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Optimal control of a fuel cell/wind/PV/grid hybrid system with thermal heat pump load

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ABSTRACT

This paper presents an optimal energy management strategy for a grid-tied photovoltaic–wind-fuel cell hybrid power supply system. The hybrid system meets the load demand consisting of an electrical load and a heat pump water heater supplying thermal load. The objective is to minimize energy cost and maximize fuel cell output, taking into account the time-of-use electricity tariff. The optimal control problem is solved using a mixed binary and real linear programming. The supply switch to the heat pump water heater and the power from the grid, power to/from the inverter, electrolyzer hydrogen power and fuel cell power are the control variables. The temperature inside the water storage tank and the hydrogen in the storage tank are the state variables. The performance of the proposed control strategy is tested by simulating different operating scenarios, with and without renewable energy feed-in or rather export to the grid, and the results confirm its effectiveness, as it increases the supply reliability of the system.

1. Introduction

Rising costs, depletion and environmental concerns about fossil fuel-based energy resources have led to significant research effort in renewable and cleaner energy resources. Globally, governments are adopting policies to promote the development and application of various renewable energy (RE) technologies for generating electricity. The main challenge associated with RE technologies such as solar and wind generator is their intermittent nature, which affects their ability to provide 100% supply reliability. Combining these RE sources with battery storage and diesel generator systems has been shown in various studies to be cost-effective (Hove and Tazvinga, 2012; Dufo-Lopez et al., 2011; Tazvinga et al., 2015). Currently there are limitations to the fraction of RE (wind and solar) that can be incorporated in the grid system because of their intermittency and base load considerations. With the latest developments pointing towards the feasibility of the hydrogen economy, solar and wind power fractions can be safely extended within the grid system by compensating for their intermittency with an energy storage medium such as hydrogen. Interest in hydrogen is mainly driven by its ability to reduce carbon dioxide emissions, thereby helping to mitigate climate change, improve local air quality, improve energy security by reducing energy imports, increase energy supply options, reduce dependence on fossil fuels, and contribute to the introduction of advanced fuel cell (FC) technologies with high efficiency.

FCs are promising sources of electricity that are environmentally friendly. Use of hydrogen FCs for power production is receiving a lot of interest in many research communities, with industrial applications in automobile industries and heat pumps (Ellis et al., 2001). FCs can serve as emergency sources of energy in the event of a long-term power outage and in stand-alone applications. They are replacing battery systems and are increasingly being used in distributed generation systems. Hydrogen, once produced and stored, can generate power on demand. In order for photovoltaic (PV) and wind systems to meet demand completely, there is a need for backup systems such as diesel generators (DGs), hydrogen FCs and battery storage in a hybrid system (Wang et al., 2016; Reihani et al., 2016; Feng et al., 2015; Purvins and Sumner, 2013). Hybrid energy systems present a solution to the time correlation of intermittent RE sources (Ranaboldo et al., 2015; Tazvinga et al., 2013). RE-based power systems are being deployed globally to provide autonomous power for various remote applications and also in grid-tied systems. Improvements in the performance of these systems for both grid and off-grid applications continue globally in many research communities (Bouzerdoum et al., 2013).

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Nomenclature

$P_{w,t}$	wind generator power output (kW)
$P_{pv,t}$	photovoltaic power output (kW)
$P_{g,t}$	grid power (kW)
$P_{hp,t}$	heat pump water heater rated power (kW)
$P_{RE-IN,t}$	direct renewable power supply (kW)
$P_{el,t}$	power supply to the electrolyzer (kW)
$P_{H2,t}$	eletrolyzer hydrogen power output (kW)
$H_{2,t}$	stored hydrogen energy (kWh)
$P_{FC-IN,t}$	fuel cell power output (kW)
$P_{\text{Load},t}$	domestic load (kW)
$P_{FC,t}$	hydrogen power input to the fuel cell (kW)
COP	coefficient of performance
u_t	heat pump power supply switch control variable (0 or 1)
T_t	hot water temperature inside the tank (°C)
T_{low} and T_{up}	lower and upper hot water temperature set points (°C)
T_a	ambient temperature (°C)
T_o	initial hot water temperature (°C)
$T_{in,t}$	inlet cold water temperature (°C)
R	South African rands (1R = 0.074 USD as of 22.09.2015)
$\lambda_{(t)}$	time-of-use electricity price (R/kWh)
N	total number of sampling intervals
t_s and k	sampling time (*hour*) and kth sampling interval respectively
J	cost function
Q_D	total losses due to water demand
Q_L	total standby (convectional) losses
$W_{D,t}$	flow rate (liters/hour)
q_{loss}	conventional loss in (W/m^2)
$\triangle x$	thickness of the insulation (m)
h	surface heat transfer coefficient (W/m^2 K)
κ	thermal conductivity (W/m K)
S_{area}	total surface area (m^2)
c	specific heat capacity of water (J/kg °C)
ø	diameter (m)
$\dot{T}$	derivative of temperature
L	mass of water inside the tank (kg)
h_{ref}	anemometer reference height (m)
φ	ground surface friction coefficient
v_{hub}	wind speed at the desired height h_{hub}
v_{ref}	wind speed at the reference height h_{ref}
V	wind speed at the hub height (m/s)
χ	Weibull shape parameter
P_r	rated wind electrical power (kW)
V_{in}	cut-in wind speed (m/s)
V_r	rated wind speed (m/s)
V_{out}	cut-off wind speed (m/s)
MILP	mixed integer linear program
TOU	time-of-use electricity tariff
Eskom	South African power utility company

Various energy management strategies have been proposed for different hybrid system configurations (Choudar et al., 2015; Korpås and Holen, 2006; Tazvinga et al., 2014). A standalone RE/FC hybrid system that uses at least one RE source and a polymer electrolyte membrane (PEM) FC as backup source is analyzed in Bizon et al. (2015). Frequency fluctuation analysis of a wind, DG and FC hybrid power system connected to a local utility point has been presented in Singh et al. (2015) and the results show that the FC system can give better performance for stabilizing the frequency of the system in comparison to DGs. Electrochemical energy storage systems such as hydrogen systems can offer sufficient flexibility for operation in connection with stochastic generation from wind and PV and local energy storage can also increase the exploitation of the energy source (Korpås and Holen, 2006). Use of hydrogen as a storage medium for variable energy sources is a promising alternative in the long run, since it can be used as a clean fuel in the transport sector and for power production in stationary FCs (Korpås and Holen, 2006; Bizon et al., 2015).

It is important to note that energy consumption in buildings, especially in developed countries, accounts for close to 42% of global energy production and 60.51% of this energy is used for space heating, while 23.60% goes for water heating at domestic level (Rahman et al., 2010; Chow et al., 2012; Zhang et al., 2013). Therefore, only energy-efficient equipment such as heat pump water heaters (HPWH) should be used to produce the much needed thermal energy. The use of HPWHs in demand side management (DSM) yields more benefit than its counterpart, cylinder hot water heaters, owing to its coefficient of performance (COP). Great success in optimal design and control of HPWHs in the last decades has increased their application even at domestic level (Chua et al., 2010). Safdarian mentioned that domestic heating systems has a potential for DSM (Safdarian et al., 2016; Seo et al., 2014). HPWHs have advantages such as they could be applied in heating, ventilation, and air-conditioning (HVAC) systems (Fabrizio et al., 2014; Huang et al., 2006; Arteconi et al., 2013; Kilkis, 1999). Nevertheless there are still a few drawbacks, such as heating water to the required temperature in a short time and the initial investment cost (Verhelst et al., 2012; Rousseau and Greyvenstein, 2000). RE integration with such energy-efficient equipment is in its infancy stage (Roonprasang et al., 2008; Sichilalu and Xia, 2015; Sichilalu et al., 2015).

In most of the work done by various researchers, DGs and battery storage are the common power back-up in RE hybrid systems, instead of greener hydrogen FCs. The main focus in FC technology has been the evaluation of performance index on life cycle cost, optimal sizing and hybridization only (Rodatz et al., 2005; Pukrushpan et al., 2004; Pukrushpan et al., 2002) rather than optimal control (OC). While most of these back-up systems, (e.g. DGs) are expensive to run and have negative environmental effects. Though FCs technology seems to have a high initial investment cost, it is in fact cheaper and greener in the long term. This paper presents a first-ever OC strategy model on an integrated RE-FC-grid system with an energy-efficient thermal load under a time-of-use (TOU) tariff. This model presents a practical FC feed-in OC strategy. This paper simulates a 24-h control horizon, giving a comprehensive hourly energy usage pattern and its implications. Often customers do not change their energy usage behavior because of lack of detailed short-period energy consumption/bill correlation in the accumulative monthly bill.

This paper is structured as follows: Sections 2 present the mathematical model formulation and Section 3 the simulation results and discussion. The last part, Section 4, is the conclusion.

2. Mathematical model formulation

2.1. Schematic diagram of the model

The schematic layout is shown in Fig. 1. The PV modules $P_{pv,t}$ and wind generator $P_{w,t}$ feed through their respective inverters into the direct current (DC) bus. The DC bus then supplies through $P_{RE-IN,t}$ to the loads and the other $P_{el,t}$ to the FCs electrolyzer for the generation of hydrogen. The generated hydrogen, $P_{H2,t}$, is stored in the hydrogen storage tank, H_2, which later supplies