Sizing Optimization of Stand-Alone Wind Power System Using Hybrid Energy Storage Technology

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Abstract— In this study, the hydrogen production potential and costs by using wind/electrolysis system were considered. In order to evaluate costs and quantities of produced hydrogen, number of wind-turbines and hub heights are considered as the variable Levelized cost of electricity method was used in order to determine the cost analysis of wind energy and hydrogen production. The results of calculations brought out that
the electricity costs of the wind turbines and hydrogen production costs of the electrolyzers are decreased with the increase of turbine hub height. The maximum hydrogen production quantity was obtained 1420KWh/year.

I. Introduction:

Renewable energy sources have gained significant attention in the last decades due to the harmful effects of the fossil fuels on the environment. Electricity generation from wind energy has no adverse effects on the environment besides it is relatively cheaper than most of the other renewable and conventional energy sources. It is reasonable to use wind energy to generate electricity in the region where has enough wind potential. There are many studies about usability of wind energy systems in different regions all over the world
[1-9]. Hydrogen is a secondary energy source, which has more advantages than fossil fuels. Hydrogen which is accepted as the energy carrier of future is always in compound form in the nature so it needs to be decomposed by using methods such as steam reforming, electrolysis, partial oxidation, fermentation etc. The simplest method for hydrogen production is electrolysis of water [10]. Electrolysis of water has been very popular because in this method there is no need to establish complicated systems and harmful emissions do not occur. Although most commonly used electrolyzers are alkaline electrolyzers, Proton Exchange Membrane (PEM) electrolyzers are being developed rapidly and are being commercialized due to their low operation temperatures, good power input responds and good integration with renewable energy systems [11]. In fact, it is not economical to produce hydrogen from electrolysis by using grid electricity directly. But it is more attractive if the electricity used for producing hydrogen is generated from other renewable resources such as solar or wind energy or solar-wind hybrid systems. In the case of an electrolyzer is integrated in a wind turbine system, excess energy can be used to produce hydrogen, and then this produced hydrogen can be stored in a number of ways. When wind turbine cannot produce electricity because of absence of wind or structural restrictions, a fuel cell can supply electricity by using this stored hydrogen. Currently, with this consideration, several wind-hydrogen energy systems have been built.

II. Description of the Wind Electrolyzer-Fuel Cell System

A configuration of the considered grid-dependent wind electrolyzer- fuel cell system was given in Fig. 1. As is shown in Fig. 1, the system has an electrolyzer, a fuel cell and a wind turbine, and they were connected to supply the electricity. Furthermore, it was assumed that there was a compressor to deliver the produced hydrogen from electrolyzer to hydrogen storage tank, and a hydrogen tank to store hydrogen with high pressure, and a converter for DC to AC or AC to DC conversion. In addition, PEM electrolyzer and PEM fuel cell system were chosen due to their remarkable operation conditions.

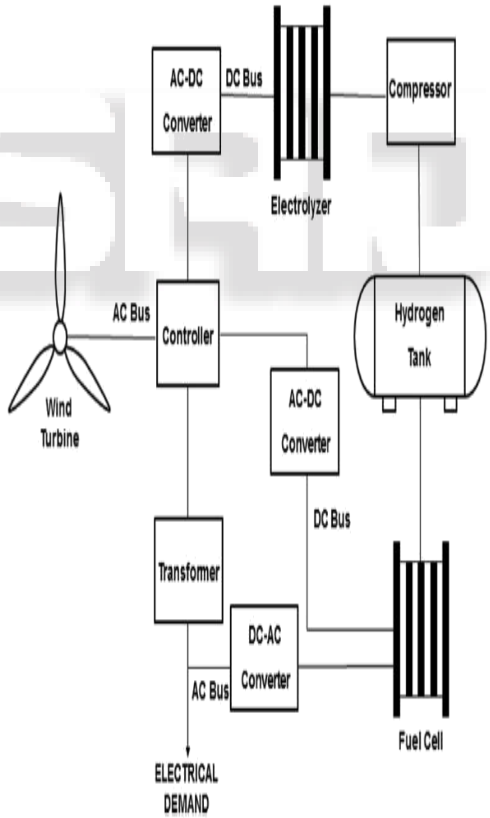

Fig. 1: Schematic of the wind-electrolyzer-fuel cell system

A. Energy management

The energy management is very important for sustainable development. the wind-electrolyzer-fuel cell energy system must supply the energy demand without interruption .In this study, it was assumed that when the wind energy output was higher than the energy demand, the excess energy was used to produce hydrogen by using the electrolyzer, and then the hydrogen was stored to use in fuel cell to produce electricity if wind speed was not enough to produce wind energy. As is apparent from the flowchart of the wind-electrolyzer-fuel cell system in Fig. 2, the energy management of the farm was taken into account as:

1. If electricity was greater than demand, excess energy was used in electrolyzer to produce hydrogen.
2. If the electricity was less than demand, a fuel cell was used to generate electricity by using hydrogen in the storage tank.
3. If the electricity was less than demand and there was not enough hydrogen in the storage tank, network electricity and wind energy were combined to supply energy demand.

B. *Wind turbine*

There are three main factors which determine the power output of a whole wind energy conversion system (WECS), i.e., the power output curve of a chosen wind turbine, the wind speed distribution of a selected site where the wind turbine is installed, and the hub height of the wind tower. Choosing a suitable model is very important for wind turbine power output simulations. The most simplified model to simulate the power output of a wind turbine can be described by:

$$P_w(v) = \begin{cases} P_R \cdot \frac{v \;\; v_C}{v_R \;\; v_C} & (v_C \leqslant v \leqslant v_R) \\ P_R & (v_R \leqslant v \leqslant v_F) \\ 0 & (v \leqslant v_C \text{ and } v \geqslant v_F), \end{cases}$$

Where Pr is the rated electrical power; vC is the cut-in wind speed; Vr is the rated wind speed; and Vf is the cut-off wind speed. For small-scale wind turbines, the cut-in wind speed is relatively smaller, and wind turbines can operate easily even when wind speed is not very high.

C. *Fuel cell*

Proton exchange membrane (PEM) fuel cells possess a good startup and shutdown performance. As the residential back-up generator, it may be the most suitable choice among all kinds of fuel cells. The PEM fuel cell stack is composed of several fuel cells connected in series. The fundamental structure of a PEM fuel cell can be described as two electrodes (anode and cathode) separated by a solid membrane. Hydrogen fuel is fed continuously to the anode and the air (or pure oxygen) is fed to the cathode. The consumed oxygen usually comes from the air. The hydrogen consumption of rated power 1 kW fuel cells in 1 h can be calculated by

$$M_{fc} = \frac{I_{fc} \times N_{fc}}{2 \times F} \times \frac{1}{\mu_{fc}} \times 3600 = \frac{P_{fc}}{2 \times V_{fc} \times F} \times 3600 = \frac{1000 \times 3600}{2 \times 0.7 \times 96487} = 26.8(mol.h^{-1})$$

$$P_{fc} = I_{fc} \times V_{fc} \times N_{fc}$$

$$\mu_{fc} = {m_{H,th}}/{m_{H,act}}$$

$$\eta_{fc} = \mu_{fc} \times \frac{V_{fc}}{1.48} \times 100\% = 47\% \Rightarrow V_{fc} = 1.48 \times 47\% = 0.7(V)$$

where Mfc is the amount of the hydrogen consumed by the fuel cells, Ifc, Vfc and Pfc are the output current, voltage, and power of the fuel cell, respectively, Nfc is the number of the fuel cells, mfc is Faraday's efficiency, F is the Faraday constant (96 485 Cmol_1), and m Hth and mH ,act are the theoretical and actual hydrogen flow rates through the fuel cells, respectively. The efficiency of the fuel cells is assumed to be 47% (generally between 40% and 60%) [], the value of 1.48 V represents the maximum output voltage that can be obtained, and the value of mfc is 100% considering the unused hydrogen will be recycled. According to Eq. , the hydrogen consumption to produce 1 kWh electrical energy is 26.8mol h_1 under given working conditions.

D. *Electrolyzer*

A water electrolyzer consists of several cells connected in series. Two electrodes of the electrolyzer are separated by an aqueous electrolyte or solid polymer electrolyte (SPE). Electrical current through the electrolyzer enables the decomposition of water into hydrogen and oxygen.
The electrical efficiency he of electrolyzer is defined as the product of the current efficiency hi and the voltage efficiency [18,19]. The current efficiency at the temperature of 313.15 K is
Defined by

$$\eta_i = 96.5 \times \exp(0.09 / I_{elec} - 75.5 / I_{elec}{}^2)$$

$$\eta_v = \frac{1.48}{V_{elec}} \times 100\%$$

The voltage efficiency of the electrolyzer is equal to 74% [18] in this study. Thus, the value of the working voltage Velec is 2 V (1.48/0.74). According to Faraday's law, the amount of hydrogen produced by rated power 1 kW electrolyzer in 1 h can be calculated by

$$Melec = \frac{I_{elec} \times N_{elec}}{2 \times F} \times \eta_i \times 3600$$

$$= \frac{P_{elec}}{2 \times V_{elec} \times F} \times 3600 = \frac{1000 \times 3600}{2 \times 2 \times 96487} = 9.33(mol.h^{-1})$$

$$Pelec = Ielec \times Velec \times Nelec$$

$$\eta_i = 1$$

Where Melec is the amount of hydrogen produced by the electrolyzer, Nelec is the number of the electrolyzer cells, and Pelec is the rated power of the electrolyzer. The pressure has an important effect on the FC performance instead of the electrolyzers reaction efficiency [20]. In Ref. [21]

III. COST FUNCTIONS

A. *Cost functions*

Several metrics are developed to evaluate the economic and technical performance of the hybrid power systems. Three economic metrics are defined by [28]:

$$C_{ic} = \sum_{components} C_{cap,\,comp} \times S_{comp}$$

$$Cacap = Ccap \times \frac{i(1+i)^{Yproj}}{((1+i)^{Yproj} - 1)}$$

$$Carep = Crep \times \frac{i}{((1+i)^{Lcomp} - 1)}$$

$$C_{tac} = C_{acap} + C_{arep} + C_{aom}$$

$$C_{tac} = \sum_{components} (C_{acap,\,comp}(C_{cap,\,comp}, i, L_{proj})) + \sum_{components} (C_{arep,\,comp}(C_{rep,\,comp}, i, L_{proj}, L_{comp})) + \sum_{components} (C_{aom,\,comp}(C_{om,\,comp}, i, L_{proj}))$$

where Scomp is the component size, Eae is the annual electricity usage, Ccap, comp (Crep, comp, Com, comp) is the capital (replacement, O&M) cost of the system component, Cacap, comp, (Carep, comp, Caom, comp) is the annualized capital (replacement, O&M) cost of the component, and Lproj (Lcomp) is the project (component) lifetime. The annual real interest rate i is the discount rate used to convert between one-timecosts and annualized costs. The initial cost Cic is the sum of the products of component cost and its size. The total annualized cost Ctac is the sum of the annualized capital cost Cacap, the annualized replacement cost Carep, and the annualized O&M cost Caom of the PV power system. The electricity cost Ccoe is the average cost per kWh of electrical energy. The project lifetime Lproj is 40 years and the real interest rate i is 0.5 in this work.

B. Energy management strategy

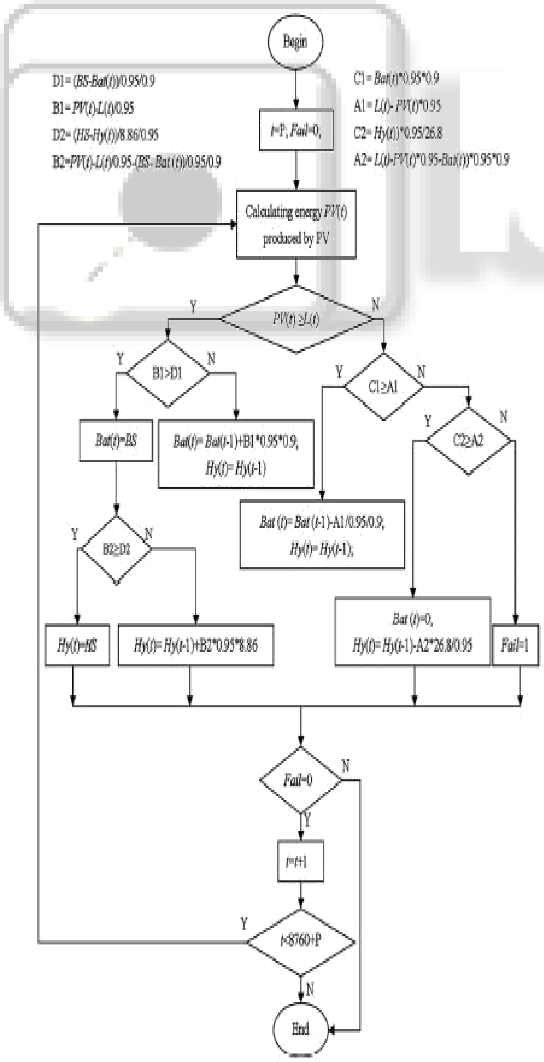

Fig. 2: Flow chart of energy management strategy.

Rated power (kw)	Cut-in-speed Vc (m/s)	Rated speed Vr(m/s)	Cut-off-speed Vf(m/s)	Hub height (m)
2.5	3	8.5	25	12

Table 1: Specifications of the wind turbine

Component	Capitl cost($/KW)	Replacement cost(USD/KW)	O&M cost(% of investment cost)	Lifetime(year)	Lproj
Wind turbine	2600	2166	0	25	40
Battery	120	118	1.0	4	40
Electrolyzer	1000	980	2.0	10	40
Hydr.tank	30	27	0.5	20	40
Fuel cell	2500	2437.5	2.5	5	40

Table 2: Initial cost and lifetime of the system components

IV. RESULTS

S.no	Wind speed	Load data	Wind output(kw) Conventional	Wind output(KW) using GA
1	10	1.7	1.7	1.7
2	13.5	1.6	1.6	1.6
3	12.4	1.5	1.52	1.52
4	11.6	1.5	1.49	1.49
5	10.9	1.4	1.46	1.46
6	9.98	1.4	1.42	1.42
7	9.15	1.4	1.41	1.41
8	8.36	1.4	1.41	1.41
9	12.8	1.5	1.53	1.53
10	11.6	1.9	1.85	1.85
11	10.6	1.9	1.90	1.90
12	9.6	2.1	2.1	2.1
13	9.7	2.2	2.16	2.16
14	8.9	2.2	2.16	2.16
15	8.2	2.1	2.11	2.15
16	7.4	2.1	1.78	1.84
17	6.7	2.1	1.48	1.54
18	5.6	2.2	1.22	1.27
19	5.4	2.2	1.03	1.05
20	5.6	2.2	1.09	1.14
21	5.1	2.3	0.90	0.95
22	5.9	2.1	1.20	1.25
23	5.6	2.0	0.88	0.92
24	4.7	1.8	0.60	0.63

Table 3: Manual and GA results

In this section, the results of optimal sizing after the implementation of proposed GA are discussed.

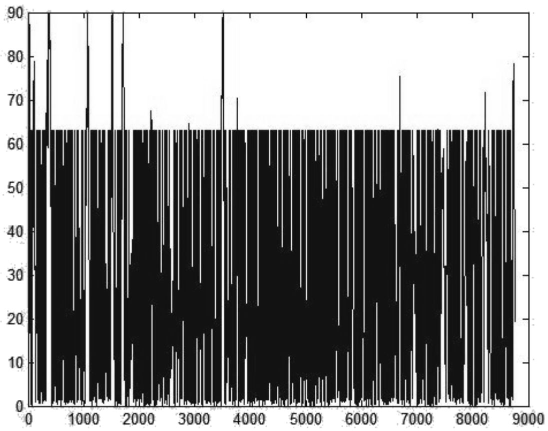

Fig. 4: Storage level of batteries for the minimal cost system throughout the year

The algorithm toolbox is implemented in MATLAB to solve the problem. The main objective is to minimize the cost of generation using GA. Both manual and GA results are compared.

Implementing Genetic Algorithm with two variables Hub height of the wind turbine and the number of wind turbines. The minimum and maximum limit for hub height are 10 & 30.The minimum and maximum for wind turbines are 1&5.

Graph plotted between time and Soc

Graph plotted between time and Soc of hydrogen

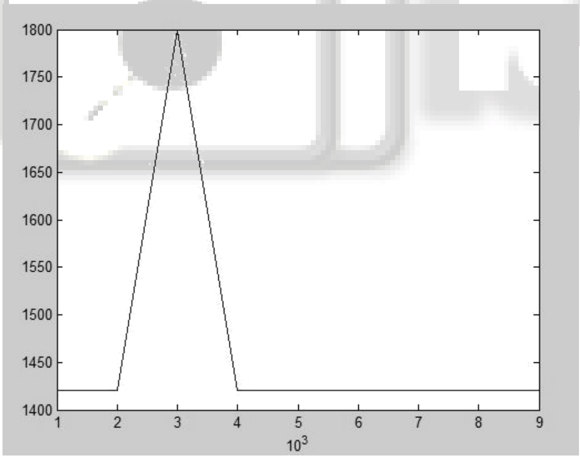

Fig. 5: Storage level of hydrogen tanks for the minimal cost system throughout the year.

V. Conclusion

Three stand-alone photovoltaic power systems using different energy storage technologies are modeled and optimized in this paper. The proposed component models facilitate the estimation of the storage capacity and calculation of the system efficiency. Three cost metrics and three efficiency metrics provide comprehensive standards of system evaluation. The method of ascertaining the minimal system configuration lays the foundation for the impartial comparison among the three power systems. For the wind/Battery system, the expensive battery with a short lifetime makes the minimal cost configuration with a low system efficiency and the maximal system efficiency configuration with a high system cost. The minimal cost of the PV/FC system is higher than that of the wind/Battery system although the configuration has almost achieved its maximal system efficiency. The high efficiency of batteries and the low cost of hydrogen tanks help the proposed Wind/FC/Battery hybrid system acquire the configuration with a lower system cost, higher system efficiency and less wind turbines as compared with either single storage system. In this work wind power is included in a normal conventional system and by using GA. Main advantage of using wind is, it is naturally available source and it reduces the usage of Fossil fuels. n GA, selection of Parameters is important

Hence the proposed method gives the optimal results when compared to the conventional method.

VI. References

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