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# Reliability/Economic/GHG implications of Grid-Connected Wind Energy System Based on Genetic Algorithm

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***Abstract*–Greenhouse gas, economic, and reliability issues are becoming more important for the emerging wind markets worldwide. With the interconnection of wind energy system into the electric grid, the fluctuating nature of the energy produced has a different effect on the overall system reliability/economic and GHG emissions as well as the fluctuating nature of energy produced by grid. Optimum reliability/economic and pollutant emission are multi-objective problem because reliability is conflicting with annual cost and GHG emissions. The reliability index is analyzed using probabilistic concept in order to find loss of load probability and annual customer damage cost. Therefore, this paper presents a study to find optimum design of wind energy system with electric grid from reliability/economic and pollutant emission point of view based on genetic algorithm (GA). The methodology is carried out over one year using the hourly data of the load demand and wind speed at Zafarâna site, located on the western coast of the Seuz Gulf, latitude 29.07o N and longitude 31.36o E, Egypt as an example. The optimization results do not just show economic merit but satisfy both of reliability level and environmental issues. Moreover this methodology can be applied at any site in the world to determine the optimal design and impact of reliability and GHG emissions of interconnected renewable energy system with electric grid.**

***Index Terms*** –Reliability; Emission; genetic algorithm

## 1. INTRODUCTION

As the energy demands around the world increase, the need for a renewable energy source that will not harm the environment has been increased. Some projections indicate that the global energy demand will almost triple by 2050 [1]. Wind energy is one of the most encouraging renewable energy sources free from release of GHG, and it has prospective in regard with demand of energy because of its obtainability which increases interest worldwide. It is one of the firmest emerging and lucrative resources of renewable energy from all the other resources that have been used for ecological environment friendly power systems [2]. A 30% contribution to world energy supply from renewable energy sources by year 2020 would reduce the energy related CO2 emission by 25% [1]. On the other hand, Egypt targets to increase the renewable energy sector to produce 20% of total power generation by 2020, 12% of which will be generated by wind energy. Reliability evaluation and economic study of wind energy system interconnected with electric power systems has attracted the attention of researchers around the world. In ref. [1], a complete study, from reliability point of view, is presented in order to determine the impact of interconnecting photovoltaic/wind system into utility grid. Ref. [3] presents a designed PV–wind–diesel system for two different load profiles, considering the costs and pollutant emissions based on evolutionary algorithm. Ref. [4-5] recommends an optimal sizing method to optimize the configurations of a hybrid solar–wind system employing battery banks based on a GA considering reliability and minimum annualized cost of system, ACS. Ref. [6] presents optimization method involving of cost, reliability and pollutant emission into optimization process for of Wind-Diesel-Battery based on GA. Ref. [7] proposes a new equivalent model for reliability evaluation of interconnected power systems considering WTGs of multi-states operation. Ref. [8] proposes a reliability and cost evaluation methodology for small autonomous power systems that contain only renewable energy source. Economics and pollutant emissions play a major role in the application of reliability concepts and the attainment of an acceptable level of reliability. Most of the researches are considering the reliability evaluation, economic consideration with or without taking into account GHG emission in the design process. Optimum reliability/economic and pollutant emission are multi-objective function because reliability is conflicting with annual cost and GHG emissions. This paper presents a GA optimization methodology to obtain the optimum design and impact of reliability and GHG emissions of interconnection of wind energy system interconnected with electric grid.

## 2. SYSTEM DESCRIPTION

The configuration of a wind energy system, WES interconnected with electric grid, EG is shown in Fig. 1. Main power source will be generated by WES to feed load demand. Deficit power will be purchased from secondary power source, EG. On the other hand excess power will be sold to the secondary power source, EG. The Wind turbine generators, WTGs are connected to AC-bus via AC/AC converter, while the load is connected to AC-bus. The mathematical modeling of each component is described in following sub-sections.

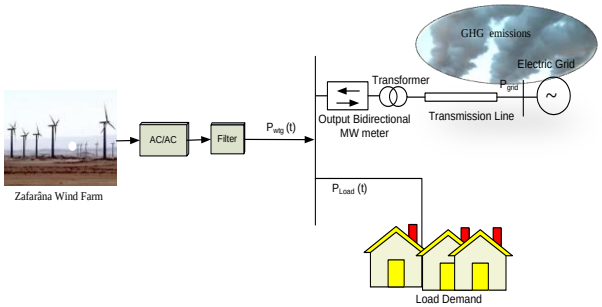


Fig. 1. Schematic of Grid-connected WES

### 2-1 Wind turbine Model

The characteristic of power output from Wind turbine generators, WTG's can be described by the following formula [9-10]:-

$$P_{wtg}(t) = \begin{cases} 0 & : v(t) < V_c \\ 0.5.C_p \cdot \eta_m \cdot \eta_g \cdot A_w \cdot v^3(t) & : V_c \le v(t) < V_r \\ P_{rated} & : V_r \le v(t) < V_f \\ 0 & : v(t) > V_f \end{cases} \quad (1)$$

Where; v(t) is the wind speed; m/s, $P_{rated}$ is the rated power; kW, $A_w$ is the effective swept area; $m^2$. The wind power plant consists of identical wind turbines, and that the wind conditions are the same for all turbines. In this paper, a V66-1.75 WTG's model is implemented. The measured average wind speed and the number of observation of each wind speed during the year of observation has been taken form Egyptian Metrological Authority for El'Zafarana site. Figure 2 shows the average hourly wind speed over the year seasons as a sample data [11].

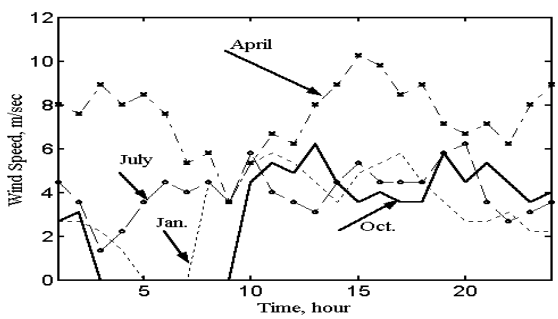


Fig. 2 Wind Speed during January, April, July and October.

### 2-2 Electricalgrid Model

EG will act as a secondary power source. The grid capacity should be sufficient to provide the maximum electric load demand at times of zero renewable power generation. The power exchanged with the marked system is calculated from the power balance Equation as follows:-

$$\mp P_{grid}(t) = P_{wtg}(t) - P_{Load}(t) \quad (2)$$

$$-P_g^{max} \le P_{grid}(t) \le P_g^{max} \quad (3)$$

Where;

$P_{grid}(t)$ : The export or import power to grid, kW

$P_{wtg}(t)$ : The WTG's output power, kW,

$P_{Load}(t)$ : The load demand, kW,

t : Time, h,

$P_g^{max}$ : The maximum allowable transmission of power to the grid. Power export/import corresponds to values for $P_{grid}(t)$ and is measured at the load side of the transmission line.

### *2-3 GHG emission Model*

GHG Emissions of the main pollutants were calculated in order to assess the environmental impacts of the energy system. Pollutants emitted into the ambient atmosphere taken into account are: $CO_2$, $NO_x$, $SO_2$, and particulate matter less than 10 µm in diameter, $PM_{10}$. Emission factors for $CO_2$, $NO_x$, $SO_2$ and$PM_{10}$ are 638 ,1.148,1.859, 0.171 g/kWh respectively [12-14].The total GHG emissions are calculated by multiplying the combined margin of GHG emission factor by the amount of annual electricity purchased, AEP form the electric grid.

Annual GHG emission

$$= \frac{\text{AEP (kWh)} \,.\, \text{GHG emission factor (g/kWh)}}{1{,}000{,}000} \quad \text{ton} \quad (4)$$

It is well known that carbon dioxide ($CO_2$) emission is the main cause of greenhouse effect so that the total amount of $CO_2$at the atmosphere, it must be minimized in order to reduce the global warming.

### *2-4 Load Characteristics*

The load demand in Egypt has been evaluated along one complete year of operation. Figure 3 shows the assumed load demand during each month for one day in the period of 168:191 hour. The minimum and maximum loads are set to15 MW and 100 MW respectively with an average load demand of 44.85 MW. Yearly energy demand equal to 387.540 GWh.

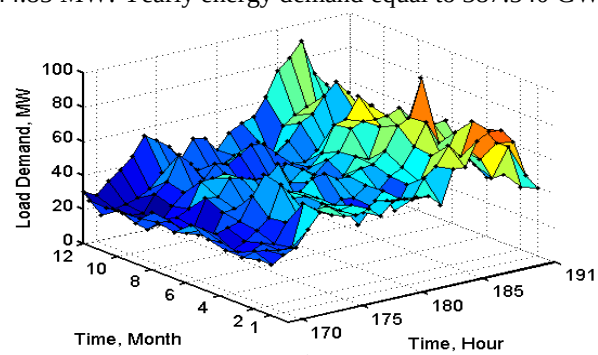


Fig. 3. Variation of the load demand

## 3. METHODOLOGY

### 3.1 Probabilistic Modeling and Reliability Index

Probabilistic reliability index serves as an accurate and consistent basis for assessing reliability of power systems, where components outage and load demand are of stochastic nature [15]. The reliability analysis for Grid-Connected Wind Energy System uses a capacity outage probability table, which is an array of capacity levels and the associate probabilities of existence. This is obtained by combining the generating unit's availability and unavailability using basic probability concepts. From the individual probability table, cumulative probability table have been prepared[11], [16] . The basic elements used to evaluate generation adequacy are shown in Fig. 4.

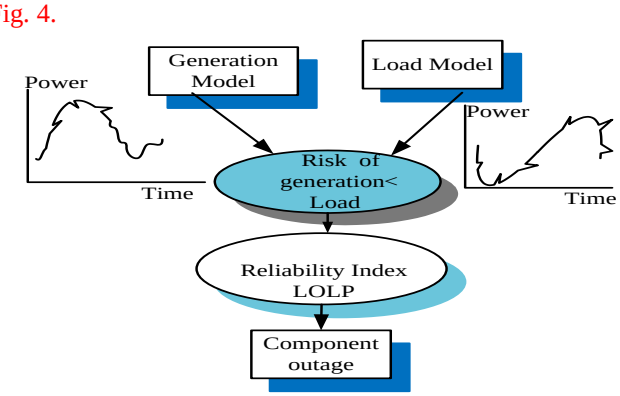


Fig. 4 Elements of generation reliability evaluation[11]

The cumulative probability of a particular capacity outage state of *X MW* after adding a two-state unit of capacity $P_{gx}(t)$ *MW* with forced outage rate, γis given[17-18]as:

$$P(X,t) = (1-\gamma).\acute{P}(X,t) + \gamma.\acute{P}\big(X - P_{gx}(t)\big) \quad (5)$$

Where;

*P'*(*X*,*t*) and *P*(*X*,*t*) denote the cumulative probabilities of the capacity outage state of *X MW* before and after the unit is added at time t.

$P_{gx}(t)$ :The capacity outage of state Xfor the WTGs being added or decreased.

The above expression is initialized by setting:-

P'(X,t) =1.0 for X <= 0 and P'(X,t) =0.0 otherwise.

γ : Forced outage rate given by the following equation:-

$$\gamma = \frac{ForcedOutageinHours}{ForcedOutageinHours + InServicesHours} \quad (6)$$

Eq. (5) can be modified as follows to include multi-state unit representations.

$$P(X,t) = \sum_{x=1}^{n} p_x.\acute{P}\big(X - P_{gx}(t)\big) \quad (7)$$

Where;

*n* :The total number of units,

$p_x$ :The probability of existence of the unit state x and is defined as follow [17-18]:-

$$p_x = \sum_{r=k}^{n} \binom{n}{r}.\gamma^r.(1-\gamma)^{n-r} \quad (8)$$

Where,

k : Minimum number of units required to the system succeed.

$$\binom{n}{r}\frac{n!}{(n-r)!.r!} \quad (9)$$

The overall probability that the load demand will not be met is called LOLP is computed as:-

$$LOLP(t) = \sum_{r=k}^{n} p_x.P\big(P_{Load}(t) > P_{gx}(t)\big) \quad (10)$$

Where,

$P_{Load}(t)$ : Load demand at hour t,

$P\big(P_{Load}(t) > P_{gx}(t)\big)$: Probability of loss of load at hour, t.

LOLP(X,t) : Loss of load probability at hour t for state X.

Then , the reliability index of the system can be expressed as the following Equation

$$\text{Reliability} = \left(1 - \frac{\sum_{t=1}^{8760} \text{LOLP(t)}}{8760}\right) * 100\ \% \quad (11)$$

The forced outage rate of WES can be calculated using effective forced outage rate of WTGs ($EFOR_W$). This concept can be explained using sliding window approach, which allow for variability in wind speed or solar radiation through time and can be calculated as follows [11]:-

$$\text{EFOR}_w = \left(1 - \frac{\text{Maxium energy of WES}}{\text{Total energy of WES}}\right) \quad (12)$$

### 3.2 Economical Calculations [5,19]

Economical calculation based on the concept of ACS. ACS is composed of annual capital cost (ACC), annual operation maintenance cost (AOM) and the annualized replacement cost (ARC) for other components. It can be calculated from following equation:

$$ACS = \sum_{k=Componet} ACC(k) + ARC(k) + \text{AOM}\big(\text{k}, Y_{proj}\big) \quad (13)$$

Where;

ACC(k) :Annualized capital cost of each components taken into account the installation cost (including wind Foundation, electric installation, control systems, land, financial costs and road et al.), and it can be calculated by the following Equ:-

$$ACC(k) = IC(k).CRF\big(i, Y_{proj}\big) \quad (14)$$

Where;

IC(k) : The initial cost of the each component in the system.

CRF :The capital recovery factor. It can be defined as follows:-

$$CRF\big(i, Y_{proj}\big) = \frac{i.(1+i)^{Y_{proj}}}{(1+i)^{Y_{proj}} - 1} \quad (15)$$

$Y_{proj}$ :The component lifetime, year.

The annual real interest rate *i* is related to the nominal interest rate *í* (the rate at which you could get a loan) and the annual inflation rate *f*which can be calculated by the equation given below.

$$i = \frac{\acute{i} - f}{1+f} \quad (16)$$

ARC(K) :Annualized replacement cost of the system component.It can be calculated as follows:

$$ARC(k) = C_{rep}(k).SFF\big(i, Y_{rep,k}\big).S(k) \quad (17)$$

Where;

$C_{rep}(k)$ :The replacement cost of the component, US$/kW; S(k) :Size of each component, kW. $Y_{rep,k}$ :The lifetime, year; SFF :The sinking fund factor. It can be estimated as follows:-

$$SFF\big(i, Y_{rep,k}\big) = \frac{i}{(1+i)^{Y_{rep,k}} - 1} \quad (18)$$

AOM (k,$Y_{proj}$ ) : Annual operation and maintenance cost of the system. It can be calculated from the following equation:-

$$AOM\big(k, Y_{proj}\big) = C_{amain}(k,1).(1+f)^{Y_{Proj,k}} \quad (19)$$

Where;

$C_{amain}$ (k, 1) :The system maintenance cost of the first year.

### 3.3 Genetic Algorithm

A GA is an advanced search technique and robust used to find exact solutions of multi-objective problems.It has been developed to imitate the evolutionary principle of natural genetics. Although the binary representation is usually applied to power optimization problems, in this paper, a real values representation scheme used for solutions. The following are the basic steps involved in GA:-

1. Build an initial population of chromosomes (solutions) created randomly or using some initialization method. The chromosome is a point that can be applied on the fitness function. The value of the fitness function for a chromosome is its score. In this paper, each chromosome consists of one gene in form of [NWTG]. Where, NWTG is number of WTGs.

2. Calculate the fitness function
   The fitness function is the objective function. The GA tries to find the minimum of the fitness function. It is written as an M-file which is treated as a function handle input argument to the main genetic algorithm function. It can be expressed as follows:-

$$\text{Fitness Function} = \text{ACS} + \text{AEP} - \text{AES} - \text{AEC} + \text{ACDC} \quad (20)$$

3. After selection of initial chromosome, apply the genetic operators of an arithmetic crossover operator. After crossover is completed, mutation is performed. In the mutation step, a random real value makes a random change in the nth element of the chromosome. After mutation, all constraints are checked whether violated or not. Then, the best solution so far obtained in the search is retained and used in the following generation. The genetic algorithm process repeats until stopping conditions and reached minimum fitness function.
4. Populations and Generations: A population is an array of chromosome. In this paper, the number of variables in the fitness function is number of wind turbine. The flowchart of the GA technique is shown in Fig. 5.

Where;

AEP is Annual electricity purchased from gird at a discount rate of $ 0.05/kWh.

AES is Annual electricity sold to grid at a discount rate of $0.04/kWh.

AEC is Annual emission cost.Costs of pollutants in dollars per ton called environmental damage costs which differ from country to country and depended on type of power system generation. AEC can be calculated from the following equation.

$$\text{AEC=Annual\_GHG\_emission*Cost\_factors US\$} \quad (21)$$

Where, Cost factors for $CO_2$, $NO_x$, $SO_2$ and$PM_{10}$ are 40 , 4579, 7057, 5032 US $/ton respectively [12-15].

ACDC is Annual Customer Damage Cost.There are a small number of published studies that contain customer damage cost [8,19].To calculate of the ACDC, the customer damage functions (CDFs) have been calculated from Equ. (22).The ACDC can be calculated from Equ. (23).

$$\text{CDF} = 0.1738 * \left(\sum_{t=1}^{8760} \text{LOLP(t)}\right)^2 + \left(0.6083 * \sum_{t=1}^{8760} \text{LOLP(t)}\right) - 0.3001 \ \frac{\$}{\text{kW}} \quad (22)$$

$$ACDC = \left(\sum_{t=1}^{8760} \text{LOLE(t)}\right).\text{CDF} \quad \$ \quad (23)$$

Where, LOLE is loss of load expected. It can be calculated as follows:

$$LOLE(t) = \sum_{t=1}^{8760} \text{E}\big(\text{LOLP(t)}\big) \quad (24)$$

Where; E(LOLP(t)) is the expected value of loss of load at $t^{th}$ time step. The flowchart of the GA technique is shown in Fig. 5.

## 4. Application and Results

The optimal configuration of WES/EG have been determined by GA taking into consideration the overall system reliability, economic study and GHG emissions. The concept of GA is different from traditional search. The first step of optimal configuration process is loading of annual wind speed, load demand, specification of WTG, economic parameters, and emission parameters. The second step is initialization of the first population, and then GA will evaluate the objective function every generation. In this case, the objective function as shown in Equ.(20) is minimizing according to high reliability, minimum cost and minimum GHG emissions cost. The flowchart of optimization process is shown in Fig. 6. After calculating objective function, GA will search the number of WTGs which satisfy minimum cost, high reliability and minimum GHG emissions. In this simulation, GA parameters consist of 20 populations, and 100 maximum generations. The values of crossover and mutation probabilityare 0.75 and 0.015 respectively. These values are determined by trial and error in order to find the optimal value quickly.

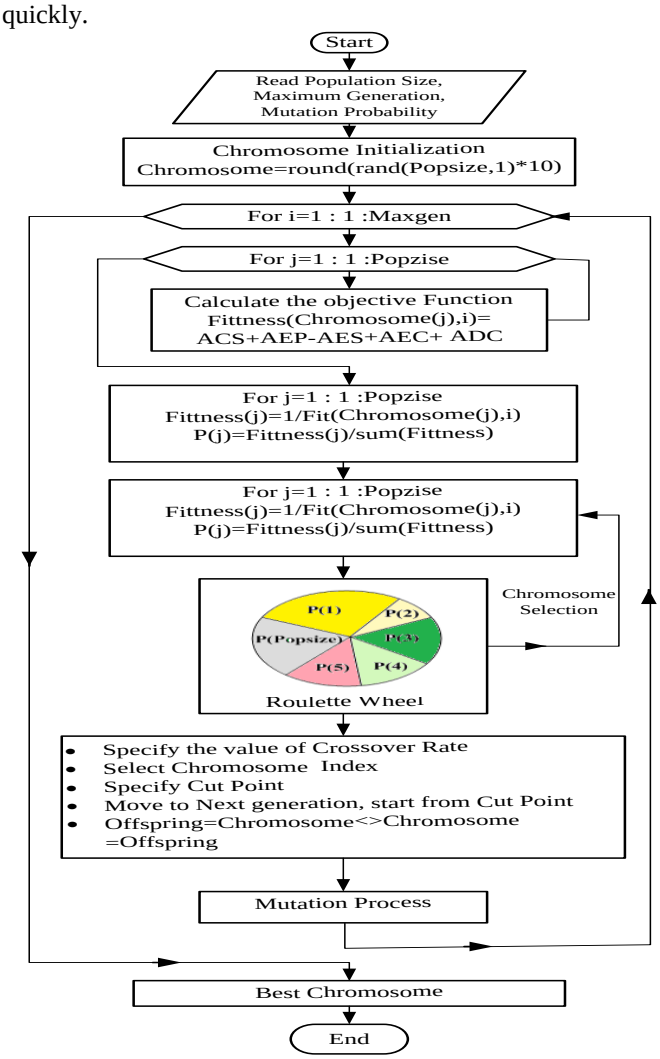


Fig. 5. Flow chart of GA

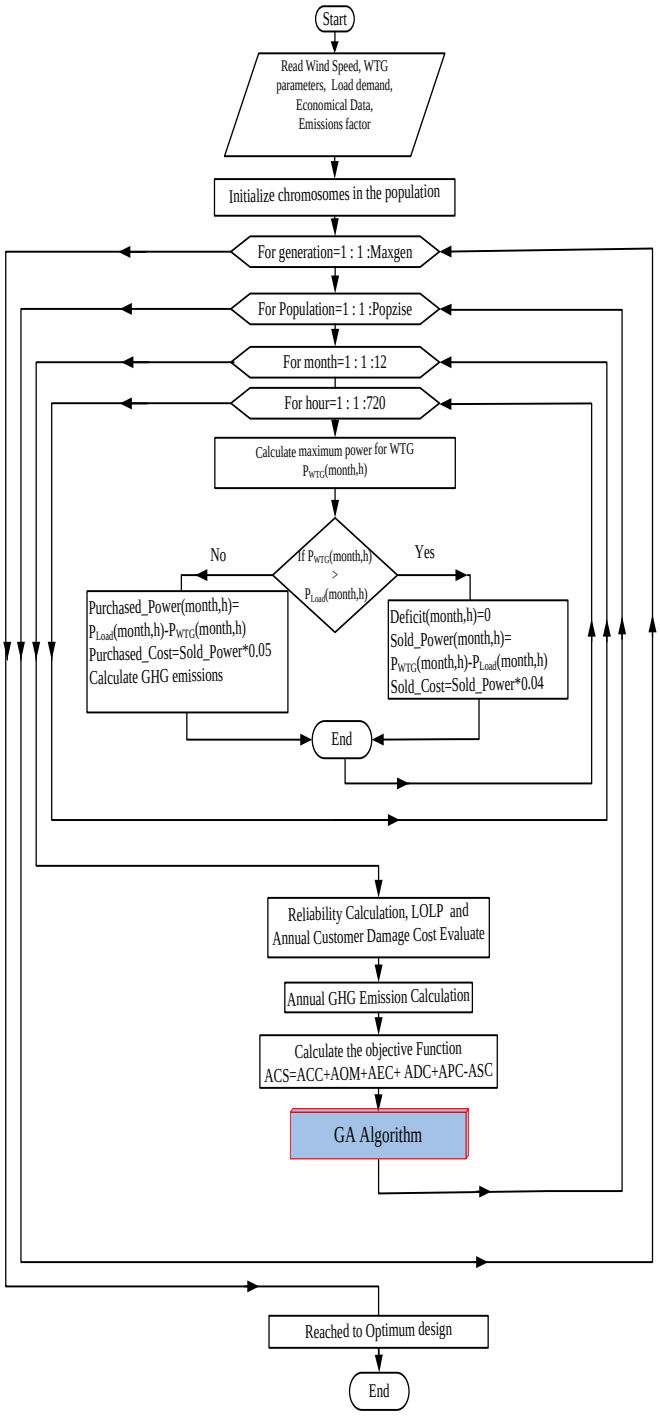


Fig. 6. Flowchart of WES/EG System optimization

The convergence curve of the GA is depicted in Fig. 7 for best values and mean values for each population. It can be seen that the optimal values can be obtained closed to 44 number of generations as shown from Fig. 8. From Fig. 8, it can be seen that, the optimal size of WTG obtained from the optimization process is 57 WTG. The initial capital cost, operation & maintenance cost in the first year and the lifetime of key components (WTG, and other devices) are listed in Table 1.

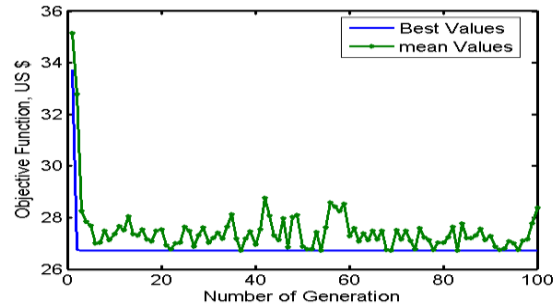


Fig. 7.Convergence of the optimization algorithm.

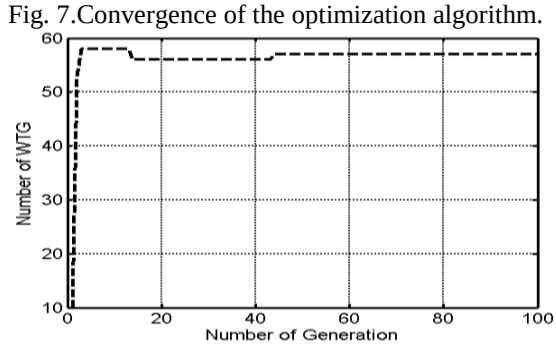


Fig. 8 Best Chromosome with Number of generation

Table 1 Expected costs in US $/kW and lifetime for the system components

| | Initial capital cost | Replacement cost | O&M cost in first year | Life time (year) | Interest Rate *i*% | Inflation Rate % |
|---|---|---|---|---|---|---|
| WTG | 1738 | Null | 10 | 25 | 3.75 | 1.5 |
| Other components | 750 | 250 | 5 | 15 | | |

From Table 1, result from Fig. 8 and methodology, Total capital cost of all WTGs was found 19,434,315 US$ with annual energy generated from wind farm was 387.625513E6 kWh. On the other hand, yearly energy demand equal to 387.540 GWh. Annual deficit energy was 132.9301E6 kWh with cost 6.64651 M US $ from electric grid. On the other hand, annual surplus energy was 133.0126E6 kWh with cost 5.32050 M US $ sold to grid.

The fluctuating nature of the energy produced by WES has a different effect on the overall system reliability, therefore, reliability estimation of grid-connected WES can be calculated based on $EFOR_W$ every month as shown in Equ. (12). The EFORw for all months of the year is shown in Fig. 9. On the other hand, the capacity outage table for grid-Connected WES as shown in Table 2. Meanwhile, comparison between the hourly LOLP for electric grid only and grid-connected WES during year is shown in Figure 10. From this figure it can be seen that the total LOLP during each month was improved when load demand was fed from WES/EG. For example, LOLP during June was 1.32320067 h when load was fed from EG, on the other hand during June was 0.6229512 h when load was fed from WES/EG.

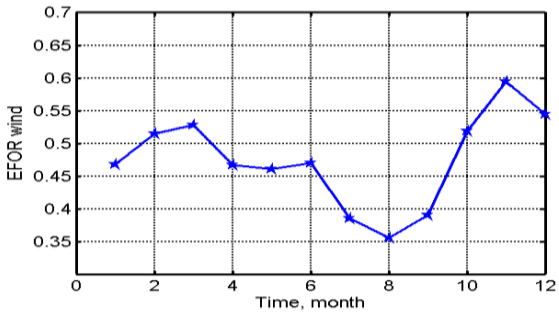


Fig. 9 Effective forced outage rate for WES/EG

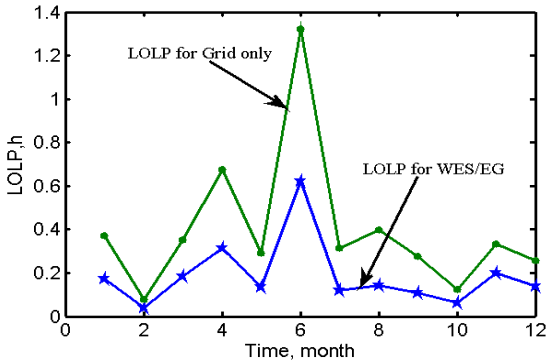


Fig. 10 Total hourly LOLP values for all months during the year

Table 2 WES/EG power system capacity outage table

| State i | MW output | MW input | Probability $p_i$ | Commutative probability p(Load>Input) |
|---|---|---|---|---|
| 0 | 0 | 144.86 | 3.72E-01 | 1.00E+00 |
| 1 | 44.86 | 100 | 4.45E-01 | 6.28E-01 |
| 2 | 10 | 134.86 | 7.60E-02 | 1.83E-01 |
| 3 | 54.86 | 90 | 9.08E-02 | 1.07E-01 |
| 4 | 20 | 124.86 | 6.98E-03 | 1.62E-02 |
| 5 | 64.86 | 80 | 8.34E-03 | 9.20E-03 |
| 6 | 30 | 114.86 | 3.80E-04 | 8.64E-04 |
| 7 | 74.86 | 70 | 4.54E-04 | 4.84E-04 |
| 8 | 40 | 104.86 | 1.36E-05 | 3.05E-05 |
| 9 | 84.86 | 60 | 1.62E-05 | 1.69E-05 |
| 10 | 50 | 94.86 | 3.32E-07 | 7.41E-07 |
| 11 | 94.86 | 50 | 3.97E-07 | 4.09E-07 |
| 12 | 60 | 84.86 | 5.65E-09 | 1.25E-08 |
| 13 | 104.86 | 40 | 6.75E-09 | 6.89E-09 |
| 14 | 70 | 74.86 | 6.59E-11 | 1.46E-10 |
| 15 | 114.86 | 30 | 7.87E-11 | 7.98E-11 |
| 16 | 80 | 64.86 | 5.04E-13 | 1.11E-12 |
| 17 | 124.86 | 20 | 6.02E-13 | 6.07E-13 |
| 18 | 90 | 54.86 | 2.29E-15 | 5.20E-15 |
| 19 | 134.86 | 10 | 2.73E-15 | 2.91E-15 |
| 20 | 100 | 44.86 | 4.67E-18 | 1.78E-16 |
| 21 | 144.86 | 0 | 5.57E-18 | 1.73E-16 |

The total LOLP when the load feed form WES/EG is equal to 2.444315 h compared with 4.7890254h for grid only. The percentage reliability equal to (8760-2.444315)/8760*100= 99.9720968 % compared with 99.9453% for grid only. On the other hand, LOLE in kW is equal to 7473.5048 kW. The value LOLE is used to determine the value of ACDC using Equ. (23) Which is equal to 14,503.834 US $ compared with 105,057 US $ for grid only.

Finally,GHG emissions of $CO_2$, $NO_x$, $SO_2$ and $PM_{10}$ for each month are shown in Fig. 11. Converting the projected emissions to their equivalent dollar, Fig. 12shows monthly cost of GHG emissions in US $. From Fig. 12 it can be seen that, the largest environmental cost was $CO_2$, which was 9892203 US$, about 57.02% of total environmental costs. Total saving of GHG emissions was 248,537 tons with total environmental cost was 17,348,617 US $. On the other hand, for electric grid only, total GHG emissions in air was 248,484tons with total environmental cost was 17,344,925US $ and for WES/EG, the total GHG emissions due to deficit energy was 85,232 ton. So, the net total saving of GHG emissions was 248537-85232=163,305 tons. Hence, an optimal design of 100MW WES/EG configuration could be expected to decrease GHG by 66 %.

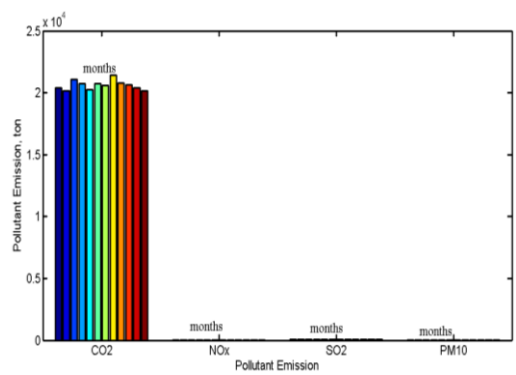


Fig .11 Amount of GHG emissions for each month

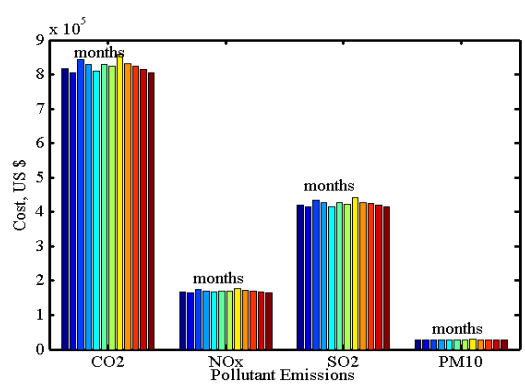


Fig. 12 Cost of GHG emissions for each month

## 5. Conclusions

GHG, economic, and reliability issues are becoming more important for the emerging wind markets worldwide. Optimum reliability/economic and pollutant emission are multi-objective problem because reliability is conflicting with annual cost and GHG emissions. This paper presents a complete study to find optimum design of wind energy system with electric grid from reliability/economic and pollutant emission based on genetic algorithm. From results obtained above, the following are the salient conclusions can be drawn from this paper:-

1. An optimization technique based on GA has been proposed to determine an optimum design of grid-Connected WES taking into account customer damage cost, total annualized cost and GHG emissions.
2. Total number of wind turbines was found 57 with a capacity of 1700 kW for each wind turbine.
3. The reliability level for grid only was found 99.9453% and for WES/EG was found 99.9720968 %. ACDC was equal to 105,057 US $ for grid only and 14,504 US $ for WES/EG.
4. The annual total emission of GHG was found 248,484 ton for grid only. On the other hand, annual total saving of GHG emissions for WES/EG was found 248,537 ton with total annual environmental saving cost was 17,348,617 US $. It may be noted that to generate clean and environmentally friendly using grid only has to spend extra cost due to capturing pollutant mission. The percentage decrease of GHG emissions by 66 %.
5. Finally, This paper recommends an optimal sizing method based on GA to optimize the configurations of a wind energy system interconnected with electric grid to achieve the minimum customers damage cost, minimum GHG emissions from electric grid with a minimum annualized total cost of system.

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