

Optimal Type and Installation Time of Wind Farm in a Power System, Considering Service Providers

M. H. Abedi, A. Jalilvand

Abstract—The economic development benefits of wind energy may be the most tangible basis for the local and state officials' interests. In addition to the direct salaries associated with building and operating wind projects, the wind energy industry provides indirect jobs and benefits. The optimal planning of a wind farm is one most important topic in renewable energy technology. Many methods have been implemented to optimize the cost and output benefit of wind farms, but the contribution of this paper is mentioning different types of service providers and also time of installation of wind turbines during planning horizon years. Genetic algorithm (GA) is used to optimize the problem. It is observed that an appropriate layout of wind farm can cause to minimize the different types of cost.

Keywords—Renewable energy, wind farm, optimization, planning.

I. INTRODUCTION

THE conversion of wind power into electrical power is performed by wind turbines which are grouped into a wind farm in order to minimize the installation, operation, and maintenance cost.

As the number of wind turbines in the farm increases, the average power output per wind turbine decreases because of the presence of wake effects within the wind farm [1]. Wind energy is one of the more promising options amongst the various renewable energy generation technologies and is expected to play a significant role in reducing the environmental implications of meeting modern societies demand for electrical power [2].

A number of wind turbine generator (WTG) types with different design parameters, such as the rated capacity, and the turbine cut-in, rated, and cut out wind speeds, are commercially available [3]. Each WTG has specific economic parameters, such as the capital, maintenance, and operating (M&O) costs.

The generation probability distribution of a WTG can be evaluated from the wind speed probability distribution obtained using the autoregressive and moving average (ARMA) wind speed model [4], and the nonlinear relationship between the power output of the WTG and the wind speed. Both Monte Carlo simulation and analytical methods have been utilized in the adequacy evaluation of generation systems.

In [5], the effects of using different hub height wind

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turbines in a small onshore wind farm are investigated with nested GA.

An artificial neural network (ANN) model is addressed in order to estimate the optimal number of wind turbines and the total produced power in a wind farm [6].

Reference [7] introduces the Powell's optimization method which is developed in order to determine the optimal number of wind turbines and the total produced power in a wind farm. The minimization of the cost per unit of produced energy was the criterion of the optimization.

The WTG design parameters, such as the turbine cut-in, rated, and cut out wind speeds, have considerable impact on the generation output distributions and the reliability performance. Different types of WTG usually have different economic parameters, such as the capital and M&O costs.

Reference [8] presents a model based on the equivalent annual cost for determining the optimal WTG installation scheme at each specific wind site, formulated as a combinatorial constrained optimization problem with a nonlinear and nondifferentiable objective functions solved by GA.

In this report, an objective function has been presented which contains: The capital, M&O costs, fossil energy cost, and customer interruption costs are considered in the objective function. GA with integer variables is implemented for optimizing the problem.

II. WTG OUTPUT POWER MODELING

The output power of the wind turbines depends on the wind speed characteristics as well as on the availability of the electrical generator. These factors are given by the turbine manufacturer, designated as power curve of the turbine [9]. There are three threshold speeds for wind turbine operation as cut-in, rated and cut-out speeds. According to (1), the output power of WTG is obtained when the speed of turbine is more than cut-in value. While the speed is between cut-in and rated speeds, output power and speed have non-linear relation. Constant power is generated when the wind speed differs from rated and cut-out. For safety the unit is shut down for high wind speeds which are more than cut-out [10].

$$P_t = \begin{cases} 0 & 0 \leq v < V_{ci} \\ [A + B \times v + C \times v^2] \times P_r & V_{ci} \leq v < V_r \\ P_r & V_r \leq v < V_{co} \\ 0 & V_{co} \leq v \end{cases} \quad (1)$$

where A, B, and C are constants and determined based on parameters of wind turbine. Fig 1 illustrates a sample output power curve of a WTG.

$$A = \frac{1}{(V_{ci} - V_r)^2} \left(V_{ci} (V_{ci} + V_r) - 4 \times V_{ci} \times V_r \left[\frac{V_{ci} + V_r}{2V_r} \right]^3 \right)$$

$$B = \frac{1}{(V_{ci} - V_r)^2} \left(4(V_{ci} + V_r) \left[\frac{V_{ci} + V_r}{2V_r} \right]^3 - (3 \times V_{ci} + V_r) \right)$$

$$C = \frac{1}{(V_{ci} - V_r)^2} \left(2 - 4 \left[\frac{V_{ci} + V_r}{2 \times V_r} \right]^3 \right)$$

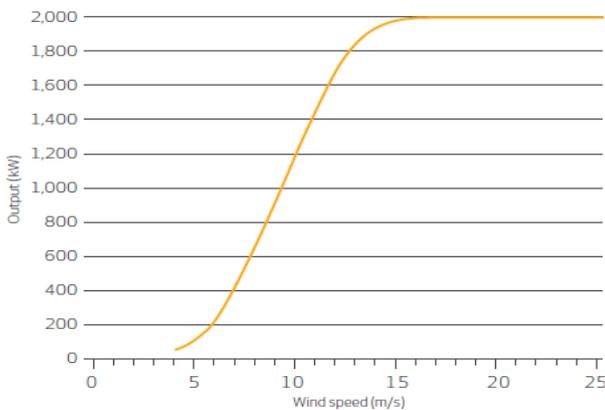


Fig. 1 Power curve of a WTG

III. OPTIMAL WTG INSTALLATION MODEL

As noted earlier, the major economic factors related to WTG installation schemes in a power system are the wind regime at the site location, the WTG cut-in, rated, and cut out wind speeds, the WTG capital and installation costs, M&O costs and etc. The objective of the proposed model is to minimize the total cost, including the capital cost, M&O cost, fossil energy cost and investment interruption cost. An annual equivalent cost model is incorporated to consider the different useful life of WECS.

A. Wind Farms Capital Cost

Denote the total capital cost of the t^{th} ($t = 1, 2, \dots, T$) WTG type as C_{ct} . About three fourths of the capital cost is associated with the turbine, while the remaining portion covers costs related to turbine erection, grid connections, foundations, roads, and buildings [8].

The total capital cost of the WECS at a wind site is given by:

$$C_c = \sum_{t=1}^T C_{ct} \cdot N_{ft} \quad (2)$$

where N_{ft} is the number of WTG installed in t^{th} wind farm.

B. Maintenance and Operating Costs

The M&O costs include regular maintenance, repairs, stocking spare parts, insurance, land lease fees, and administration [8]. This cost is a significant component of the total cost of wind power projects and occurs every year in the economic life of a WECS. The total annual equivalent M&O cost of a wind power project is given by:

$$C_M = \sum_{t=1}^T C_{Mt} \cdot N_{ft} \quad (3)$$

where C_{Mt} is the annual equivalent M&O cost associated with the t^{th} -type WTG.

C. Fossil Energy Cost

The electrical energy which feeds the local load from upstream substation consists of two parts:

- Before installation of wind farm,
- After installation of wind farm.

Therefore, the cost of providing electrical energy (C_f) is as:

$$C_f = \sum_{y=1}^i L_y \cdot C_{yf} + \sum_{y=i}^h (L_y - P_w) \cdot C_{yf} \quad (4)$$

where i and h , are year of installation and the horizon year respectively, L_y is the load of the network in year y considering the load growth rate, P_w is the mean output power of each WTG and C_{yf} , represents cost of fossil energy in y^{th} year considering the inflation rate.

D. Service Provider Company Interruption Cost

Regarding to yearly economic interest, the portion of investment money is considerable because of interruption of wind farm facilities.

Considering r^{th} provider type ($r=1, \dots, R$), calculation of this cost is:

$$C_i = \sum_{y=1}^{i_r} C_{cr} \cdot p_y \quad (5)$$

where C_{cr} is investment cost of r^{th} provider, i_r is installation year of r^{th} provider and p_y is the interest rate of money in year y .

E. Total Cost Model

The objective of the installation problem for the wind farm is the minimization of the total cost:

$$C_T = C_c + C_M + C_f + C_i \quad (6)$$

Subjected to

$$N_{\min} < N_{ft} < N_{\max} \quad (7)$$

$$I < P < R$$

IV. SOLUTION APPROACH USING GA

The GA approach has been used in a wide range of power system problems and has shown good performance for solving optimal problems with nonlinear and nondifferentiable objective functions and constraints. The optimal WTG installation problem was solved using the GA approach in this report. Several individuals make up a population, and within this population, parent individuals are reproduced.

The fittest individuals will be selected, and parent pairs will be reproduced by crossover. In a uniform crossover operation, any point in the string has potential to become a crossover point. Mutation is the random switching of a gen in the individual string to the opposite value and ensures that the GA does not locate a false minimum as the solution.

A GA searches for the solution space through the evolution of candidate solutions. Each individual of the population is represented by a binary or decimal string. When a GA is applied to the installation problem for the WTG, the solutions of the problem are represented as integer strings and shown in Fig. 2.

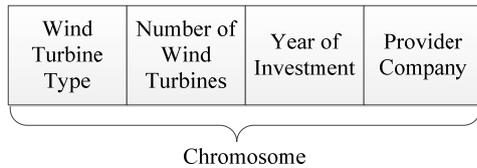


Fig. 2 The structure of chromosome

There are four parts in a chromosome where the first one represents the WTG type, the second one represents the number of WTG, the third part the year of investment (between now and the horizon year), and the provider company type.

The main algorithm and procedure of the optimal installation problem for the WTG is as follows:

- Step 1. Calculate the mean output power of a WTG in selected area.
- Step 2. Generate the initial population of NP chromosomes.
- Step 3. Calculate the total cost containing capital cost, M&O costs, fossil energy cost and the service provider company interruption cost.
- Step 4. Calculate the objective function for each chromosome in the population.
- Step 5. The chromosomes are selected into the next generation in accordance with their reproduction probability.
- Step 6. The crossover and mutation operators are done in some chromosomes based on the probabilities of them.
- Step 7. Go to Step 2 and repeat the process until the termination criterion is satisfied.

Fig. 3 represents the proposed method in a flowchart.

V. CASE STUDY

A computer program was developed to execute the proposed method. A 400 MW local load with a growth year is assumed. Four wind farms are chosen to find out the best layout in horizon of ten years, which their statistic data are shown in Table I. Table II shows the 12 WTG types assumed and utilized in the case studies. Each WTG unit has useful life of 25 years irrespective of the size.

TABLE I
DIFFERENT WIND SITE SPECIFICATIONS

Site	1	2	3	4
Mean Wind Speed (km/h), μ	19.46	16.78	19.52	16.42
Standard Deviation (km/h), σ	9.70	9.23	10.99	9.59

Economical parameters of the power system are:

- fossil energy cost = 60 \$/MWh,
- inflation rate = 15%,
- interest rate = 20%,
- load growth rate = 10%.

TABLE II
WTG UNIT PARAMETERS

Type	Rated capacity (MW)	Cut-in speed (km/h)	Rated speed (km/h)	Cut-out speed (km/h)	Capital cost 10^3 \$/MW	M&O Costs 10^3 \$/MW/yr
A	0.5	10	40	80	1350	36
B	0.5	10	45	70	1350	36
C	1	12	40	80	1250	35
D	2	12	30	55	1120	30
E	1	13	33	60	1220	33
F	1	14	40	90	1250	32
G	2	15	33	50	1100	35
H	2	15	33	60	1100	30.5
I	1	15	37	70	1200	32
J	1	18	48	70	1250	32
K	2	18	45	70	1100	30
L	2	18	35	75	1100	30

In this report, five types of service providers are assumed. The interruption of installing WTGs after contraction and the price of services are different. Table III indicates the complete information about the discussed service providers.

TABLE III
SERVICE PROVIDERS SPECIFICATIONS

Service Provider	Normalized selling price	Interruption in installation (year)
1	1	0
2	0.95	0.5
3	0.92	1
4	0.90	1.5
5	0.88	2

After implementing the proposed algorithm, the results of optimization are obtained as Table IV.

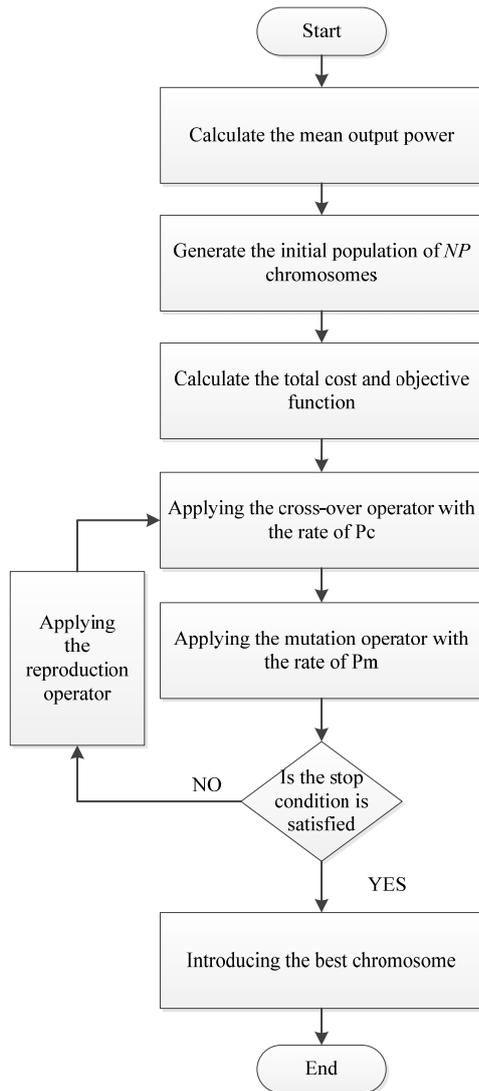


Fig. 3 Flowchart of the proposed method

TABLE IV
OPTIMAL INSTALLATION SCHEME FOR DIFFERENT WIND SITES

Site	1	2	3	4
Number of WTG	51	40	70	25
WTG Type	G	G	D	H
Installation Capacity (MW)	102	80	140	50
Year of Installation	1	1	1	1
Service Provider	2	2	2	4
Capital Cost (M\$)	86.73	41.18	74.4	24.7
M/O Cost (M\$)	15.03	7.2	13.8	3.95
Fossil Energy Cost (G\$)	7.21	7.56	7.16	7.65
Service Provider Company	17.35	8.3	14.9	0.9
Interruption Cost (M\$)				
Total Cost (G\$)	7.33	7.62	7.26	7.8

It can be seen from Table IV that the optimal installation schemes for the sites with various wind regimes are considerably different due to the different objective function used in the model. These results indicate that the proposed

technique is suitable for searching different objectives. The reduction of total cost in iterations is visible in Fig. 4.

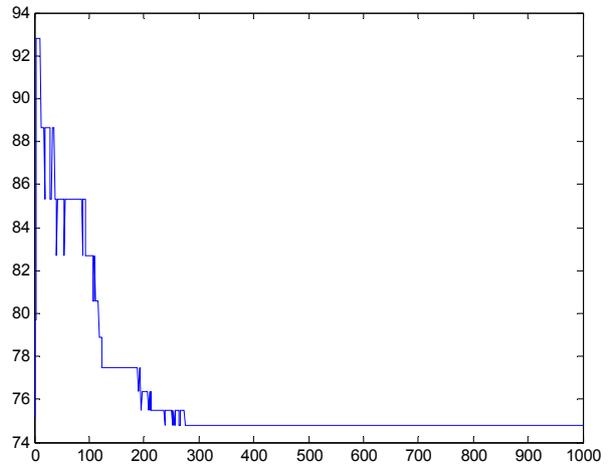


Fig. 4 Total cost evolution for site 1

VI. CONCLUSION

The WTG design parameters, such as the turbine cut-in, rated, and cut out wind speeds, have considerable impact on the generation output distributions and the reliability performance. Different types of WTG usually have different economic parameters, such as the capital and M&O costs. On the other hand, service provider type has important role in final planning cost. Time of installation and price of facilities of each service provider are different. Also in a horizon plan, decision of the year of constructing a wind farm is important.

This report presents a model based on the equivalent 10 year cost for determining the optimal WTG installation scheme at each specific wind site, formulated as a combinatorial constrained optimization problem with a nonlinear and nondifferentiable objective functions optimized with GA approach. The results also show that the proposed technique can search satisfactory optimal solutions, although there are many similar WTG types in the possible cases. Significant economic benefits can be obtained by selecting the appropriate matching combinations of the number and type of WTG and service provider and time of installation at the various available sites.

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