T} U_{it} P_i^{\max} + \sum_{h=1}^{N_H} U_{ht} P_h^{\max} + \gamma \sum_{w=1}^{N_W} P_{s,w}^{\max} \ge P_t^D + R, \quad \text{for all } t \in T \tag{13}$$

The GMS penalty cost given by (17) is added to the objective function in (3) if the maintenance schedule generated cannot satisfy the GMS constraints given in (11-16). The penalty value for each constraint violation is proportional to the amount by which the constraint is violated.

$$PC_{GMS} = \sum_{c=1}^{N_c} \omega_c \left| V_c \right| \tag{14}$$

III. MPSO-D FOR SOLVING THE GMS PROBLEM

Bio-inspired and evolutionary techniques have been shown to be very effective optimization tools in solving maintenance scheduling problems [1], [5]. Hence their application in solving the wind-hydrothermal GMS problem presented in this paper.

MPSO-D is a combination of DPSO and an evolutionary strategy to enhance the standard DPSO algorithm to perform better search for optimal solutions under complex environments. This version of MPSO-D is a newer variant of the original formulation of the DPSO to solve discrete optimization problems as explained below [1], [15]. A mutation operator is introduced into the MPSO-D algorithm to increase the diversity of the population. This leads to a better search performance by MPSO-D compared with DPSO. In addition, the inertia weight is dynamically adjusted.

Let X and V denote a particle's coordinates (position) and its corresponding flight speed (velocity) in a search space, respectively. Therefore, the lth particle is represented as $X_{ld} = (X_{l1}, X_{l2}, \ldots, X_{lN})$ in the d-dimensional space. The best previous position of the lth particle, referred to as *pbest*, is recorded and represented as $P_{lbd} = (P_{lb1}, P_{lb2}, \ldots, P_{lbN})$. The index of the best particle among all the *pbest* in the swarm is referred to as the *gbest* and is represented by P_{gd}. The rate of the velocity for particle lth is represented as $V_{ld} = (V_{l1}, V_{l2}, \ldots, V_{lN})$. In this version of PSO, the velocity is limited to a certain range [- V_{max}, V_{max}] such that V_{ld} always lies in that range. The new velocity and position for each particle i in dimension d is determined according to the velocity and position update equations given by (15) and (16) respectively. The inertia weight w_{iner} is updated according to (17).

$$\begin{aligned} V_{ld}(k) &= round(w_{iner} \cdot V_{ld}(k-1) + c_1 \cdot rand_1 \cdot (P_{lbd}(k-1) - X_{ld}(k-1)) \\ &\quad + c_2 \cdot rand_2 \cdot (P_{gb}^*(k-1) - X_{ld}(k-1))) \end{aligned} \tag{15}$$

$$X_{ld}(k) = X_{ld}(k-1) + V_{ld}(k) \tag{16}$$

$$w_{iner} = w_{iner}^{\max} - \left(\frac{w_{iner}^{\max} - w_{iner}^{\min}}{iter_{\max}} \right) \times iter \tag{17}$$

A mutation operator is introduced into the MPSO-D algorithm, so that the swarm's best position in dimension d is updated according to (18).

If $rand < M_r$

$$P_{gd}^*(k-1) = P_{gd}(k-1) + ceil(randn \times P_{gd}(k-1) / \beta_{gb}) \tag{18}$$

else

$$P_{gd}^*(k-1) = P_{gd}(k-1) \tag{19}$$

end

$d = 1, 2, \ldots, N$

where β_{gb} can be either dynamically changing or fixed.

IV. CASE STUDY AND DISCUSSIONS

A. Nigerian Grid System

The test data for this case is taken from a real power system presented in [1], whose thermal generating units are characterized with convex fuel cost coefficients ($\alpha = 0$ in (3)) for simplicity. Table A of the Appendix presents the Nigerian thermal stations fuel cost coefficients. A 9% spinning reserve is used to improve the system reliability and provide sufficient ramping capacity for balancing wind power variability in addition to existing load variations. The available crew/manpower, allowed maintenance window and downtime are presented in [1]. The anticipate wind farm/plant for integration with the hydrothermal power system is located in wind farm Area 3 as shown in Fig. 1. A load demand of 3625MW plus a 5% load increase is considered during the seasonal hot period in Nigeria, which also associates with the peak demand period [1].

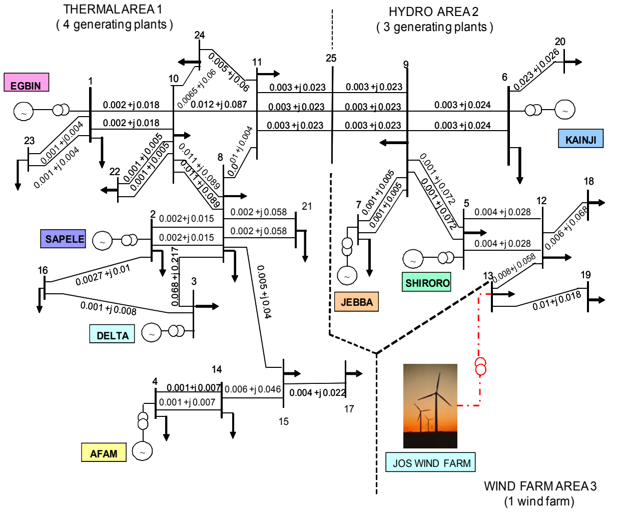

Fig. 1. Nigerian wind integrated-hydrothermal 330-kv, 24-bus grid system

B. *Numerical Results and Analysis*

All numerical results are obtained based on programs developed in the Matlab environment on a PC with 2.2GHz CPU speed and 1.5GB of RAM.

The following MPSO-D and wind-powered plant parameters are used for GMS calculation: population size of 30, $w_{iner}^{\min}$ and $w_{iner}^{\max}$ of 0.4 and 0.9 respectively, c_1 and c_2 of 2, V_{max} is 20% of the dynamic range of the variable on each dimension, M_r of 0.15, $Iter_{max}$ of 500, β_{gb} of 2, ρ of 1.2kgm^{-2}, A_w of 5024m^{-2}, and C_p of 0.59 [7]. The penalty cost coefficients, $C_{E,w}$ and $C_{D,w}$ are empirically tuned to values between 0 and 1000 according to (6), to effectively enforce the constraints in (6). The values are also in accordance with maximum wind power available. The costs paid to hydro and wind plants owners for the generated power actually used from hydro units C_h and wind units C_w are each set to 0, since both are owned by common utility operator (Nigerian government holds ownership of both plants).

The electricity generated by a utility-scale wind turbine is normally collected and fed into utility power lines, where it is mixed with electricity from other power plants and delivered to utility customers. The output of a wind turbine depends on the turbine's size and the wind's speed through the rotor. Wind turbines being manufactured now have power ratings ranging from 250W to 5MW. Most manufacturers of utility-scale turbines offer machines in the 700KW to 2.5MW range. 500 wind turbines of 2MW capacity each would make a 1000MW wind farm facility.

Fig. 2 shows the wind farms' generation patterns [15], while Table I presents the corresponding statistical variation of seven wind farms power outputs used for illustration in this paper. The seven wind farms are geographically dispersed across various regions of Nigeria, representing areas with significant amount of wind gusts and speed. From Fig. 3 and Table I it can be seen that wind farm cited in Jos area projects the highest wind power output with a relatively low standard deviation and hence low degree of wind variability and intermittency, compared with the remaining six wind farms. The Jos wind farm located in wind farm area 3 of Fig. 1 is therefore used as the only viable wind generation resources that can effectively participate in the wind integrated-hydrothermal maintenance scheduling. An annual mean of 408.34MW represents about 40.83% capacity factor for a wind farm facility of 500 wind turbines, each rated at 2MW. The Jos wind turbine's actual maximum power output is 1.585MW, while the wind farm's total actual maximum power generation is 792.474MW, assuming all the turbines are operating at their actual maximum power output capabilities. A wind plant is "fueled" by the wind, which blows steadily at times and not at all at other times. Although modern utility-scale wind turbines typically operate 65% to 90% of the time, they often run at less than full capacity [7]. Therefore, a capacity factor of 25% to 40% is common, although they may achieve higher capacity factors during windy weeks or months. A capacity factor of 40% to 80% is typical for conventional plants. The 52 weeks wind farm generation pattern for Jos, shown in Fig. 2 represents the available wind farm power output $P_{av,wt}$ used for illustrating the GMS problem for wind integrated–hydrothermal power system. The anticipated and scheduled wind power generation $P_{s,wt}$ required from Jos wind farm for the power system to meet load demand must equal the available generation $P_{av,wt}$, otherwise penalty cost is placed by enforcing (6).

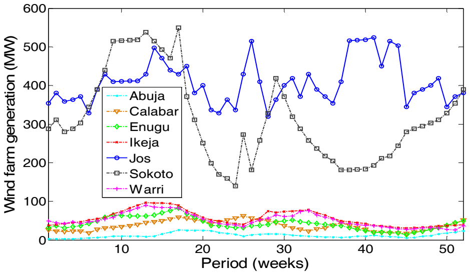

Fig. 2. Wind farms generation patterns [16]

TABLE I
STATISTICAL VARIATION OF SEVEN
WIND FARMS POWER OUTPUT [16]

Wind farm		Wind farm output power (MW)	
No.	Location	Annual mean	Standard deviation
1	Abuja	12.03	6.22
2	Calabar	36.05	12.96
3	Enugu	41.97	16.97
4	Ikeja	56.54	19.96
5	Jos	408.34	56.55
6	Sokoto	309.86	115.04
7	Warri	51.4	18.11

*2003 wind data

Table II shows maintenance schedules generated by MPSO-D algorithm for the 49 generating units over a period of 52 weeks obtained over 100 trials. The results are obtained for three different degrees of uncertainty in wind generation. The table shows the units scheduled for maintenance on weekly basis over 52 weeks and also presents the weekly maintenance costs, with an annual maintenance cost of 41120000 Naira over the entire maintenance window. A unit's maintenance cost in Naira/week is provided as a fixed quantity for each of the 49 generating units [1]. The maintenance cost is calculated by multiplying the fixed maintenance cost per week times the maintenance downtime of each unit in maintenance. Once a unit's maintenance is started it cannot be aborted, and each unit must undergo scheduled maintenance once per year. Table II also shows the annual generation costs for the five different degrees of uncertainty in wind generation. The annual cost of generation decreases with decreasing degree of uncertainty in wind generation.

Figs. 3 and 4 show typical maintenance cost and maintenance crew plots respectively for the 49-unit Nigerian hydrothermal system using the MPSO-D algorithm. It can be deduced from these figures that weeks 5, 14, 50-51 indicate periods with heavy maintenance work resulting in large maintenance costs, compared with weeks 18-19, 32-33 and 43 representing periods with relatively low maintenance tasks. The weekly manpower requirement depicted in Fig. 5 clearly satisfies the crew constraint in (8), and shows a mean and standard deviation of 12±6.20.

Table III presents the statistical comparison of the annual generation cost considering uncertainty in wind generation.

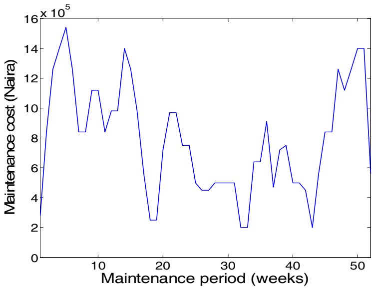

Fig. 3. Typical maintenance cost plot for the 49-unit Nigerian hydrothermal system with MPSO-D solution

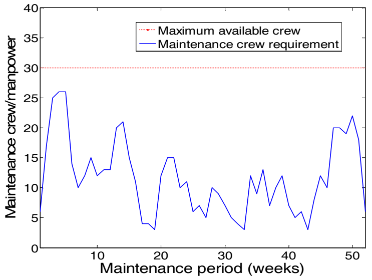

Fig. 4. Typical maintenance crew plot for the 49-unit Nigerian hydrothermal system with MPSO-D solution

TABLE II
ANNUAL MAINTENANCE SCHEDULES, MAINTENANCE AND GENERATION COSTS CONSIDERING DIFFERENT DEGREES OF UNCERTAINTY IN WIND GENERATION

Week no.	Degree of uncertainty (γ) in wind generation																
	GMS #1 with γ=1.0 (No wind generation)		Week no.	GMS #1 with γ=1.0 (No wind generation)		Week no.	GMS #2 with γ=0.5		Week no.	GMS #2 with γ=0.5		Week no.	GMS #3 with γ=0		Week no.	GMS #3 with γ=0	
	Gen. units scheduled for maint.	Weekly maint. cost (Naira)		Gen. units scheduled for maint.	Weekly maint. cost (Naira)		Gen. units scheduled for maint.	Weekly maint. cost (Naira)		Gen. units scheduled for maint.	Weekly maint. cost (Naira)		Gen. units scheduled for maint.	Weekly maint. cost (Naira)		Gen. units scheduled for maint.	Weekly maint. cost (Naira)
1	16,20	560000	27	38	250000	1	20	280000	27	32,36	500000	1	16	280000	27	37,38,39	750000
2	7,8,13,14,16,20	1120000	28	46	200000	2	1,3,6,20	1120000	28	36,37,43	720000	2	16	280000	28	37,38,39	750000
3	5,7,8,13,14,16,20	1400000	29	36,46	450000	3	1,3,6,10,16,20	1540000	29	36,37,43	720000	3	12,13,16,19	840000	29	37,38,39	750000
4	4,5,9,16,20	1260000	30	36,48	450000	4	1,3,6,7,9,10,11,16,20	1960000	30	33,37,43	720000	4	12,13,16,19	840000	30	49	200000
5	2,4,5,9	980000	31	36,48	450000	5	1,3,6,7,9,11,16	1540000	31	33,37	500000	5	4,19	560000	31	42,49	420000
6	2,4,5,17	1120000	32	36,49	450000	6	1,3,6,12,15,16	1540000	32	33,34,44	750000	6	2,4,6,19	1120000	32	42,46	420000
7	2,4,5,17	1120000	33	49	200000	7	12,15,18	700000	33	33,34,44	750000	7	2,3,6	840000	33	36,42,46	670000
8	2,4,6,17	1120000	34	33	250000	8	15,17,18	840000	34	34,44	500000	8	1,2,3,4,6,8	1540000	34	34,36	500000
9	2,3,6,10,15,17	1540000	35	33,37	500000	9	4,13,15,17,18	1260000	35	34,44	500000	9	1,2,3,4,5,6,8,15,18	2380000	35	34,36,41,43	940000
10	1,3,6,10,12,15,19	1680000	36	33,37	500000	10	2,4,13,14,17,18	1400000	36	49	200000	10	1,2,3,5,6,15,18	1960000	36	34,36,41,43	940000
11	1,3,6,11,12,15,19	1680000	37	33,37	500000	11	2,4,14,17	980000	37	35,49	450000	11	1,3,5,7,15,18	1540000	37	32,34,41,43	940000
12	1,3,6,11,15,19	1540000	38	37,47	450000	12	2,4,5,8,19	1260000	38	35	250000	12	1,3,5,7,10,15,18,20	1960000	38	32,33	500000
13	1,3,18,19	1120000	39	42,47	420000	13	2,4,5,8,19	1260000	39	35	250000	13	5,9,10,17,20	1120000	39	32,33,40	720000
14	1,18	560000	40	35,39,41,42,44,45	1440000	14	2,5,19	840000	40	35,39,47	700000	14	9,11,14,17,20	980000	40	32,33,40,45	970000
15	18	280000	41	35,39,40,41,42,43,44,45	1880000	15	5,19	560000	41	39,47	450000	15	11,14,17,20	840000	41	33,40,45	720000
16	18	280000	42	35,39,40,41,43,44,45	1660000	16	5	280000	42	39,46	450000	16	17	280000	42	45,47	450000
17	-	0	43	35,39,40,43,44,45	1440000	17	-	0	43	39,46	450000	17	-	0	43	45,47	450000
18	32	250000	44	25,30,31	700000	18	38,41,45	720000	44	21,27,30	840000	18	44	250000	44	22,24,29	700000
19	32	250000	45	22,25,26,27,28,30,31	1680000	19	38,41,45	720000	45	21,25,27,30	980000	19	44,48	450000	45	22,24,27,29	980000
20	32,34	500000	46	21,22,26,27,28,29,30,31	2100000	20	38,41,45	720000	46	21,22,24,25,27,30	1400000	20	44,48	450000	46	21,22,23,27,29,30,31	1820000
21	32,34	500000	47	21,22,27,28,29	1960000	21	38,40,45	720000	47	21,22,23,24,27	2240000	21	44	250000	47	21,22,23,25,27,	1960000
22	34	250000	48	21,22,27,28,29	1400000	22	40,42,48	640000	48	21,22,23,26,28	1680000	22	35	250000	48	21,22,25,27,28,	1820000
23	34	250000	49	21,22,23,24,29	1120000	23	40,42,48	640000	49	22,26,28,29,31	1260000	23	35	250000	49	21,28,30,31	1120000
24	38	250000	50	21,23,24	560000	24	32,42	470000	50	22,28,29,31	1120000	24	35	250000	50	21,26,28	700000
25	38	250000	51	-	0	25	32	250000	51	-	0	25	35	250000	51	26,28	420000
26	38	250000	52	-	0	26	32,36	500000	52	-	0	26	37,38,39	750000	52	-	0
Total maintenance cost over 52 weeks (Naira)				-	41120000	-	-	-	-	-	18380000	-	-	-	-	-	20610000
Annual generation cost (Naira)				-	1078900000	-	-	-	-	-	1051100000	-	-	-	-	-	1028100000

The results are obtained after 100 trials of 500 iterations over the entire maintenance period of 52 weeks. The results show minimum, maximum and average percent cost savings in generation of 4.94%, 4.94% and 5.08% respectively that could result from choosing to implementing GMS #3 (γ=0) compared with GMS #1 (γ=1.0). Similar analysis can be made for any GMS considering different degrees of uncertainty other than 0.

TABLE III

STATISTICAL COMPARISON OF ANNUAL GENERATION COST CONSIDERING UNCERTAINTY IN WIND GENERATION

S/N	Degree of uncertainty (γ) in wind generation	Annual generation cost (x100000)			
		Minimum (Naira)	Maximum (Naira)	Mean (Naira)	Standard deviation
1	GMS #1 with γ=1.0 (No wind generation)	10789	10814	10804	±7.518
2	GMS #2 with γ=0.5	10511	10520	10517	±11.949
3	GMS #3 with γ=0	10281	10305	10282	±9.248
Percent of cost of energy saving from wind penetration between implementing GMS #1 (γ=1.0) and GMS #3(γ=0)		4.94%	4.94%	5.08%	

Table IV shows the minimum and maximum limits of energy cost savings that can be obtained when implementing GMS #1, #2, or #3 for the different degrees of uncertainty in wind generation considered in this paper. The result shows how the degree of uncertainty in wind penetration is translated into evaluating commensurate levels of annual cost saving.

TABLE IV

ANNUAL COST SAVING CONSIDERING UNCERTAINTY IN WIND GENERATION

S/N	Degree of uncertainty (γ) in wind generation	Annual cost saving with wind penetration (x100000 Naira)	
		Minimum	Maximum
1	GMS #1 with γ=1.0 (No wind generation)	0	0
2	GMS #2 with γ=0.5	278	294
3	GMS #3 with γ=0	508	509

V. CONCLUSIONS

The challenging problem of optimal preventive generator maintenance scheduling in a smart grid environment comprising wind-hydrothermal energy resources has been presented. A discrete modified particle swarm optimization algorithm is applied in solving the GMS problem. Handling variability and intermittency of wind power in solving the GMS problem have been formulated and demonstrated. The degree of uncertainty in wind generation is shown to impact the annual cost saving. One of the key benefits associated with the wind power penetration is the additional capacity added to the system. The capacity benefit of wind generation is determined as the saved cost of having to generate more energy from thermal units and hence consume more fuel. It is demonstrated that the wind generation displaces electricity produced from thermal units (thermal generation is ramped down), thus the quantity of fuel burnt by the thermal units is reduced and the wind generation provides a fuel saving. The result presents potential for incorporating additional practical generator constraints and increasing the dimensionality of the problem. The result also shows long term planning platforms for optimized energy and preventive generator maintenance management in the presence of uncertainty in wind generation.

APPENDIX

TABLE A

NIGERIAN THERMAL STATIONS' FUEL COST COEFFICIENTS

Power station	Fuel cost coefficients		
	a_i (Naira/hr)	b_i (Naira/MWhr)	c_i (Naira/MW^{2}hr)
Sapele	6929.000	7.840	0.130
Delta	525.740	6.130	1.200
Afam	1998.000	56.000	0.092
Egbin	12787.000	13.100	0.031

Nigerian Naira=0.008US$ at 2003.

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