Energy and Buildings 102 (2015) 406–416

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Energy management of a grid-tied residential-scale hybrid renewable generation system incorporating fuel cell and electrolyzer

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ARTICLE INFO

Article history:
Received 6 February 2015
Received in revised form 22 April 2015
Accepted 28 May 2015
Available online 10 June 2015

Keywords:
Economical energy management
Hybrid systems
Management strategy
Fuel cell
Electrolyzer
Wind turbine
Photovoltaic array

ABSTRACT

In this paper, a new methodology has been discussed on economical power management of a grid-connected CHP system which consists of a wind turbine, photovoltaic array, polymer exchange membrane fuel cell and an electrolyzer. Hence, the paper also attempts to present the thorough modeling of energy management of the hybrid system in the form of a nonlinear optimization problem; through which offline energy management is regarded to use the available options in order to determine the role of each generator in producing heat, power and hydrogen in the system under study. In addition to this, variable tariffs of daily exchange with local grid have been taken into account in different operation conditions so as to reach real utilization requirements. Based on these facts, choosing the most suitable model for each element of the hybrid system has been considered in regard to their dynamic behavior. The proposed hybrid system is to supply the electrical and thermal demands of renewable energy laboratory of Shahid Bahonar University of Kerman (SBUK). The economical energy management is comprehensively studied and surveyed in the form of various scenarios while the hybrid system is connected to the grid.

1. Introduction

The exhaustibility of fossil fuel resources not only entailed energy crisis in the following decade but also has brought intricate hazards into human life regarding the environmental challenges of their use. That is because fossil energy is still considered as the major energy resource of the world consumption [1]. As of today fossil fuels contribute 93% of the resources used to produce electricity in Iran; 75% of which is gas and 18% of which is oil [2]. Therefore sustainable and environmentally adaptive energy supplying has been regarded as the developmental perspective of many countries. The increasing daily consumption and difficult accessibility of natural resources will result in energy price increase. Besides, greenhouse gas emission, which arises from the use of fossil fuels threaten the ecosystem. Obviously in such a situation renewable energy resources are regarded by far more than before [3].

The sun and wind are the two renewable energy resources which are lionized because of their ease of access and inexhaustibility [4]. However, energy production out of aforementioned resources is influenced by climatic and geographical conditions and this is a major challenge for sustainable generation [5]. In order to overcome such unsustainability, energy conversion may happen in the process of energy supplying or operation. As an example, pumped-storage hydropower plants pump water into high altitude during light load hours so that its potential energy is used in peak hours in order to operate a hydro-generator and generate power. Among all, the most efficient type of conversion is of gas into electrical power and vice versa. Indeed, when energy exceeds consumption, hydrogen can be produced and then stored in a high level of efficiency to be used as the fuel of a fuel cell in case of energy shortage [3].

Numerous recent investigations have demonstrated that placing fuel cell beside wind turbine and photovoltaic array can form an optimal structure as a sustainable energy source called as hybrid generation system [6–9]. A hybrid energy system, in comparison to a single mode one has degrees of freedom to determine the level of participation of each subsystem which improves operational efficiency. Such structures are remarkably more secure and weather conditions do not affect its sustainable production [10,11]. It is obvious that enjoying the discussed advantages depends upon intelligent energy management among different generating subsystems. Accordingly optimal energy management is of much importance in such a structure and has been seriously discussed and considered. As an example, in Ref. [3] the aforementioned structure has been studied as a stand-alone hybrid system and its energy management process has been done using a classic decision-making algorithm. Similarly, in Ref. [12] energy management was

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http://dx.doi.org/10.1016/j.enbuild.2015.05.046
0378-7788/

Nomenclature

$a_k^d(t)$	acceleration of kth object at time t, in dth dimension
C_t	total operation costs ($)
$\cos t_m^i$	maintenance costs during ith time interval ($)
D_e^i	electrical demand during ith time interval (kW)
D_{th}^i	thermal demand during ith time interval (kW)
$F_{kl}^d(t)$	force applied to mass k by mass l in the dimension of d at the time period t
$F_k^d(t)$	the force applied to mass k, in dimension d at time t by other system masses
$fit_k(t)$	fitness value of kth object at interval t
$G(t)$	gravity at time period t
I_r	irradiation (W/m^2)
m	number of objects
Mg_k	gravitational mass of object k
Mi_k	inertia mass of object k
n	number of time intervals
MDT	maximum down time limit (interval)
MUT	maximum up time limit (interval)
$N^{\max}$	maximum number of starts–stops
$N_{start-stop}$	number of starts–stops of fuel cell
p_w^i	wind turbine power production at interval i (kW)
p_w^r	rated power of wind turbine (kW)
p_s^i	photovoltaic array power production at interval i (kW)
p_s^r	rated power of photovoltaic array (kW)
$P_{EL}^{\min}$	minimum limit of consumption power of electrolyzer (kW)
$P_{EL}^{\max}$	maximum limit of consumption power of electrolyzer (kW)
$P_{FC}^{\min}$	minimum electric generation output of fuel cell (kW)
$P_{FC}^{\max}$	maximum electric generation output of fuel cell (kW)
$\bar{P}_H$	price of hydrogen (cent/Nl)
p_{FC}^i	fuel cell electrical power production at interval i (kW)
p_a	internal consumption power of fuel cell (kW)
p_{th}^i	thermal recovered power from fuel cell at interval i (kW)
p_g^i	electrical power exchanged with local grid (kW)
p_{EL}^i	electrolyzer electrical power consumption at interval i (kW)
PLR_i	part load ratio of fuel cell at interval i (kW)
r_l	lth random coefficient
r_{th}^i	thermal to electrical power ratio at interval i
R_C	down limit of irradiation = 150 (W/m^2)
R_{STD}	up limit of irradiation = 1000 (W/m^2)
$R_{kl}(t)$	Euclidean distance between kth & lth object
soc_o	initial state of charge of hydrogen tank (%)
soc_{end}	final state of charge of hydrogen tank (%)
$SOC_{\min}$	minimum limit of state of charge of hydrogen tank (%)
$SOC_{\max}$	maximum limit of state of charge of hydrogen tank (%)
SOC_i	state of charge of hydrogen tank at interval i (%)
$\bar{T}$	duration of time interval (min)
T_{i-1}^{on}	duration during which fuel cell is continuously on (interval)
T_{i-1}^{off}	duration during which fuel cell is continuously off (interval)
tr_{buy}^h	purchasing tariff in hth hour ($/kWh)
tr_{sell}^h	selling tariff in hth hour ($/kWh)
U_i	equals 1 if fuel cell is on and zero if it is off
v_i	wind speed at interval i (m/s)
V_i	cut-in speed of wind turbine (m/s)
V_o	cut-in speed of wind turbine (m/s)
V_r	rated wind speed of wind turbine (m/s)
v_k^d	velocity of object k in dimension d
X_k	position vector of object k
x_k^d	the position of mass k in dimension d
η_e^i	electric efficiency of fuel cell in interval i
η_H	electric heating system efficiency
Δp_{FC}^u	ramp up rate limit of fuel cell (kW/min)
Δp_{FC}^d	ramp down rate limit of fuel cell (kW/min)
Δp_{EL}^u	ramp up rate limit of electrolyzer (kW/min)
Δp_{EL}^d	ramp down rate limit of electrolyzer (kW/min)
ε	a very small constant
α	a parameter equal to 20
β	a parameter equal to 100
τ	number of iterations

implemented without the participation of power grid in a structure formed by a wind turbine, fuel cell, photovoltaic array and a battery. An intelligent controller has been proposed in Ref. [12] for optimal gain scheduling. In Ref. [13] the same structure, by replacing battery instead of wind turbine, was discussed and applied in Homer environment. In Ref. [9] the required energy supply of an apartment has been investigated with the help of a hybrid system which includes a super capacitor, solar module, fuel cell and also an electrolyzer. The load shape data and solar radiation intensity were obtained from a real case study. In some studies only direct hydrogen production with the help of electrolyzer and solar array has been regarded [14]. In another study, a solid oxide fuel cell stack has been coupled with a solar-electrolyzer to satisfy the required heat and power of a remote location. In addition to this, here scholars introduced two appropriate static models of fuel cell and electrolyzer [15]. There are also a few researches in which heuristic methods have been widely applied to power management of hybrid systems [16]. Optimal size selection and capacity planning of each element in hybrid systems is one of the other approaches of this matter which has been recently paid attention [17–19]. Noting these researches shows linking fuel cell to photovoltaic array and wind turbine, as well as prior attempts, leads to independency over climatic conditions and increases reliability associated with the hybrid system. Other attracting and undeniable features of fuel cell such as high efficiency, simultaneous production of heat and power, rare contamination, modular structure and the fast speed of its technology progression has led to an increase of its use in hybrid structures [3,10]. Since applying all of these sources yields an appropriate potential in order to supply load with higher quality in comparison to a single source generation system, therefore, a grid-connected hybrid combined heat and power (CHP) plant is proposed which includes wind turbine, photovoltaic module, fuel cell stack and electrolyzer. The paper presents an economical energy management in order to meet thermal and electrical demands of a building through an offline optimization process. Since the possibility of load supplying by local grid is one of the assumptions of the scheduling problem, daily variant buying and selling tariffs are considered in problem formulation. In order to cover technical limitations of each subsystem, energy management is formulated as a constrained nonlinear optimization problem. It is also tried to use the compatible model regarding the dynamic behavior of each subsystem. It should be mentioned that the daily load profile used here are daily