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OPTIMAL SIZING OF HYBRID SYSTEMS AND ECONOMICAL COMPARISON

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ABSTRACT

Aim of study finding the best configuration among a set of system components. Power fluctuations and load disturbances in hybrid systems cause power inequality and system stability problems. Using hybrid energy storage systems is an effective solution in order to overcome unbalancing between power generating and load demands. In this paper, a methodology to perform the optimal sizing for Distributed Energy Resources (DERs) in three hybrid systems is developed, and reliability index is considered as a constraint. The optimum system configuration can meet the customer's required Equivalent Loss Factor (ELF=0) with the minimum cost, and comparison cost between them. In these configurations, power generators are photovoltaic (PV)/wind turbine and three combination of battery bank and hydrogen tank is used as an energy storage system. Particle Swarm Optimization (PSO) algorithm has been used to optimize the cost function, and has been simulated in MATLAB for justification purpose.

Keywords: Comparison cost, Hybrid system, Optimal sizing, PSO algorithm, Reliability.

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1. INTRODUCTION

Wind, geothermal, biomass, solar and hydropower are renewable energies and recently are alternatives for electricity generation. The use of these green energies can reduce the environmental impact of the gas. In recent years, hybrid PV/wind systems (HPWS) have become viable alternatives to meet environmental protection requirements and electricity demand capacity. Energy storage is needed in these systems due to the stochastic nature of wind and solar energy [1]. With the complementary characteristics between solar and wind energy resources for certain locations, HPWS with energy storage system presents an unbeatable option for the supply of small electrical loads at remote locations where there is no access to the power network [2]. To use solar and wind energy resources more efficiently and economically, the optimal sizing of hybrid PV/wind system associated with energy storage system plays an important role in this respect [3]. In addition, solar photovoltaic (PV) and wind power generations play essential roles in a small stand-alone micro-grid. Regard to these small stand-alone power generation, some studies are done. These studies include optimization [4] and Kabouris and Contaxis [5] enumeration [6-8] and reliability analysis [9-12]. Usually, the optimization uses some algorithms to reduce the cost of fuel, operation and investment. In Ying-Yi and Ruo-Chen [13] an optimization method by considering the available diesel units is discussed. In reference [14] Loss of Power Supply Probability (LPSP) technique has been used for optimal sizing of DERs in a hybrid system. Proper design of standalone renewable energy power systems is a challenging task. In reference [13] an optimal sizing using the genetic algorithm (GA) was proposed where the main objectives of the optimization are power reliability and cost. In this paper, optimal sizing and economic analysis have been performed for a PV/wind system having both the hydrogen tank and battery bank as storage elements, which meets the desired system reliability requirements, and its analytical results were compared to that of a same PV/wind system, which

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has merely one of the energy storage elements at a time (battery or hydrogen tank). First, the mathematical model of the hybrid PV/wind system, including PV modules, wind turbines, electrolyzer, fuel cell, hydrogen tank and battery was developed. Then, the system's economical model, based on the cost was obtained. Afterwards, optimal sizing applied to the three mentioned system configurations using PSO algorithm, which has the capability of attaining the global optimum relatively with a rather computational simplicity, The first system possess battery as the energy storage element, the second system uses hydrogen tank and the third one uses both hydrogen tank and battery. Finally, the simulation results and comparison results of the three considered systems will be dealt.

2. PROPOSED HYBRID SYSTEM STRUCTURES

The Proposed structures for the three mentioned hybrid systems are shown in Fig.1 collectively. In the first system, battery and in second system, hydrogen tank and in third system hybrid hydrogen tank/battery, are used as energy storage system. In Fig.1, P_{WT} is the output power of the wind turbine (kW). P_{PV} shows the output power of each PV array, P_{Gen} illustrates the total power generated by the renewable units (kW), P_{Gen_ele} is the transition power from renewable power sources to electrolyzer (kW), P_{Gen_inv} delivered power from the renewable power sources to the power converter DC/AC (kW). P_{ele_tank} presents the delivered power from the electrolyzer to the hydrogen tank (kW), and P_{inv_load} indicates the delivered power from the power converter DC/AC to the load (kW).

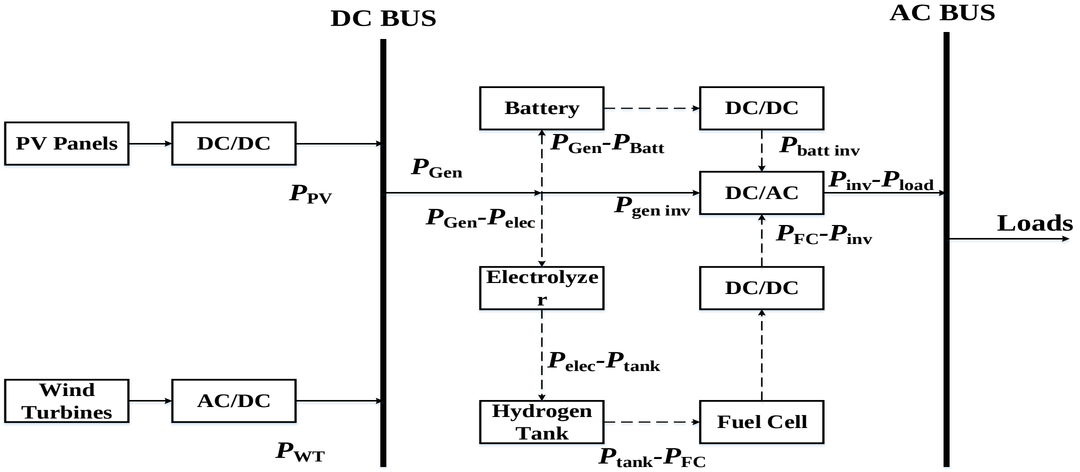

Fig-1. Porposed structures

In these systems, the generated power by the wind turbines and the PV arrays delivered to the load. If the power produced by wind turbines and PV arrays exceed the load demand, surplus energy is stored in the energy storage system. In case the energy produced by the wind turbines and the PV arrays can't meet the load demand, the energy storage systems get to work to cover the deficiency.

3. MODEL SYSTEM COMPONENTS

A. Photovoltaic

The electric equivalent of the absorbed solar energy by the surface of each PV array can be obtained through the following equation (1):

$$P_{PV} = G/_{1000} \times P_{PV,rated} \times \eta_{pv,conv} \qquad (1)$$

where, G is the perpendicular radiated power on the surface of each array (W/m2), and $P_{PV,\ rated}$ is the rated power of each array, such that G=1000W/m2. Also, $\eta_{pv,conv}$ is the efficiency of the DC/DC converter between each array and DC bus. The rest of required data are as follows: Rated power of each PV array: 1 (kW), Investment cost: 7000 \$/unit, Replacement cost: 6000 (\$/unit), Annual cost of maintenance and repair: 20 (\$/unit.yr) [15].

B. Wind Turbine

The output characteristic of a wind turbine (P_{WT} in terms of wind speed) which has been used in this paper, in which the rated power and the rated voltage are 7.5 kW and 48 V respectively, can be approximated as follows:

$$P_{WT} = \begin{cases} 0 & ; v_w \le v_{cutin}, v_w \ge v_{rated} \\ P_{WT\max} \times \left(\dfrac{v_w - v_{cutin}}{v_{rated} - v_{cutin}} \right) & ; v_{cutin} \le v_w \le v_{rated} \\ P_{WT\max} & ; v_{rated} \le v_w \le v_{rated} \end{cases} \qquad (2)$$

where, v_{cutin}, v_{cutout}, and v_{rated} are the cut-in, cut-out, and rated speed of turbine (m/s), respectively. Also, $P_{\mathrm{WT\ max}}$ is the maximum output power of the turbine (kW). The rest of required data are as follows:

Rated power: 7.5 (kW), Cut-in speed: 3 (m/s), Cut-out speed: 25 (m/s), Maximum output power: 8.1 (kW), Output power at the cut-out speed: 5.8 kW, Investment cost: 19400 ($/unit), Replacement cost: 15000 ($/unit), Annual cost of maintenance and repair: 75 ($/unit.yr), Lifetime: 20 (yr) (M.J. Khan, M.T. Iqbal).

C: Battery

The Difference of the generated power and the load demand will decide whether battery to be in charging or discharging state. The charge quantity of the battery bank at time *t* can be calculated by equation (3)

$$E_{bat}(t) = E_{bat}(t-1)(1-\theta) + (E_{Gen}(t) - E_L(t))\eta_{bat} \qquad (3)$$

where, $E_{\mathrm{bat}}(t)$ and $E_{\mathrm{bat}}(t\text{-}1)$ are the charge quantities of the battery bank at the time *t* and *t*-1, θ is the hourly self-discharge rate, $E_{\mathrm{Gen}}(\mathrm{t})$ is the total energy generated by the renewable energy source, $E_{\mathrm{L}}(t)$ is the load demand at the time t ,and η_{bat} is the charge efficiency of the battery bank [16]. The rest of required data are as follows: Investment cost: 1250 ($/unit), Replacement cost: 1100 ($/unit), Annual cost of repair and maintenance: 20 ($/unit.yr), Lifetime: 4 (yr)
(M.J. Khan, M.T. Iqbal).

D: Electrolyzer

The electrolyzer output power, $P_{\mathrm{ele\_tank}}$ can be calculated as follows.

$$P_{ele\_\tan k} = P_{Gen\_ele} \times \eta_{ele} \qquad (4)$$

where, $P_{\mathrm{Gen\_ele}}$ is the delivered electric power to electrolyzer, and η_{ele} is the electrolyzer efficiency. In this paper, the electrolyzer's efficiency is considered to be constant during operation time. The rest of required data are as follows: Investment cost: 2000 ($/unit), Replacement cost: 1500 ($/unit), Annual cost of repair and maintenance: 25 ($/unit.yr), Lifetime: 20 yr (M.J. Khan, M.T. Iqbal).

E: Hydrogen Tank

The stored energy in the hydrogen tank for each step-time can be calculated by the following equation (5):

$$E_{\tan k}(t) = E_{\tan k}(t-1) + P_{el-\tan k} \times \Delta t - P_{\tan k-FC}(t) \times \Delta t \times \eta_{storage} \qquad (5)$$

where, *t* is the duration of each step-time which is equal to an hour, and storage is the efficiency of storage system which is assumed to be 95% [16]. The rest of required data are as follows: Investment cost:1300 ($/unit), Replacement cost: 1200 ($/unit), Annual cost of repair and maintenance: 15 ($/unit.yr), Lifetime: 20 (yr) [15].

F: Fuel Cell

The Proton Exchange Membrane (PEM) fuel cells possess a reliable performance in the course of non-continuous operation conditions [17]. Output power of the fuel cell in terms of the input hydrogen power and its efficiency η_{FC}, which may be assumed constant, can be calculated using relation (6). The rest of required data are as follows: Investment cost: 3000 ($/unit), Replacement cost: 2500 ($/unit), Annual cost of repair and maintenance: 175 ($/unit.yr), Lifetime: 5 yr [15].

$$P_{FC-in} = P_{\tan k-FC} \times \eta_{FC} \qquad (6)$$

G: DC/AC Converter

The DC/AC converter converts DC power to AC power with a desired frequency. To consider the impact of converter loss on output power of MG, the following equation can be used:

$$P_{inv-load} = (P_{Gen-inv} + P_{FC-inv} + P_{bat-inv}) \times \eta_{inv} \qquad (7)$$

where, η_{inv} is the converter's efficiency. The rest of required data are as follows: Investment cost: 800 ($/unit), Replacement cost: 750 ($/unit), Annual cost of repair and maintenance: 8 ($/unit.yr), Lifetime: 15 (yr), and Efficiency: 90% (M.J. Khan, M.T. Iqbal).

4. SYSTEM RELIABILITY

To evaluate the system's reliability level, the Equivalent Loss Factor Index (ELF) has been exploited from various types of the reliability indices. The ELF index can be expressed by the following relation:

$$ELF = \frac{1}{N}\sum_{i}^{N}\frac{Q(t)}{D(t)} \qquad (8)$$

where, $Q(t)$, and $D(t)$ are the total load loss and the total load demand at *t-th* step-time, respectively. Also, N is the total number of step-times [18].

5. MODELING TO OPTIMAL SIZING

In essence, the general purpose of this paper is to demonstrate the optimal size of system components. The system costs can be divided into investment, replacement, maintenance and repair cost of devices, and the associated cost to load curtailment during 20 years horizon. In this paper don't need fuel cost because of not using fuel. We choose Net Present Cost (NPC) for calculation of system cost.

A. Equipment Cost

The NPC for a specific device can be expressed by the following equation (9) [17]:

$$NPC_i = N_i \times (CC_i + RC_i \times K_i + O\&MC_i \times PWA(ir, R)) \qquad (9)$$

where:

N	Number of the units and/or the unit capacity (kW or Kg)
CC	Capital investment cost ($/unit)
RC	Replacement cost ($/unit)
K	Single payment present worth
RMC	Repair and Maintenance cost ($/unit-yr)
PWA	Present Worth Annual Payment
ir	Real interest rate (6%)
R	Project lifetime (yr)

B. Objective Function

The objective function of the problem is defined as below:

$$J = \min_x \left\{ \sum_i NPC_i \right\} \qquad (10)$$

where, i indicate i-th equipment, and x is the optimization variables vector.

$$E[ELF]=0 \quad (11)$$

$$N_i \geq 0 \quad (12)$$

$$E_{\tan k}(0) \leq E_{\tan k}(8760) \quad (13)$$

$$E_{bat}(0) \leq E_{bat}(8760) \quad (14)$$

The aforementioned objective function must be optimized with respect to the following constraints.
The constraint (13) and (14) represent the energy content of tank and battery at the beginning of a year, and should not be less than its initial energy.

6. PARTICLES SWARM OPTIMIZATION

The PSO formulation defines each particle as a potential solution to a problem I dimensional space with a memory of its previous best position and the best position among all particles, in addition to a velocity component. At each iteration, the particles are combined to adjust the velocity along each dimension, which in turn is used to compute the new particle position. Since each dimension is updated independently of others and the only links between the dimensions of the problem space are introduced via the objective function, an analyzed can be carried out on the 1-D case without loss of generality. The original version was found to lack precision in a local search solution. The particle dynamics in one dimension are given by:

$$v_{t+1} = w \times v_t + c_1 \times (p(l) - x_t) + c_2 \times (p(g) - x_t) \quad (15)$$

$$x_{t+1} = x_t + v_{t+1} \quad (16)$$

Where v_t is the particle velocity at the t th iteration, x_t is the particle position at the t th iteration, p (l) is the personal best position or the particle's best position thus far, p (g) is the best global position or the best solution among all particles, w is the inertia factor, and c_1 and c_2 control coefficient. We assumed $c_1=c_2=2$, $w=0.7$ and took a population size of $p=60$ and the number of iteration of the algorithm was $g=300$ [19].

7. SIMULATIONS RESULTS

Using PSO, the objective function (relation 10) optimization, considering its related constraints, was simulated in MATLAB environment. Hourly average wind speed, daily sun light data over a period of one year, which was collected in a remote location in Davarzan, are shown in Figs. 2 and 3. An extraction with the precision of one sample per hour is shown in Fig. 4.

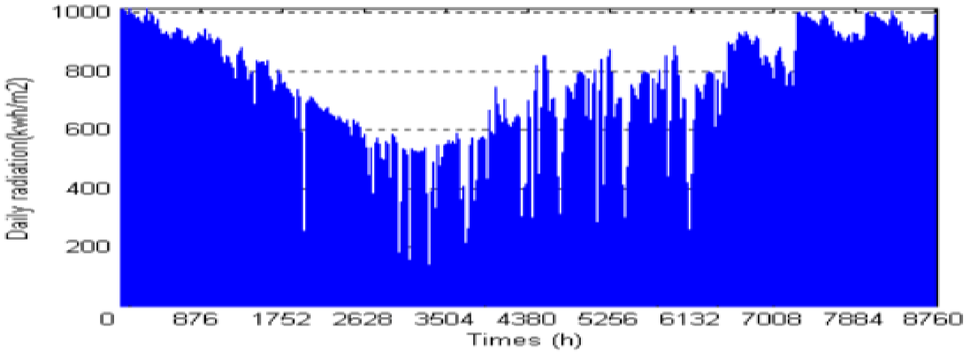

Fig-2. Hourly values of solar irradiation on titled plane.

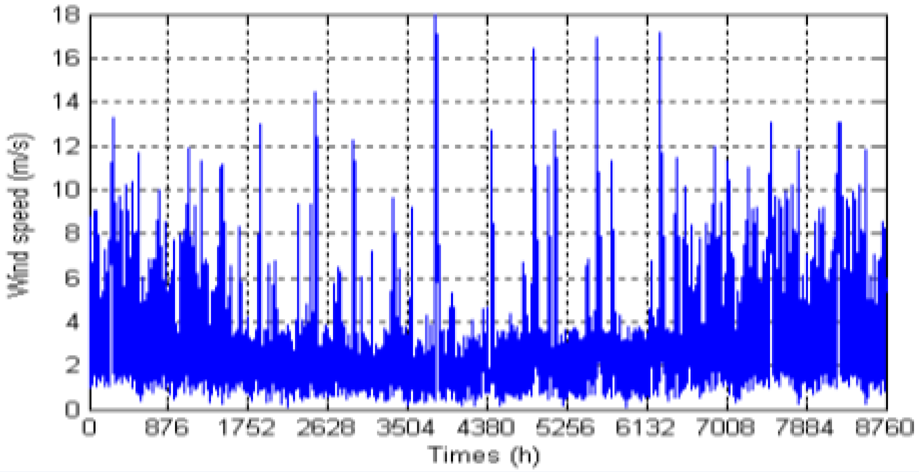

Fig-3. Hourly values of wind speed

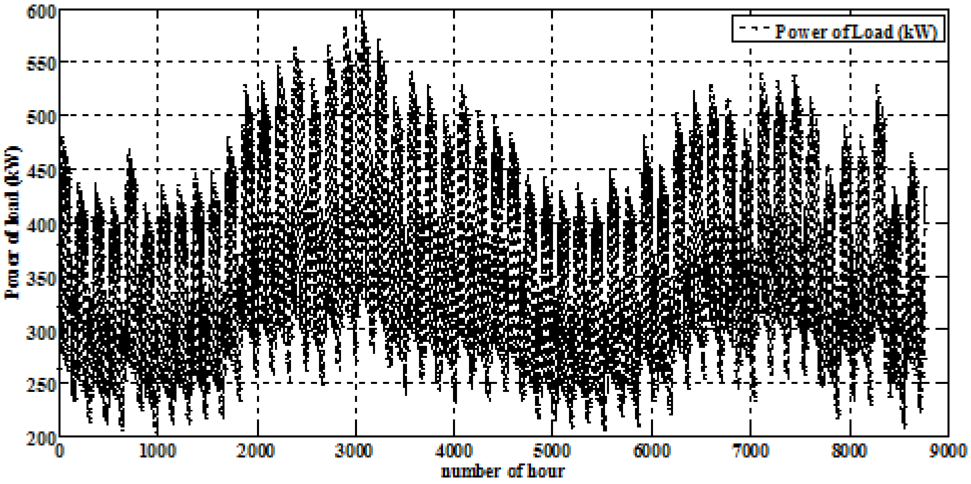

Fig-4. Annual load pattern for IEEE RTS test system

Results of optimal sizing for the distributed energy sources, considering reliability index of 0 for the three proposed hybrid systems, is listed in table (1), where raw 1 to 3 represent optimal numbers of distributed generations for battery, hydrogen tank and combination of both, respectively, as storage systems. System cost trend versus iteration number of PSO algorithm for the three hybrid systems is illustrated in Fig. 5.

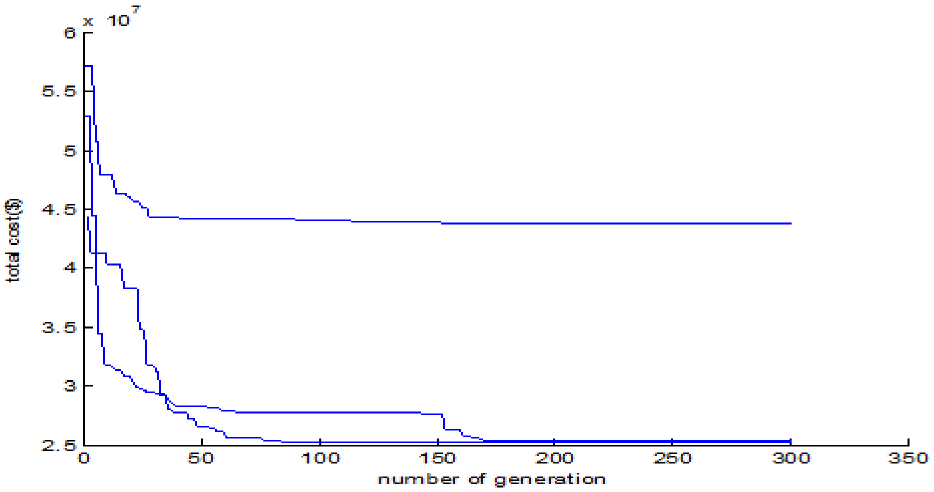

Fig-5. System cost versus number of iteration

Results show that using hydrogen tank as an energy storage system will be cost-effective, but it is slow in load tracking process. On the other hand, battery as a storage element is not economic, but its load tracking speed is high with respect to hydrogen tank system. Cost of using hybrid hydrogen tank/battery is closer to cost of using hydrogen tank system but its speed, in load tracking is high. Furthermore, it is an effective solution in order to overcome unbalancing between power generating and load demands.

Table-1. Optimal result with considering reliability for three hybrid system

	Wind Turbine Unit NO.	**Photovoltaic Unit NO.**	**Electrolyser Unit NO.**	**Hydrogen Tank Unit NO.**	**Fuel Cell Unit NO.**	**Battery Unit NO.**	**Total cost($)**
System No.1	14	1885	------	------	------	8199	4.3871×10^7
System No2	96	1991	3194	1293	841	------	2.51036×10^7
System No.3	162	1917	1416	673	506	6	2.5358×10^7

8. CONCLUSION

System reliability is one of the most important issues which must be considered in the design and operation of power systems. The serious drawback of photovoltaic units and, particularly wind turbines, is the discontinuities of electricity generation. So combination of electricity generating sources with complementary characteristics of electricity generation (like wind and sun) can be a viable solution. In this paper, optimal sizing of DERs in three different hybrid systems was investigated where the systems are combinations of battery bank, hydrogen tank and combination of both as energy storage systems. For all the systems, optimizations were performed using PSO algorithm. The results show that the combination unit (combination of tank/battery) is more efficient and effective than the others for its high load tracking behavior and low cost of implementation, which shows its viability and effectiveness as a solution for unbalancing issue of generated power and load demands.

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