Energy Conversion and Management 154 (2017) 224–243

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Performance characterization of zero carbon emission microgrid in subtropical climate based on experimental energy and exergy analyses

Kuldeep Kumar, Jagendra Srivastava, Dibakar Rakshit*, Viresh Dutta

Photovoltaic Laboratory, Centre for Energy Studies, Indian Institute of Technology, Delhi, 110016 Hauz Khas, New Delhi, India

ABSTRACT

Energy and exergy analyses are effective tools to characterize the microgrid performance in different operating conditions and to identify the scope of making system more efficient. Exergy analysis provides details information regarding maximum possible work, losses, types of losses and its locations. In present study an attempt has been made to characterize the performance of photovoltaic (PV) and fuel cell (FC) based AC microgrid using the energy and exergy analyses. A microgrid comprising of PV (5 kW_p) and FC (1 kW) as primary and auxiliary generators respectively is developed at Centre for Energy Studies (CES), Indian Institute of Technology (IIT) Delhi. Excess PV electricity is used to generate the hydrogen using electrolyzer that is stored in metal hydride (MH) tank. Experimental energy and exergy analyses are carried out for different operating conditions that give energy efficiencies of PV system, FC system, MH and electrolyzer as 12.6%, 59.1%, 83.4% and 49.4% respectively. Maximum exergy efficiencies of PV, FC, MH and electrolyzer are estimated as 13.5%, 59.4%, 82.8% and 49.6% respectively. The exergy values are calculated at various environment reference temperatures (0 °C, 8 °C, 16 °C, 20 °C, 25 °C, 30 °C, 35 °C, 40 °C and 45 °C) to estimate the seasonal effects on the exergy performance of system. The exergy efficiency of entire hydrogen generation and utilization cycle increases with increase in reference environment temperature. The overall energy and exergy analyses of entire AC microgrid in different operating modes are also performed. According to the obtained experimental results maximum overall energy and exergy efficiencies of AC microgrid are 12.57% and 13.47% respectively.

1. Introduction

Renewable power generators such as photovoltaic (PV) and fuel cell (FC) based microgrid energy system renders best solution of existing problems in conventional grid such as transmission losses, power quality, unavailability in remote areas and hazardous environmental emissions. Performance of such kind of microgrid should be well studied in different operating conditions for characterization of its energy flow and losses. Energy and exergy analyses give a realistic approach to assess the performance of any energy system and scope of further improvement in performance. Exergy analysis is very helpful for the system designer that gives optimum possible utilization and irreversibility in the given energy system according to varying environment reference conditions.

Performance of hybrid systems consisting of PV and proton exchange membrane fuel cell (PEMFC) systems with other power generators such as diesel and battery have been studied based on technical, economic and environmental constraints [1,2]. Studies show the feasibility and advantages of such kind of hybrid system especially having low emissions.

Considerable work has been done on PV-FC hybrid system in last two decades in simulation and system domain. Ganguly et al. [3] have reported the modeling and analysis of PV-FC-greenhouse integrated power system. In modeling, excess PV power was used to produce hydrogen that was utilized by FC to supply load demand during power deficit period. Modeling results were validated with case studies. Singh et al. [4] have done a techno -economic feasibility analysis for PV-FC-battery microgrid for an academic research building using the HOMER pro software. Degiorgis et al. [5] have reported the hydrogen production with mix of hydro and PV electricity. Dynamic simulation of hybrid system in TRNSYS has been also reported that has shown the technical and economic feasibility of the system. Beccali et al. [6] have reported the energy, economic and environmental analyses of renewable energy technology (RET)-hydrogen hybrid system in Homer software tool. It was concluded that FC based energy systems have better environmental performance especially in case of hydrogen generation by renewable sources. Gomez et al. [7] have reported optimization of PV-FC hybrid system for telecom application using the TRNSYS simulation tool. Little

* Corresponding author.
E-mail address: dibakar@iitd.ac.in (D. Rakshit).

http://dx.doi.org/10.1016/j.enconman.2017.10.044
Received 30 July 2017; Received in revised form 9 October 2017; Accepted 15 October 2017

Nomenclature

Abbreviations

CES	centre for energy studies
CO_2	carbon dioxide
EL	electrolyzer
EMS	energy management system
FC	fuel cell
MH	metal hydride
MPP	maximum power point
NL	nominal liter
PEMFC	proton exchange membrane fuel cell
PV	photovoltaic
PV-FC	photovoltaic-fuel cell
RET	renewable energy technology

Symbols

A_s	area of solar modules (m^2)
c_p	specific heat capacity of hydrogen (J/kg K)
$\dot{EL}_{in}$	electrolyzer energy input rate (W)
$\dot{EL}_{out}$	electrolyzer energy output rate (W)
$\dot{EL}_{loss}$	electrolyzer energy loss rate (W)
ex_{ph}	physical exergy (J/kg)
ex_{ch}	chemical exergy (J/kg)
ex_{CH0H_2}	standard chemical exergy of hydrogen (J/kg)
$\dot{Ex}_{FCout}$	FC exergy output rate (W)
$\dot{Ex}_{FCdes}$	FC exergy destruction rate (W)
$\dot{Ex}_{Load}$	load exergy rate (W)
$\dot{Ex}_{ELin}$	electrolyzer exergy input rate (W)
$\dot{Ex}_{ELout}$	electrolyzer exergy output rate (W)
$\dot{Ex}_{ELdes}$	electrolyzer exergy destruction rate (W)
$\dot{Ex}_{PVin}$	PV exergy input rate (W)
$\dot{Ex}_{PVU}$	PV exergy output rate (W)
$\dot{Ex}_{PVdes}$	PV exergy destruction rate (W)
$\dot{FC}_{in}$	fuel cell energy input rate (W)
$\dot{FC}_{out}$	fuel cell energy output rate (W)
$\dot{FC}_{loss}$	fuel cell energy loss rate (W)
I_{PV}	current produced by PV System (A)
I_{EL}	input current to electrolyzer (A)
I_{FC}	output current of fuel cell (A)
k	adiabatic exponent
LHV_{H_2}	lower heating value of hydrogen (J/kg)
$\dot{m}_{FC}$	fuel cell hydrogen input flow rate (kg/s)
$\dot{m}_{EL}$	hydrogen generation rate in electrolyzer (kg/s)
$\dot{PV}_{in}$	energy input rate of PV system (W)
$\dot{PV}_{out}$	energy output rate of PV system (W)
$\dot{PV}_{loss}$	energy loss rate in PV system (W)
P_0	atmospheric pressure
R_{H_2}	hydrogen gas constant
S_T	incoming solar radiation (W/m^2)
S. I	sustainability index
T_0	environment reference temperature (K)
T_{Sun}	temperature of the Sun (K)
T_{FCH_2}	FC hydrogen temperature (K)
T_{ELH_2}	electrolyzer hydrogen temperature (K)
V_{EL}	input voltage to electrolyzer (V)
V_{FC}	output voltage of fuel cell (V)
V_{PV}	voltage produced by PV System (V)
x	mole fraction

Greek symbols

η_{EL}	electrolyzer efficiency (%)
η_{FC}	fuel cell efficiency (%)
η_{MH}	metal hydride efficiency (%)
η_{H_2cycle}	overall energy efficiency of hydrogen cycle (%)
$\eta_{PVsystem}$	overall energy efficiency of PV system (%)
$\eta_{PVarray}$	energy efficiency of PV array (%)
$\eta_{ACmicrogrid}$	energy efficiency of overall AC microgrid (%)
η_{PVI}	energy efficiency of PV inverter (%)
ψ_{PV}	exergy efficiency of PV system (%)
ψ_{PVI}	exergy efficiency of PV inverter (%)
ψ_{EL}	exergy efficiency of electrolyzer
ψ_{FCI}	exergy efficiency of FC inverter (%)
ψ_{MH}	exergy efficiency of MH system (%)
ψ_{H_2cycle}	overall exergy efficiency of hydrogen cycle (%)
$\psi_{ACmicrogrid}$	overall exergy efficiency of AC microgrid (%)
ΔT_0	uncertainty in measurement of ambient temperature
ΔT_{ELH_2}	uncertainty in measurement of hydrogen temperature of electrolyzer
ΔT_{FCH_2}	uncertainty in measurement of hydrogen temperature of FC
ΔS_T	uncertainty in measurement of solar radiation
$\Delta \dot{m}_{FC}$	uncertainty in measurement of hydrogen input flow rate at FC
$\Delta \dot{m}_{EL}$	uncertainty in measurement of hydrogen output flow rate at electrolyzer
ΔP_{FCH_2}	uncertainty in measurement of hydrogen pressure of FC
ΔP_{ELH_2}	uncertainty in measurement of hydrogen pressure of electrolyzer
$\Delta \dot{Ex}_{Load}$	uncertainty in measurement of load exergy

et al. [8] have worked on the integration of PV-wind-FC system. Simulation and experimental results of system performance were also reported. Bilodeau et al. [9] have worked on PV-wind-hydrogen energy system with advanced algorithm to control the operation of hydrogen production and then again hydrogen conversion to electricity. Onar et al. [10] have shown the designing and modeling of PV-wind-FC-ultra capacitor hybrid system.

Liu et al. [11] produced hydrogen using excess PV electricity and stored it to MH cylinder. A 48 V AC/DC converter was used to run electrolyzer from PV/grid power. Ghosh et al. [12] developed a standalone PV-FC hybrid system using DC/AC inverter that feeds power to a captive load. Fracas [13] has also reported PV-FC application for transportation application. Calderon et al. [14] have done study on the energy analysis of wind-PV-FC standalone hybrid system. The energy efficiency of PV system and combination of electrolyzer and FC system were reported 8.41% and 26.67% respectively. Calderon et al. [15] have worked on the automatic energy flow management system for the PV-FC application. The working of energy flow management system was validated using the results from case study. Caliskan et al. [16] have worked on the energy and exergy analyses of wind-PV-FC hybrid system. According to the modeling results overall energy and exergy efficiencies of system were reported 3.44% and (5.838–5.865%) respectively. Ezzat et al. [17] have studied the application of PV-FC hybrid system in vehicle in different operating configurations. In configuration 1 (FC-battery), FC provides power to load and battery charging. In configuration 2 (FC-battery-PV), PV-FC both provide power to load and battery charging. The results from the study show that the overall energy and exergy efficiencies become 39.46% and 56.3%, respectively for configuration 1. Energy and exergy efficiencies are found to be 39.86% and 56.63% for configuration 2. In another study, Zhang et al. [18] have done a simulation study on grid- tied PV-FC microgrid in different modes of operation. It was concluded that emissions and service quality are higher without FC operation. Majidi et al. [19] have studied the effect of load response on PV-FC-battery microgrid