Multi-Objective Optimization of a Hybrid Generating System

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ABSTRACT

Renewable generating systems are a sustainable solution for the electrical energy production; however the costs associated with the initial investment and due to that usually these kind of electrical generating systems are over-sized with the aim of satisfying the electrical load connected to them, implies an increase in the costs of investment, maintenance and operation as well as a reduction of their overall efficiency. Therefore, optimal sizing is an important issue in the design of renewable generation systems, in order to reach an efficient relationship between cost and benefit. Likewise, the random nature of the renewable sources increases the complexity for sizing a renewable generating system with regard to a conventional system. This paper is aimed to estimate the cost/sizing relationship of a hybrid energy solar-wind-diesel generator system using solar irradiation and wind data. The hybrid energy system uses the hydrogen as storage vector, so that it employs a fuel cell and electrolyzer for such task. The formulation is made up as a multi-objective optimization problem, solved by a genetic algorithm. The optimizer calculates the best system configuration to meet the commitment between the energy supply reliability and cost. Moreover, the optimizer allows an easy way for optimal sizing without depth knowledge of the relationship between the hybrid system costs and the generated power. Results are presented for a domestic installation load located in the south-east region of Mexico (Chetumal city).

Keywords: fuel cells; genetic algorithm, multi-objective optimization.

1. Introduction

At the present time, daily activities in the society are mostly dependent on non-renewable fossil fuels that have been and will continue to be an important factor of pollution and climate change. Because of these problems and our dwindling supply of petroleum, finding sustainable alternatives is becoming increasingly urgent. Perhaps the greatest challenge in realizing a sustainable future is to develop technology for integration and control of renewable energy sources in smart grids distributed generation (Strzelecki, 2008; Keyhani, 2010).

The interest in distributed generation systems (DGs) is rapidly increasing, particularly for on-site generation. This interest is because larger power plants are economically unfeasible in many regions due to increasing system, fuel costs, and more rigorous environmental regulations. In addition, recent technological advances in small generators, power electronics, and energy storage devices have provided a new opportunity for distributed energy resources at the distribution level; in particular, the incentive laws to utilize renewable energies have also encouraged a more decentralized approach to power delivery (Keyhani, 2010).

There exist various generation sources for DGs: conventional technologies (diesel or natural gas engines), emerging technologies (micro-turbines or fuel cells or energy storage devices), and renewable technologies (small wind turbines or solar/photovoltaics or small hydro-turbines). These DGs are used for applications to a standalone, a standby, a grid-interconnected, a cogeneration, and peak shavings (Keyhani, 2010).

Many distributed generation sources such as photovoltaic cells, fuel cells, and advanced energy storage systems (batteries, flywheels, and ultracapacitors) produce energy in the form of DC power. Other devices can also be suited to DC output, such as micro turbines and wind turbines.

The energy losses entailed in converting DC to AC power for distribution could be eliminated with DC power delivery, enhancing efficiency and reliability and system cost-effectiveness. For instance, the total life cycle cost of photovoltaic energy (PV) for certain DC applications could be reduced by more than 25% compared to using a conventional DC to AC approach—assuming that the specific end-use applications are carefully selected. The costs of new distributed generation such as PV arrays are still high, so optimization of designs with DC power delivery may help spur adoption and efficient operation (Gellings, 2009). Meanwhile, DC/AC conversion is utilized yet, and this consideration will be taken into account here.

Since it is expected that, in the short term, the use of new technologies will be quotidian, it is quite important to be prepared with tools able to take into account such elements.

This paper formulates the problem of an optimal sizing of a hybrid energy system (wind-photovoltaic-fuel cell-electrolyzer), solved by the NSGA-II software (Srinivas, 1994). In the formulation, the concepts of loss power supply probability (LPSP) and annual costs are taken into account. The optimization process evaluates the best configuration of the hybrid energy system that satisfies the commitment between energy supply and cost.

2 HYBRID GENERATING SYSTEM

In this paper the hybrid generation system is constituted by different power sources such as the wind turbine generator (WTG), photovoltaic panels (PVs), fuel cell generator and diesel generator, figure 1.

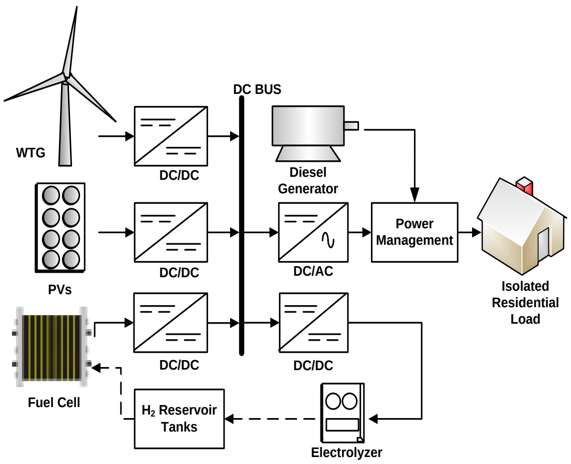

Figure 1. Hybrid generation system.

Likewise, if these renewable sources are not enough, then the non-supplied energy is taken from a fossil fuel generator.

2.1 Wind turbine generator (WTG)

The output power $P_W(t)$ from WTG subject to wind speed ($v(t)$) can be calculated by (1).

$$\begin{cases} P_W(t) = P_{nom}, \quad V_{nom} < v \quad (t) < V_{co} \\ P_W(t) = \frac{1}{2} \cdot \rho \cdot A_{eol} \cdot C_p \cdot v \quad (t)^3, \; V_{ci} < v \quad (t) < V_{nom} \\ P_W(t) = 0, \quad v \quad (t) < V_{ci}, v \quad (t) > V_{co} \end{cases} \tag{1}$$

Where V_{ci}, V_{nom}, V_{co} are the cut-in, rated, and cut-out wind speed, respectively. ρ is the air density, A_{eol} is the rotor's swept area (m^2), and C_p is the wind turbine efficiency.

Likewise, if these renewable sources are not enough, then the non-supplied energy is taken from a fossil fuel generator.

2.2 Photovoltaic panels

Sunlight is converted into electric energy by PV panels. The output energy from PVs ($P_s(t)$) can be calculated by (2),

$$P_s(t) = G(t) A_s \eta_s \quad (2)$$

where $G(t)$ is the insolation level (kW/m^2), A_s and η_s are the area and efficiency of the PVs, respectively.

2.3 Fuel cells (FC)

A simplified fuel cell model is used in this paper. We assume that the fuel cell works on a fixed operation point, so that its output power ($P_{FC}(t)$) can be evaluated from (3) (Nelson, 2005),

$$P_{FC}(t) = \eta_{FC} \left[P_{load}(t) / \eta_{inv} - P_{gen}(t) \right] \quad (3)$$

where η_{FC} and η_{inv} are the FC and inverter's efficiency, respectively. $P_{load}(t)$ is the demand, and $P_{gen}(t)$ is the total wind and PV generated power every hour, computed as (4).

$$P_{gen}(t) = P_v(t) + P_s(t) \quad (4)$$

One hour time step is employed. Thus, generated and demanded powers are equivalent to generated and demanded energies at a particular hour.

2.3.1 Electrolizer (elec)

We assume that the electrolyzer operates at a constant operating point, so that the hydrogen produced by the electrolyzer is proportional to its efficiency. The Hydrogen's equivalent energy drawn from the electrolyzer and stored in the reservoir tanks (*tk*) is described by equation (Dufo-Lopez, 2007),

$$E_{tk}(t) = \eta_{elec} \cdot (E_{gen}(t) - E_{load}(t) / \eta_{inv}) \quad (5)$$

where η_{elec} is the electrolyzer's efficiency.

2.4 Diesel generator

The Diesel generator model used in this paper calculates the fuel consumption, F_{cons} (l/h), as a function of the supplied power, P_G (kW), during an hour (5),

$$F_{cons} = B_G * P_{NG} + A_G * P_G(t) \tag{6}$$

where P_{NG} is the generator's rating power (kW), A_G and B_G are the consumption's power curve coefficients, (l/kWh). In (Skarstein, 1989) A_G = 0.2416 l/kWh and B_G = 0.08145 l/kWh are proposed.

3 SIZING METHODOLOGY

In this paper, the sizing of the stand-alone generating system is formulated as a multi-objective optimization problem,

$min\ f = [f_1\ \ f_2\ \ f_3]$

f_1: investment + operating and maintenance (O&M) costs + hydrogen's tank size

f_2 : LPSP + recovering stored energy in fuel cell each cycle (24 hours).

f_3: CO_2 emission

Thus, one of the main objectives of the hybrid system sizing is to minimize the total cost, which includes investment, operation and maintenance (O&M) cost. In this paper, the method of annualized costs is employed. The annualized investment cost for each element is calculated by,

$$C_{AC} = C_{INV} \cdot FRC(i_r, N_p) = \frac{i_r(1+i_r)^{N_p}}{(1+i_r)^{N_p}-1} \tag{7}$$

where C_{INV} is the investment cost, i_r and N_p are the annual interest rate and the lifetime of the element, respectively. FRC is the capital recovery factor, and

$$i_r = \frac{(i-f)}{(i+f)} \tag{8}$$

where i is the annual interest rate and f is the annual inflation rate.
In this paper, the components' O&M costs are calculated using (9)

$$OMC = \sum_{k=PV,WTG,...} O\&M_k * (1+f)^{N_p} \tag{9}$$

The fuel cells and electrolyzer have a shorter lifetime than the project one, thus the replacement cost of these components must be taken into account by,

$$C_{REMP} = C_R \cdot \frac{i_r}{(1+i_r)^{N_H} - 1} \tag{10}$$

where C_R is the replacement cost and N_H the replaced component's lifetime.
Thus, the objective function f_1 is described by (11), which includes investment, O&M, and replacement cost of the system's components,

$$f_1 = min\{\sum_{m=WTG,PV,elec,FC,tk}(C_{AC_m} + C_{OM_m}) + \sum_{n=elec,FC}(C_{rep_n})\} \tag{11}$$

The second objective function is related to the loss of power supply. When the renewable sources do not satisfy the demand, then there is an index to account for the loss of power supply (*LPS(t)*) during the current time *t*. This factor is calculated as follows,

$$LPS(t) = E_{load}(t) - (E_{gen}(t) + E_t(t-1) \cdot \eta_{FC}) \tag{12}$$

where $E_{load}(t)$ is the load at time *t*, $E_{gen}(t)$ is the available renewable energy at time *t*, $E_t(t-1)$ is the stored energy in the electrolyzer at time *(t-1)*, η_{FC} is the fuel cell efficiency.

The probability of the non-served power supply is described by,

$$LPSP = \frac{\sum_{t=1}^{T} LPS(t)}{\sum_{t=1}^{T} E_{load}(t)} \tag{13}$$

where *T* is the time period evaluated and *LPSP* is the Loss of Power Supply Probability. *LPSP* represents the number of days that the supply is lost over a given time period. For instance, LPSP = 0.0003 means to have a loss of power supply of roughly one day in ten years (Borowy, 1996; Abouzahr, 1991).

$$f_2 = \min\left\{LPSP + k_2[Et(1) - Et(24)]^2\right\} \tag{14}$$

where *Et*(1*)* and *Et*(24) are the stored energy in the electrolyzer during the first and the 24-*th* hour of a day. k_1 and k_2 are penalizing factors.

$$f_3 = \min\text{ (emissions of } CO_2) \tag{15}$$

The CO_2 produced per litre of consumed fuel depends upon the characteristics of the diesel generator and the type of fuel. The CO_2 produced by the fuel usually falls within 2.4 – 2.8 kg/l (Sonntag, 2002). In this paper this value is taken as 2.6 kg of CO_2 per litre.

3.1 Operating considerations

When the energy drawn from the WTG and PVs (E_{gen}) are greater than the demand (E_{load}), the excess energy is sent to the electrolyzer to be converted and stored into the hydrogen tank. Equivalent energy stored in the reservoir tanks is accounted for by,

$$E_t(t) = E_t(t-1) + (E_{gen}(t) - E_{load}(t)) \cdot \eta_{elec} \tag{16}$$

On the other hand, when the demand is greater than the available energy stemming from the WTG and PVs, the difference must be supplied by the fuel cell. The fuel cell recovers the equivalent energy stored as hydrogen in the reservoir tanks, causing a reduction in the stored energy as described by,

$$E_t(t) = E_{load}(t) - (E_{gen}(t) + E_t(t-1)) / \eta_{FC} \tag{17}$$

Likewise, one constraint is related to the maximum energy that can be stored in the reservoir tank,

$$0 \le E_t(t) \le E_{tk\max} \tag{18}$$

where E_{tkmax} is the hydrogen-tank's maximum capacity.

3.2 Optimization strategy

Figure 2 depicts the flowchart of the proposed strategy.

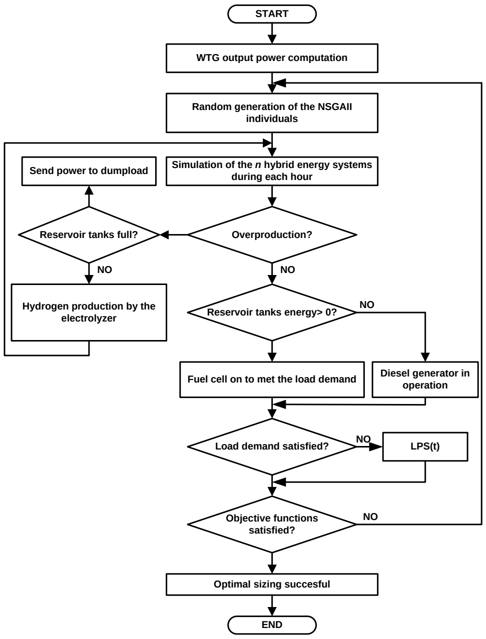

Figure 2. Flowchart of the strategy

The input data to optimize the hybrid energy system are the investment and O&M cost of each component. Likewise, efficiency and lifetime, energy demand in each hour for a period of 24 hours, as well as solar and wind resources available at the site. The optimizer determines the number of photovoltaic panels, as well as the hydrogen's initial energy storage, required to meet the energy demand and the required LPSP. In this paper the NSGA-II software is used to solve the problem. This one is selected due to its well known performance (Srinivas, 1994). The corresponding information required for simulations is shown in the appendix.
In this paper, the problem is formulated with three objective functions and two variables: (*i*) the area extended for the photovoltaic panels; (*ii*) the hydrogen-tank capacity. It is assumed that one wind-turbine generator is installed, which generated energy is subject to the available wind (Table A2 in appendix). A population of 25 individuals and 30 generation was used in the NSGA-II optimization algorithm.

4 SIMULATION RESULTS

The optimal sizing is estimated for three cases using the load in figure 3. The three cases are: (*i*) the use of renewable energy only; (*ii*) the use of renewable-diesel generator configuration; (*iii*) diesel only. The best results with respect to the total costs obtained by the multi-objective optimizer are shown in Table 1.

Table 1: Results obtained by NSGA-II

Item	Renewable System	Renewable-Diesel System	Diesel-only System
WTGs	1	1	-
PV modules	143	141	-
Energy stored in tanks	21.46 kW	21.33kW	-
Fuel (l)	-	234.7	7055.45
CO_2 emitted (tons)	-	0.62	18.34
Energy supplied	46.8 kWh	46.8 kWh	46.8 kWh
Annual total costs	$7147	$7933	$21893

As figure 3 illustrates, these stand-alone generating systems correctly satisfies the demand.

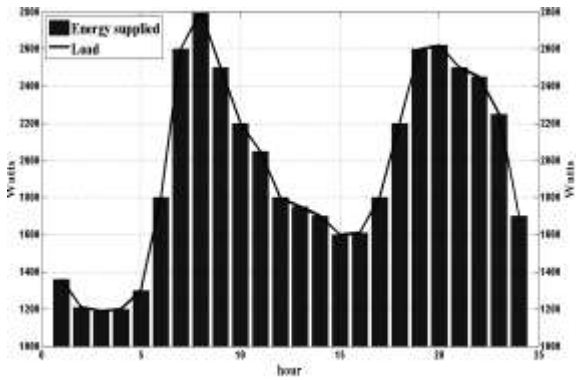

Figure 3. Load profile and supplied power.

It is noteworthy that the cost of using renewable sources is higher than the use of the diesel generator. However, it is important to limit the use of the latter one due to the emissions of CO_2 and other pollutants. Thus, in order to establish a commitment between the cost and an ecological solution to the energy supply, monetary penalization is applied for the use of the fossil fuel. In this paper, this penalization is $1.55 per fuel litre.

For the case of the renewable-diesel combination, this energy system employs during an hour the diesel generator along the year. If the economical penalization is taken into account due to the use of the fossil fuel, the total cost of this system is bigger than the renewable stand-alone system. Under this consideration, the cost of the diesel use is quite expensive. Figure 4 shows the energy stored in the hydrogen tanks when there is a residual renewable energy after to satisfy the demand.

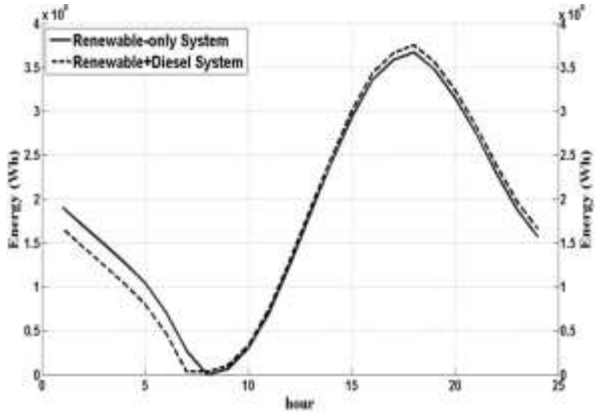

Figure 4. Equivalent energy stored in the hydrogen tanks.

CONCLUSIONS

This paper has estimated the optimal sizing of a renewable energy system using the algorithm NSGA-II. Simulation results show that the prices of the storage system elements are expensive yet, so that the total cost of the energy system using renewable sources and hydrogen storage is high. However, pollution is eliminated. Hence, in order to reduce the green energies' prices, economical penalization must be applied for the use of fossil fuels.

NSGA-II has found the optimal systems configuration to meet the commitment between the energy supply reliability and cost. The optimizer allows an easy way to attain an optimal sizing without deep knowledge about the relationship between the renewable generation system costs and the power generated by the accounted for sources.

The optimal configurations were selected and tested by the LPSP analysis. Simulations indicate the necessity of a high quantity of stored energy in the hydrogen tanks, which implies an increase in the total system cost and a voluminous solution. However, the use of hydrogen as energy storage has an important positive environmental impact.

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APPENDIX

Table A1: Parameters

System Parameters	
Nominal WTG Power (P_W)	4 kW
Nominal FC power	3 kW
Nominal electrolyzer power	3 kW
Nominal diesel generator power(P_{NG})	4 kW
Cut-in wind speed (V_{ci})	2.5 m/s
Nominal wind speed (V_{nom})	12.5 m/s
Cut-out wind speed (V_{co})	20 m/s
WTG efficiency (C_p)	0.5
PV efficiency (η_s)	0.12
FC efficiency (η_{FC})	0.5
Inverter efficiency (η_{inv})	0.95
Electrolyzer efficiency (η_{elec})	0.74
WTG price	$3000
PV panel price per module	$450
FC price	$10000
Electrolyzer price	$10000
Diesel generator price	$2100
Diesel litre price	$2
Inverter price	$2500
Reservoir tanks price	$2000
O&M costs of WTG	$72/year
O&M costs of PVs	$10/mod/year
O&M costs of FC	$800/year
O&M costs of electrolyzer	$70/year
O&M costs of diesel gen.	$900/year
Annual interest rate (i)	3.75%
Annual inflation rate (f)	1.5%
Life span of Project (N_P)	20 years
Life span of electrolyzer and FC (N_H)	5 years
Life span of diesel generator (N_{GDI})	2.5 years

Table A2: load and energy availability

hour	Load (kW)	Irradiance (W/m^2)	wind (m/s)
1	1.36	0	4.4
2	1.21	0	4.3
3	1.19	0	4.25
4	1.20	0	4.35
5	1.30	0	4.25
6	1.80	0	4.4
7	2.60	0.02	4.25
8	2.80	0.08	4.2
9	2.50	0.19	4.5
10	2.20	0.3	4.75
11	2.05	0.42	5.3
12	1.80	0.51	5.7
13	1.75	0.54	6
14	1.70	0.51	6.3
15	1.60	0.46	6.8
16	1.61	0.38	6.82
17	1.80	0.25	6.2
18	2.20	0.17	6.1
19	2.60	0.07	5.85
20	2.62	0.04	5.5
21	2.50	0.02	4.8
22	2.45	0	4.78
23	1.36	0	4.78
24	1.21	0	4.78