Optimal Sizing of Hybrid Wind/Photovoltaic/Battery Considering the Uncertainty of Wind and Photovoltaic Power Using Monte Carlo

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***Abstract*: Using hybrid renewable energy is one of the best alternatives to supply the electrical energy at remote areas. Renewable energy sources are depended to weather conditions or other factors, so for supplying load with renewable sources appropriate capacity of these sources should be selected. In determining the capacity of renewable energy such as wind and solar, considering the stochastic nature of wind speed and solar radiation is very impressive. In this paper, a new algorithm for determining the capacity of hybrid wind, photovoltaic and battery generation system with considering the uncertainty in wind and photovoltaic power production is proposed. The algorithm of determining capacity of wind, photovoltaic and battery for supplying certain load is formulated as an optimization problem that the objective function is the minimization of the cost and with constrain of having specific reliability. Probability density of wind speed and solar radiation and Mont Carlo simulation method is used to considered uncertainty in wind and photovoltaic power generation. Particle swarm optimization is used for optimal sizing of the system.**

Keyword: Monte Carlo simulation, Particle swarm optimization, Reliability evaluation, Renewable energy, Hybrid wind and photovoltaic system.

I. INTRODUCTION

Due to ever increasing energy consumption and rising public awareness of environmental protection, interest at renewable energy sources have been increased. In the past, because of expensive equipment required, electrical energy generated from renewable energy was not cost effective. In recent years, because of development in technology, applying the renewable energy is more cost effective. Hybrid wind, solar and battery is the most common combination of renewable energy that is used to generate electrical energy. The power generation of wind turbine directly related to wind speed and the power generation of the photovoltaic array related to solar radiation, due to this dependency of renewable sources to weather conditions, it is important to consider these parameters in determining the required capacity of these renewable sources for supplying the electricity demand.

In fact, considering the uncertainty in electric power generation that can be obtained from renewable energy will create a more realistic view of reliability index and cost.

In recent years, several researches have been performrd in determining capacity of hybrid renewable sources. Yang et al. [1] proposed new sizing method for a hybrid wind, solar and battery. In this method hourly data of wind speed and solar radiation are used. The reliability factor is Loss of Power Supply Probability (LPSP) and for assessment cost, Levelised Cost of Energy (LCE) model is used. The sizing problem is solved by genetic algorithm. Mousa et al. [2] designed hybrid wind and solar power generation system. The aim was minimizing the cost, and constrain was the generated power being larger than consumption. GAMS is used for solving the problem. In [3], a novel analytical approach of reliability evaluation for wind-diesel hybrid power system with battery bank is investigated. This approach is developed on the basis of the discrete wind speed frame analysis of the Weibull wind speed distribution. By employing wind speed frame analysis, the model of wind-diesel hybrid system is developed that deals with system outage as a result of component failure and wind speed fluctuation. The reliability index which is used in this paper is Loss of Load Probability (LOLP). Grimsmo et al. [4] proposed a new probabilistic method to determine the size of all components in a wind and hydrogen stand-alone power system. The method applies the Weibull distribution for wind speed and the wind turbine power curve, for analytically design the power plant. When the wind power exceeds the load, an electrolyzer produces hydrogen using the excess power. When the wind power is insufficient to supply the load, the hydrogen is utilized in a fuel cell to produce the power.

In this paper, a new algorithm for optimal sizing of a hybrid wind, photovoltaic and battery is described. In this algorithm, uncertainty in wind and photovoltaic power generations is considered. These sources supply the load as a stand-alone system. Wind turbine and photovoltaic array are used as primary sources and battery is used as an auxiliary source. The objective function is minimizing the annualized cost of the generation system over its 20-year lifetime and constrain is to obtain the satisfactory reliability factor. Uncertainty of wind and photovoltaic power generation is considered with using Monte Carlo method. For probabilistic analysis of wind and

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solar power generations, 32 years data of wind speed and solar radiation are used. The data has been used as every two-hour. For every two-hour data, best probability density functions (PDF) of wind speed and solar radiation are determined. With using Monte Carlo and appropriate power management, best sizing of hybrid wind, photovoltaic and battery is determined. Simulation without considering uncertainty of wind speed and solar radiation is done and compared with previous case. All simulation results are carried out by MATLAB software.

II. MONTE CARLO METHOD

The Monte Carlo (MC) method was coined in the 1940s by John von Neumann, Stanislaw Ulam and Nicholas Metropolis, while they were working on nuclear weapon projects in the Los Alamos National Laboratory [5]. Monte Carlo method is a class of computational algorithms that rely on repeated random sampling to compute their results. The Monte Carlo method is a widely used tool in many disciplines, including physics, chemistry, engineering, finance, biology, computer graphics, operations research and management science [6].

MC method works as a following pattern:

1- The boundary of data is determined.
2- Generate data from probability distribution of input.
3- Deterministic calculation is done on the data and the result is obtained.

III. DISTRIBUTION OF RENEWABLE ENERGY

For determining the best probability density functions (PDF) of wind speed and solar radiation, 32 years data are used. The data has been used as every two-hour, means that one year is divided to 4380 samples of wind speed and solar radiation and each two-hour sample have 32 samples of all 32 years, so the time step is two-hour. The aim is obtaining the PDF model for every two-hour of wind speed and solar radiation. The PDF for wind speed and solar radiation are calculating as following:

A. Wind distribution

The model of wind speed for a year, month and day is investigated in several articles. For a year, month and day Weibull distribution known as suitable distribution for wind speed. In this paper, a distribution model for every time step wind speed data is considered, that for each time step the parameters of distribution are different from other hours. The algorithm of finding the suitable distribution for each time step wind speed is as follows:

1- Six types of distribution are used for finding best match distribution of data. These distributions are: Exponential, Gamma, Lognormal, Normal, Rayleigh and Weibull.
2- For each of 4380 groups of data, parameters of best fitted of each above distribution with a maximum-likelihood estimation (MLE) method are obtained. Maximum-likelihood estimation is a method of estimating the parameters of a statistical model.
3- For each of 4380 groups of data, cumulative distribution function (CDF) calculated with discrete data and with best fitted of each above distribution that calculated in step2.
4- For each of 4380 groups of data, absolute of difference between the value of CDF that obtained from discrete data and from CDF of each distribution is calculated.
5- Aggregate errors of each distribution from each group of data, the distribution that has a minimum error is suitable for modeling the time step wind speed.

The above steps done and lognormal distribution is selected as a best distribution model for every time step wind speed. Fig 1, shows the PDF of a time step wind speed data that obtained from discrete wind speed value and PDF of lognormal distribution matched to these data.

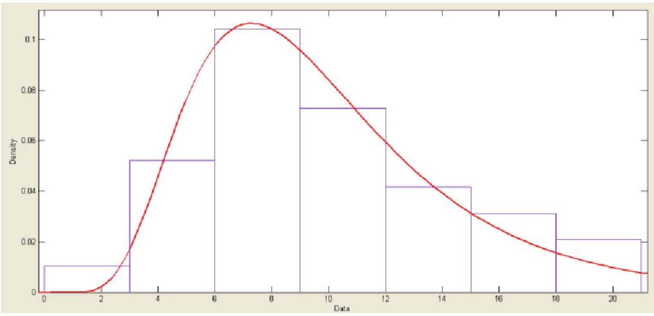

Fig. 1. PDF of a time step wind speed

A. Solar distribution

Similar to wind speed, a distribution model for every time step solar radiation data is considered, that for each time step the parameters of distribution are different from other hours.

The algorithm of finding the suitable distribution for solar radiation is similar to the algorithm of finding wind speed distribution. There are only two differences from the previous algorithm. These differences are as a following:

1- The uniform distribution is considered in addition to other distributions, in step 1. So seven distributions used for finding best distribution match with solar data.
2- Radiation of solar in some hours is zero. So for the time that solar radiation is zero, don't need to find the probability distribution and only for the time which radiation is nonzero, best distribution found.

The above steps done and normal distribution is selected as a best distribution model for every time step nonzero solar radiation. Fig 2, shows the PDF of a time step solar radiation data that obtained from discrete solar radiation value and PDF of normal distribution matched to these data.

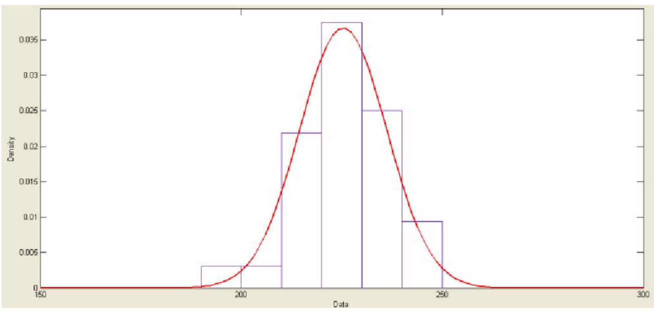

Fig. 2. PDF of a time step solar radiation

IV. HYBRID WIND/PHOTOVOLTAIC/BATTERY

In this paper, hybrid wind, solar and battery is considered for supplying the load. Fig. 3 shows the combination of these renewable sources.

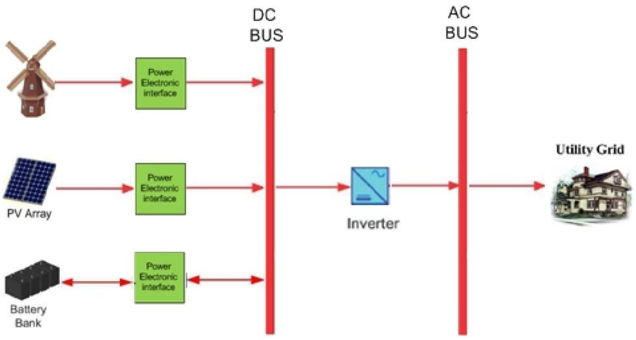

Fig. 3. Hybrid wind, photovoltaic and battery

In this paper, Bergey wind power's BWC Excel-R/48 is used for generating power from wind speed. The rated capacity of this turbine is 7.5(kW) and provide 48V dc as output. The power curve of this turbine is shown in Fig. 4.

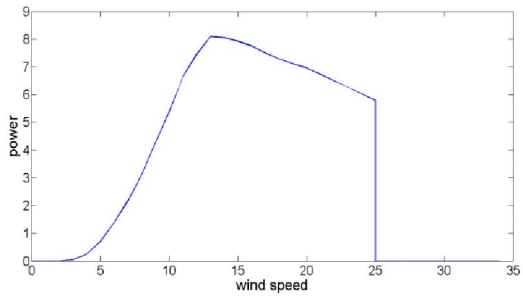

Fig. 4. Power curve of BWC Excel-R/48

This power curve of turbine is measured in the standard air density 1.225 ($\frac{kg}{m^2}$), pressure 101325 (*pa*) and temperature 288.16 (*K*), so if the place that turbine cited has different weather conditions, the power curve should be matched with the new conditions [7,8].

The power curve is divided to four parts. When wind speed is less than the cut-in speed or more than the cut-out speed the electrical output power of wind turbine become zero. When wind speed is between cut-in speed and rated speed the electrical output power can be expressed as equation (1) and when wind speed is between rated speed and cut-out speed the electrical output power can be expressed as equation (2). Equations (1) and (2) are the best equations fitted on the power curve in the certain boundary.

$$p_{wind} = -0.00089724v^4 + 0.018472v^3 + 0.040644v^2 - 0.024471v + 0.066271 \quad (1)$$

$$p_{wind} = -0.00016726v^4 + 0.013129v^3 - 0.38485v^2 + 4.7913v - 13.469 \quad (2)$$

p_{wind} is output power of wind turbine and v is wind speed.

The BWC Excel-R/48 life time is considered to be 20 years and cut-in speed, cut-out speed and rated speed are 3, 25 and 15 ($\frac{m}{s}$), respectively. The capital, replacement, operation and maintenance cost of BWC Excel-R/48 are 16400, 13000 and 75 *($/Unit)*, respectively.

The measurement of wind speed was at 30 meters and the wind turbine hub height is 19.9526(m), it is important to adjust the measured wind speed to the hub height [8].

Photovoltaic power output is proportional with solar radiation. In this paper, the photovoltaic array with rated power of 1 (*kW*) is considered. The output power of photovoltaic array can be calculated using equation (3) [8].

$$p_{pv} = \frac{G}{G_{STC}} p_{ratedpv} \eta_{pv} \quad (3)$$

where, p_{pv} is output power of photovoltaic, G is the solar radiation incident on the photovoltaic array in the current time step ($\frac{W}{m^2}$), G_{STC} is the incident radiation at standard test condition and equal to 1000 ($\frac{W}{m^2}$), $p_{ratedpv}$ is a rated power of each array (*kW*) and η_{pv} is the efficiency of PV's DC/DC converter and Maximum Power Point Tracking (MPPT).

The photovoltaic array life time is considered to be 20 years and the capital, replacement, operation and maintenance cost of photovoltaic array are 7000, 6000 and 20 *($/Unit)*, respectively. The efficiency is considered 90%.

Battery is one of the storage devices which often used in combination with the renewable energies. In this paper, battery bank is considered for storage device. Surrette-6CS25P model has nominal voltage of 6 volts and energy store 6.94 (*kWh*). This type of battery is used in this paper. Some factors influenced on battery life time for example minimum of charge or current of charge and discharge. The life time of battery is considered to be 4 years and depth of discharge is about 20%. The capital, replacement, operation and maintenance cost of battery are 1250, 1100 and 20 *($/Unit)*, respectively [7].

The problem of sizing of the hybrid renewable energy is formulated as an optimization problem. The objective function is cost function and the constrain is satisfying the reliability index. In optimization problem one of the important factors which affect the results is power management.

A. Cost function

The optimization variables are the number of wind turbine, photovoltaic array and battery, so the cost function should be the function of these variables. The lifetime of the project is considered 20 years.

Cost function is constructed with Net Present Cost (NPC) method. NPC method is formulated as equation (4) [9]:

$$NPC = \sum_{i=1}^{L} N_i (CC_i + RC_i * K_i + MC_i * PWA(ir, R)) \quad (4)$$

The cost function consists of capital (CC), replacement (RC) and operation and maintenance (MC) cost.

L is the number of renewable sources, in this analysis it is equal to three. N_i is a number of each renewable energy source, which evaluate from an optimization algorithm.

For converting the replacement cost to present, K_i is considered, which is calculated according to the following equation:

$$K = \sum_{n=1}^{l1} \frac{1}{(1+ir)^{n*l2}} \quad (5)$$

$l1$ and $l2$ are number of times, which the renewable unit replace and total life time of renewable unit, respectively. For sources, that its lifetime is equal to the lifetime of total project, K_i is equal to zero. ir is interest rate, and in this paper ir it is considered to be 0.06.

$PWA(ir, R)$ is used to convert annual cost of maintenance and operation cost to present cost, which can be calculated using the following equation:

$$PWA(ir, R) = \frac{(1+ir)^R - 1}{ir(1+ir)^R} \quad (6)$$

R is lifetime of total system. The aim of optimization method is minimizing the NPC.

B. Reliability index

In this paper, Equivalent Loss Factor (ELF) is considered for evaluating reliability. ELF calculate using the following equation [10]:

$$ELF = \frac{1}{H} \sum_{i=1}^{H} \frac{Q(i)}{D(i)} \quad (7)$$

For calculating ELF index, at the each time step of years Loss of load (Q) should be calculated and divided into load demand (D), summation of these answer divided into total number of step time (H) is ELF of the system. H, in this analysis considered equal to 4380.

C. Power management

The power management strategy, which is considered in this paper, is as follows:

When, the generated power from a wind turbine and photovoltaic array is equal to load demand, all the generated power from renewable energy is consumed by the load and the state of charge of battery is not changed. If generated power from renewable energy is less than electrical load demand, all the power is consumed by the electrical load and deficiency of generated power is supplied with battery. If the battery has no sufficient power for supplying electrical load, the amount of loads will be shed and when the generated power is more than load, the load is supplying from renewable energy, and if the battery isn't full charging the extra power is stored in battery.

V. PROPOSED METHOD

In this paper, the optimal numbers of renewable sources (wind, photovoltaic and battery) are obtained for supplying the load. Minimum cost is considered as objective function and satisfy defined reliability factor as constrain. Uncertainty in power output of the wind turbine and photovoltaic array is also considered. The algorithm of purposed method is as follows:

1- For each time step of one year find the best PDF and the parameters for wind speed and solar radiation.

2- With Monte Carlo method, generate the sample of wind speed from wind distribution for each time step of a year, therefore, 4380 wind speed data are generated. The best distribution for time step wind speed is lognormal, so lognormal rand generator should be used for generating data from wind distribution.

3- The sample of solar radiation is generated with Monte Carlo method. Monte Carlo method only generates data from solar radiation, which value of radiation in that time step is nonzero and for time step that radiation is zero, the value of zero selected for radiation. The best distribution for time step solar radiation is the normal distribution, so normal rand generator should be used for generating data from solar distribution.

4- With data generated from steps 2 and 3, and equations 1, 2 and 3, the output powers of the wind turbine and photovoltaic array for each time step of a year are calculated.

5- Now, the optimization algorithm is run and the number of renewable sources is calculated. The generated power from renewable energy at step 4, multiply with the number of each renewable source, which generated from the optimization algorithm are used to calculate all the generated power in each time step from renewable sources. Power management is run and the ELF is calculated.

6- For the number of renewable source considered in step 5, repeat step 2 to 5, until the difference between averages of ELF in the consecutive iteration is less than 0.00001. The latest mean of ELF is considered as ELF for these numbers of renewable source. Then the optimization algorithm continues its process until the defined iteration.

In this paper, Particle Swarm Optimization (PSO) is considered as optimization algorithm. In PSO algorithm, the best previous position explored by the *n*th particle is recorded and denoted as p_{best}. Another value that is recorded by the particle swarm optimizer is the best value obtained so far by any particle in the population. This best value is a global best and is known as g_{best}. Each particle tries to modify its position using the current velocity and its distance from p_{best} and g_{best}. The modification can be represented by the concept of velocity and can be calculated as shown in the equation (8) and (9). Let x and v denote the particle's position and its velocity in the search space [11].

$$v_{i+1} = wv_i + c_1 rand(p_{best} - x_i) + c_2 rand(g_{best} - x_i) \quad (8)$$

$$x_{i+1} = x_i + v_{i+1} \quad (9)$$

The constants c_1 and c_2 represent the learning rate or the acceleration term that pulls each particle towards p_{best} and g_{best} positions. The inertia weight w governs how much of the previous velocity should be retained from the previous time step. In this work a linearly decreasing inertia weight is used [11].

In this paper a modified PSO is presented. In this modified PSO, if the constraints are not satisfied, then updating process are done with equation (10). Again the constraints are checked. If again the constraints are not satisfied, updating is done by equation (11).

$$v_{i+1} = c_2 rand(g_{best} - x_i) \quad (10)$$
$$x_{i+1} = x_i + v_{i+1}$$

$$v_{i+1} = 0 \quad (11)$$
$$x_{i+1} = p_{best}$$

The parameters of PSO algorithm c_1=1.5, c_2=1.5, Iteration=40 and population is 30.

VI. SIMULATION RESULTS

In this paper, hybrid wind, photovoltaic and battery is considered for supplying the load that shown in Fig. 5. The peak load is 500 (*kW*). The data of simulation is belong to state Oregon of the United States. ELF is considered equal to 0.1 for simulation. The histogram of power generated from a wind turbine and a photovoltaic array for a time step of a year are shown in Fig. 6 and Fig. 7. Optimization algorithm run and the variables are updated in each time step. The ELF for 1000 hours is shown in Fig. 8 and the variation of average ELF, which it is obtained from each repeat of Monte Carlo Simulation method, is shown in Fig. 9.

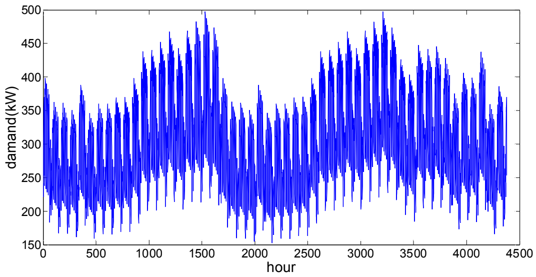

Fig. 5. two-hour load data of 1 year

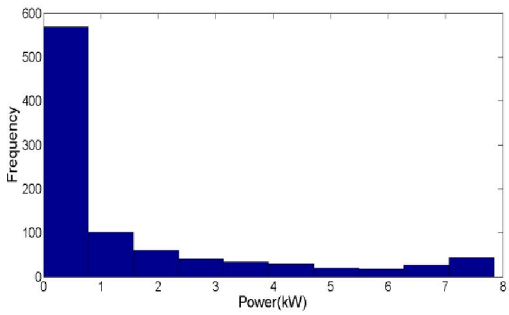

Fig. 6. Histogram of a time step wind turbine power output

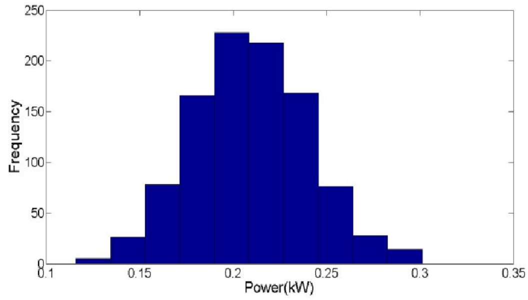

Fig. 7. Histogram of a time step photovoltaic array power output

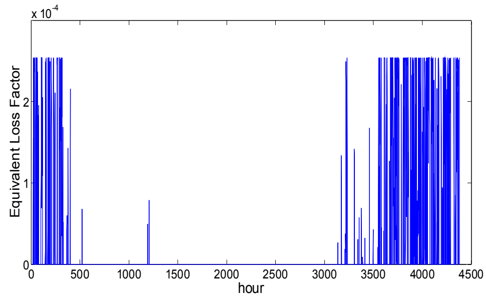

Fig. 8. Equivalent Loss Factor

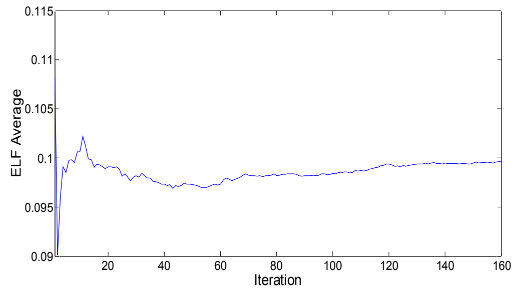

Fig. 9. Equivalent Loss Factor average

The convergence of PSO algorithm is shown in Fig. 10 and the best combination of renewable sources is shown in Table I.

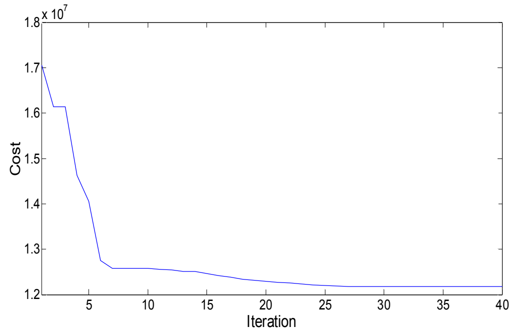

Fig.10. Convergence of PSO algorithm

Now, size of hybrid wind, solar and battery is determined without considering the uncertainty of wind and photovoltaic power output. Two-hourly wind speed and solar radiation of one year are used for simulation. Data of each time step is obtained from the average of 32 years hourly data. The optimized variables are shown in Table II.

TABLE I OPTIMIZED PARAMETERS OF HYBRID WIND, SOLAR AND BATTERY WITH CONSIDERING UNCERTAINTY			
Number of Wind Turbine	Number of Solar Array	Number of Battery	Total Cost
295	585	710	1.2176e+7

TABLE II OPTIMIZED PARAMETERS OF HYBRID WIND, SOLAR AND BATTERY WITHOUT CONSIDERING UNCERTAINTY			
Number of Wind Turbine	Number of Solar Array	Number of Battery	Total Cost
0	2032	673	1.7396e+7

Table I and Table II are shown the influence of considering the uncertainty of wind and solar power output on determining the size of the wind turbine and photovoltaic array. In this paper, when uncertainty of wind and solar power outputs is considered the total cost of system decrease compare with state that uncertainty isn't considered with same value of ELF.

The results show, that determining the size of hybrid wind, photovoltaic and battery with using the average of wind speed and solar radiation isn't suitable method.

VII. CONCLUSION

In this paper, the influence of considering the uncertainty of wind turbine and photovoltaic array output powers on sizing of hybrid wind, photovoltaic and battery is investigated. The life time of the project is considered to be 20 years. Determining the size of hybrid renewable is considered similar to the optimization problem, which variables are the number of wind turbine, photovoltaic array and battery. The objective function is cost and calculates with NPC method. For evaluating reliability of hybrid system ELF is used. ELF is considered as constrain of the optimization algorithm. Results show that considering the uncertainty reduce the cost with same reliability with state, which uncertainty isn't considered.

VIII. REFERENCES

[1] H.X. Yang, L. Lu and W. Zhou, "A Novel Optimization Sizing Model For Hybrid Solar-Wind Power Generation System," *Solar Energy,* vol. 81, pp. 76-84, 2007.

[2] K. Mousa, H. AlZu'bi and A. Diabat, "Design of a Hybrid Solar-Wind Power Plant Using Optimization," *Engineering Systems Management and Its Applications (ICESMA),* pp.1-6, Apr. 2010

[3] X.L. Islam, S. Chowdhury and A.A. Koval, "Reliability Evaluation Of a Wind-Diesel-Battery Hybrid Power System," *ICPS 2008*, pp.1-8, 4-8, May. 2008.

[4] L.N. Grimsmo, M. Korpaas and T. Gjengeda, "Probabilistic Sizing Of Wind And Hydrogen Power Systems For Remote Areas," *15th PSCC*, pp. 22-26, Aug. 2005.

[5] B.A. Berg , *Markov Chain Monte Carlo Simulations and Their Statistical Analysis (With Web-Based Fortran Code)*, Hackensack, NJ: World

[6] R. Billinton and R.N. Allan, *Reliability Evaluation of Power Systems,* Second Edition, Aug 31, 1996.

[7] A. Navaeefard, S.M.M. Tafreshi, M. Barzegari and A.J. Shahrood, "Optimal Sizing of Distributed Energy Resources in Microgrid Considering Wind Energy Uncertainty with Respect to Reliability," *Energy Conference and Exhibition,* pp. 820-825, 18-22, Dec. 2010.

[8] http://www.homerenergy.com/ homer software

[9] X. Wang and J.R. McDonald, *Modern Power System Planning,* McGraw - Hill, 9th Edition (April 1994).

[10] R.S. Garcia and D. Weisser, "A Wind–Diesel System With Hydrogen Storage Joint Optimization of Design and Dispatch," *Renewable energy*, pp. 2296-2320, 2006.

[11] M. Bashir, M. Taghizadeh, J. Sadeh and H.R. Mashhadi, "A New Hybrid Particle Swarm Optimization for Optimal Coordination of Over Current Relay," *Power System Technology (POWERCON), 2010 International Conference on* , pp.1-6, 24-28 Oct. 2010

IX. BIOGRAPHIES

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