Research Paper

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Multi Objective Optimization of Wind Energy Water Pumping System (Wewps) Using Nsgaii Approach for Industry Application

Engineering

KEYWORDS : wind energy, pumping water, LCE, LLP, NSGAII.

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ABSTRACT

This paper presents an optimization of wind energy water pumping system (WEWPS) with considering the reliability and economic aspect. This paper deals with a multi-objective optimization problem with conflicting objectives that try to find the best compromise tradeoffs among the feasible solutions in the search space. In the proposed algorithm, an external archive of non-dominated solution is kept which is updated during iteration. These solutions are known as Pareto-optimal solutions or non-dominated solutions. This attribute gives more flexibility to the planner for choosing the best final scheme among the obtained solutions. Due to nature of this optimization problem the non-dominated sorting genetic algorithm (NSGAII) has been implemented.

1. INTRODUCTION

Many researchers have focuses on wind energy power water pumping system for remotely located inhabitants not connected with national power grid. By [1] discussed the utilization of wind power for water pumping using wind speed data measured at different height. Also [2] analyzed the performance of a typical water pump under various states of wind velocities and monthly water output against average wind speed and compared the results with the experimental values provided by the producer. By [3] investigated techno-economic analysis of wind powered water pump in this area and compared to photovoltaic based water pumping system. In [4] showed that mechanical photovoltaic-wind pumping systems were economically cheaper than the diesel based water pumping system in Jordan. By [5] reviewed the industrial development of wind pumps for water pumping in remote rural areas in Africa and discovered the challenges facing the dissemination of wind pumps. In [6] presented a systematic procedure for optimization of windmills and pumps in a given water pumping situation. With information available on the wind intensity, pump and wind turbine characteristics, the best pump and turbine could be selected for the application, therefore the aim of this research is to studying the possible application of wind energy to support electrical power needed by water pump systems in remote and rural areas of Shazand, Iran.

2. INDUSTRY APPLICATION OF WIND ENERGY WATER PUMPING SYSTEM IN SHAZAND, IRAN

Fig.1 shows the topology of wind water pump used for irrigation and drinking purposes for rural communities of shazand. The presented system is consisted of a small wind turbine (SWT), AC/DC rectifier, source of water, a water storage tank and a DC motor pump. This configuration follows two aims, one is electrification and other is water pumping. The turbine produces a three phase alternating current (AC) that varies in voltage and frequency as the wind speed varies. The AC/DC converter rectifies this AC into the direct current (DC) required for motor pump.

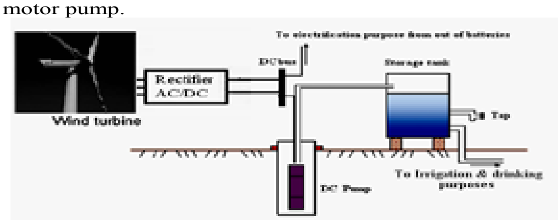

Fig.1. Block diagram of a stand-alone wind energy water pumping system

3. MATHEMATICAL MODEL OF WIND GENERATOR

To assess the operating performance of a wind turbine at a given location, its energy production is first expressed in terms of wind speed. The cumulative Weibull statistical distribution is most appropriate to describe the variations in wind speed as follows [7]:

$$f(v)=\frac{K}{C}\left(\frac{V}{C}\right)^{K-1}\exp\left(-\left(\frac{V}{C}\right)^{K}\right) \qquad 1$$

Where ***f(v)*** is the Weibull probability density function; ***K*** is the dimensionless shape factor; ***C*** is the scale factor (m/s), ***V*** is the average wind speed (m/s).

The power delivered by wind turbines is determined by following equation:

$$P_W=\frac{1}{2}\rho_{air}\times A_{ref}\times\overline{V}^{3} \qquad 2$$

Where P_W is the power in the wind (W), A_{ref} the reference area of WT, ρ_{air} the air density (kg/m^3) and $\overline{V}$ is the mean wind speed (m/s).

4. PUMPING SUBSYSTEMS MODEL

The mathematical models of the inverter and the DC motor pump set are described in a great number of researches [6-8]. In this paper, we use a mathematical model which directly links the output water flow rate Q versus the input electric power P_a and total head h. This model is based on the analysis of the experimental results of two types of pumping subsystems [9]. The equation of the used pumping model is given as follows:

$$P_a(Q,h)=a(h)Q^3+b(h)Q^2+c(h)Q+d(h) \qquad 3$$

Where ***a(h), b(h), c(h)*** and ***d(h)*** depend on total head and is discussed in detail in [10]. The ***Pa*** and ***Q*** characteristic of the used subsystem is plotted for each total head is shown in Fig.2

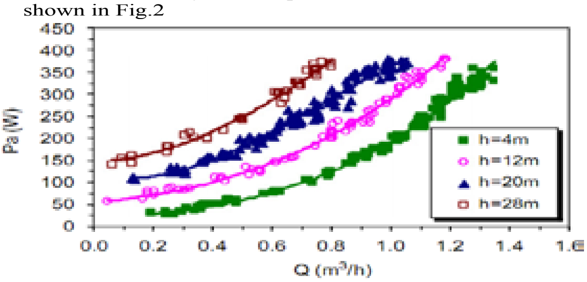

Fig.2.Electrical power versus flow rate, measured values in marked point and calculated values in continued line

5. WATER STORAGE TANK MODEL

Depending on the wind generator production and the load requirements, the state of charge (***SOC***) of water storage tank can be calculated from the following equations [8].

Water storage tank charging,

$$SOC(t)=SOC(t-1)+\left[E_{WT}(t)-E_L(t)/\eta_{conv}\right]*\eta_{\tan k} \qquad 4$$

Water storage tank discharging,

$$SOC(t)=SOC(t-1)-\left[E_L(t)/E_L(t)\eta_{conv}-E_{WT}(t)\right]*\eta_{\tan k} \qquad 5$$

where ***SOC(t)*** and ***SOC(t -1)***are the states of charge of water storage tank (***Wh***) at the time ***t*** and ***t-1***,respectively.

6. OBJECTIVE FUNCTIONS FORMULATION

6.1. Reliability Analysis

The ***LLP*** is defined as the ratio between the water deficit and the total requirement of water. The sizing of a wind energy pumping system means the sizing of the wind turbines and the water tank. This way, the wind turbines capacity, C_A is defined as the ratio between the volume of pumped water Q_v and the average daily consumption of water D_{av}. The capacity of storage, C_S is the ratio between the useful capacity of the tank, C_{UT} and the average daily consumption of water. The equations are given by:

$$C_A = \frac{Q_v}{D_{av}} \quad 6$$

$$C_S = \frac{C_{UT}}{D_{av}} \quad 7$$

The wind turbine efficiency, E_{WT} is the ratio between the operating electrical power and available wind power to the windmill/turbine and is determined as follows[7]:

$$E_{WT} = P_a / P = \frac{P_a}{0.5\eta_{mechanic}.\eta_{alternator}.\rho\pi R^2 V_r^3} \quad 8$$

Where ***P*** denotes the available power and P_a indicates the actual power (active power at generator output), $\eta_{alternator}$ and $\eta_{mechanic}$ are electrical equipment and mechanical equipment efficiency respectively, ρ is air density (kg/m^3) and ***R*** is maximum rotor radius(m), V_r is the wind velocity (m/s).

The power performance (momentum factor of rotor) of a wind turbine can be expressed for fixed angular speed. This parameter is defined by:

$$C_M = \frac{C_p}{\lambda} \quad 9$$

Wind turbines indicate various C_p values depending on the wind velocities. Therefore, their efficiency is best represented by a $C_p - \lambda$ curve. λ is the tip speed ratio and is given by:

$$\lambda = \frac{\omega R}{V_r} \quad 10$$

where ω is the rotor speed (rad/s). E_{sub} is the pumping subsystem efficiency and is defined as the ratio between the hydraulic power of the pump and the operating electrical power of the subsystem. The hydraulic power is function of water flow rate and total head. The equation of E_{sub} is given by:

$$E_{sub} = \frac{C_h Q h}{P_a} \quad 11$$

Where C_h is the hydraulic constant.

The water tank is supposed without losses. If the tank is completely full at the end of the day ***j***, then its state of filling, ***STF (j)***, is equal to 1. Otherwise at the end of the day ***j***, the filling state of the tank is given by the following relationship:

$$SFT(j) = \min\{SFT(j-1) + Q_v(j)/C_{UT}\ ;\ 1\} \quad 12$$

With

$$0 \le SFT(j) \le 1 \quad 13$$

Where $Q_v(j)$ is the volume of pumped water at end day ***j*** .

In the case, where the stocked and pumped water is inferior to the water requirement, the volume of lacking water is accounted at the end of the day ***j***.

$$SFT(j) \ge (\frac{1}{C_S}) \Rightarrow Q_{lac}(j) = 0 \quad 14$$

$$SFT(j) < (\frac{1}{C_S}) \Rightarrow Q_{lac}(j) = (1 - SFT(j))D_{av}C_S \quad 15$$

Where $Q_{lac}(j)$ is the volume of lacking water in the day ***j***.

The ***LLP*** corresponding to the wind energy water pumping system is given by:

$$LLP = \frac{\sum_j Q_{lac}(j)}{N_j D_{av}} \quad 16$$

Where N_j is the number of operating days.

6.2 Financial Analysis

The LCE is one of the commonly used indicators for financial performance evaluation of renewable-energy-based decentralized power supply system. The following expression has been used to estimate LCE delivered by a hybrid renewable energy system [6].

$$LCE = \frac{PVC\ CRF}{E_{tot}} \quad 17$$

where ***PVC, CRF*** and E_{tot} represent, respectively, the present value of costs, the capital recovery factor and the annual total delivered energy from the wind generators.

For a given discount rate, ***d***, and useful lifetime, ***T***, the ***CRF*** is defined as [2-4]:

$$CRF = \frac{d(1+d)^T}{(1+d)^T - 1} \quad 18$$

The present value of costs (***PVC***) can be calculated as follows [7-9]:

$$PVC = IC + C_m + RC \quad 19$$

Where ***IC*** is the initial cost, C_m is the present value of system life of maintenance costs of the system and ***RC*** is the present value of the replacement of parts of the installation costs.

6. SIMULATION AND RESULTS

The recommended methodology has been applied to analyze a standalone wind energy water pumping system, which is designed to supply water for drinking and irrigation in Shazand, Iran.

The technical characteristics of the wind turbine module and motor pump used in the studied project are listed in Tables 1 and 2.The load profile is assumed to be constant with a total daily requirement of 56 m^3 of water.

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Table 1.Specifications of the wind turbines used in this study

Turbine	Rated Power (W)	Rotor diameter (m)	Cut-in-speed (m/s)	Rated speed (m/s)	Cut-out-speed (m/s)	Swept area (m2)	Hub height (m)
Raum1.3 kW	1300	2.90	4.00	10	25	6.61	10

Table 2.Specifications of the motor pump used in this study.

Type	Motor	Rated power (W)	Range Voltage (V)	Maximum Current (A)
Floating centrifugal and multistage	DC	400	0-48	13

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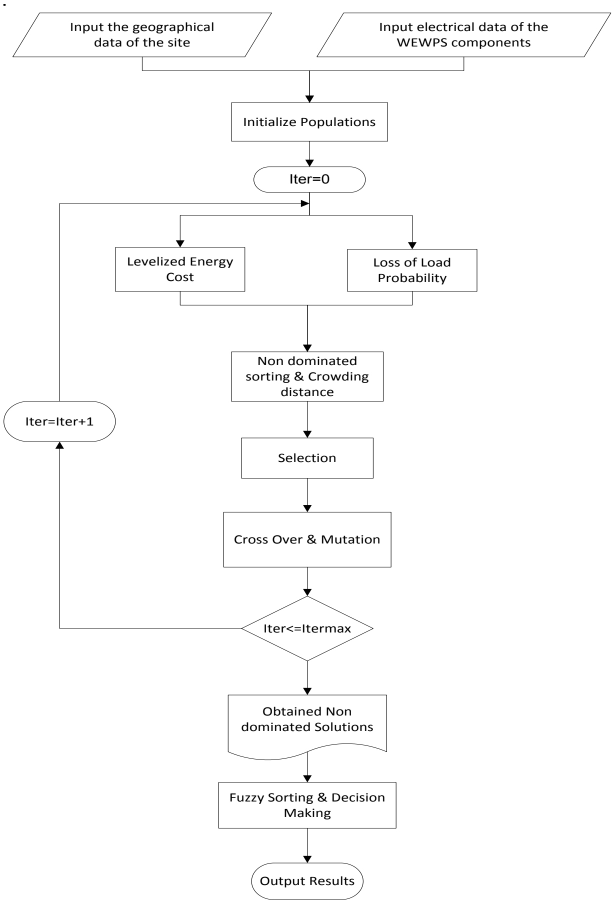

Fig.3.Flow chart of the NSGAII algorithm

Figs.4 shows the variation of wind speed at two different height 20 m from the reference height of 10 m.

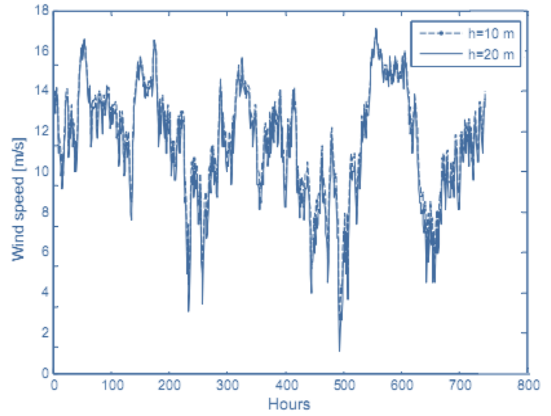

Fig.4. Wind speed at different hub heights: 10 m and 20 m Shazand – January.

These kinds of solutions are known as non-dominated solutions or Pareto solutions. Due to nature of this optimization problem the non-dominated sorting genetic algorithm (NSGAII) has been implemented.
Table 3 lists the parameters of the NSGA-II algorithm.

Table 3. Parameters of the NSGA-II algorithm.

Max_Iter	Population Size	Cross over Rate	Mutation Rate
250	50	0.8	0.4

In order to better evaluate the quality of the obtained non-dominated solutions using NSGAII algorithm, 2-D figures of non-dominated solutions for specified objective have been presented in Figs.5 and 6 for head of pumping 14 m (for low depth area) and for head of pumping 40 m (for high depth area) respectively.

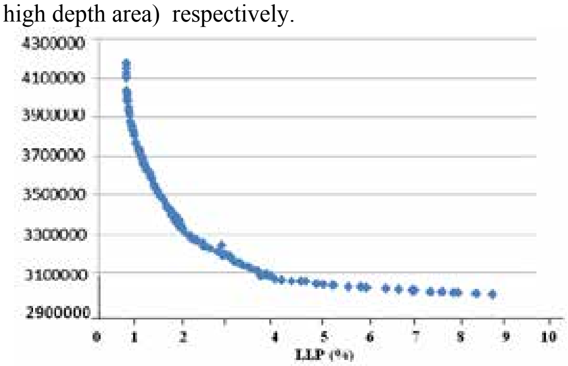

Fig.7 Pareto front, 2-D representation of non-dominated solutions for LLP and LEC for head of pumping=14m

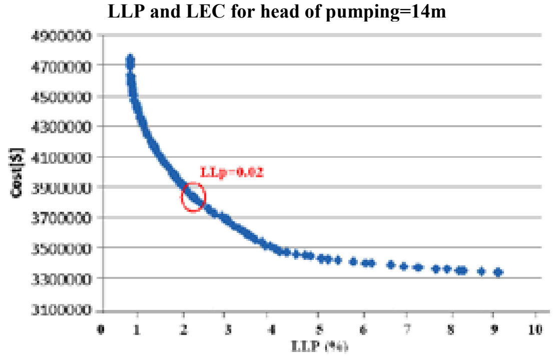

Fig.8 Pareto front, 2-D representation of non-dominated solutions for LLP and LEC for head of pumping=40m

Table 4 represents some of the obtained non-dominated solutions, and Table 5 shows the wind energy water pumping system capacities in terms of small wind turbine numbers and water storage tank capacity versus number of storage days in those solutions.

Table 4. Some of the non-dominated solutions

Solutions numbers	LLP	LCE ($)
1	0.00826	4730490.74
2	0.00686	4811901.59
3	0.00735	4837330.83
4	0.00563	3951902.29
5	0.01832	4476129.72
6	0.01102	4678214.63
7	0.00982	3999628.14
8	0.01303	4194904.08
9	0.00948	4391033.79
10	0.01410	4133029.32

Table 5. Related decision variables for obtained non-dominated solutions

Solutions numbers	Number of small wind turbine	Number of storage days
1	2.000	6.000
2	2.000	5.000
3	3.000	8.000
4	3.000	6.000
5	3.000	7.000
6	3.000	8.000
7	4.000	9.000
8	4.000	8.000
9	4.000	7.000
10	4.000	6.000

7. CONCLUSIONS

In this paper, the optimal planning of wind energy based water pumping system through optimal sizing of wind turbine energy capacity and water tank storage days is investigated. The decision variables of the WEWPS problem are discrete so that this optimization problem is the combination of discrete variables. The objectives of this problem are considered as multi objective optimization problem. The obtained results demonstrate that the obtained non-dominated solutions using the NSGAII algorithm have appropriate diversity among Pareto front and better quality.

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