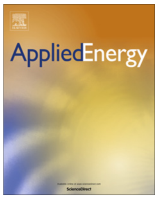
Applied Energy xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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



Model predictive control of heat pump water heater-instantaneous shower powered with integrated renewable-grid energy systems

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HIGHLIGHTS

- Robust model predictive control (MPC) strategy used to control hot water devices.
- Integrated renewable energy sources supplemented by grid used to power the devices.
- Heat pump water heater coupled with instantaneous shower is modelled.
- Potential daily energy and water saving of 32.24% and 19 l respectively.
- The proposed control strategy is suitable for peri-urban and rural home owners.

ARTICLE INFO

Article history:
Received 12 January 2017
Received in revised form 2 May 2017
Accepted 3 May 2017
Available online xxxx

Keywords:
Model predictive control
Wind energy
Solar energy
Heat pump water heater
Instantaneous shower

ABSTRACT

Energy and water are two inseparable resources that are crucial for human survival, yet, most developing nations are struggling to reliably provide them to the population especially in rapidly growing urban areas. Increasing demand is forcing governments, organizations and private sectors to encourage end-users to increase efficiency and conservation measures for these resources. Water heating is one of the largest energy users in residential buildings thus has a huge potential to improve the efficiency of both energy and water. In this regard, heat pump water heaters (HPWHs) have been found to improve energy efficiency while providing domestic hot water. However, impediments such as optimal operation, integration and high initial cost especially in developing nations hinder their uptake. Further, since they are normally centrally located in a house, there are water and associated energy losses during hot water conveyance to the end-use, as the once hot water in the pipes that cooled off has to be poured away while end-user awaits for hot water. Therefore, this paper advances the previously developed open loop optimal control model by using the closed-loop model predictive control (MPC) to operate a HPWH and instantaneous shower powered using integrated renewable energy systems. This control strategy has the benefit of robustly and reliably dealing with disturbances that are present in the system as well as turnpike phenomenon. It has the potential to save 32.24% and 19 l of energy and water in a day respectively, while also promising lower energy and water bills to the end users. In addition, there is revenue benefit through the sale of excess renewable energy back to the grid through an appropriate feed-in tariff. Life cycle cost (LCC) analysis is conducted to determine the total cost of setting up and operating the system over its life, which shows that the benefits would pay back the cost of the system even before half of its life elapses. This control strategy of both hot water devices powered using integrated renewable systems is suitable for peri-urban home owners.

1. Introduction

In most developing nations, such as African countries, increasing population has the proclivity of concentrating in urban areas and cities. Many nations in Sub-Saharan Africa have been experiencing rapid urban expansion averaging at 5% per annum [1]. The rapid growth has many social, economic and physical repercussions including increased demand for key services such as energy and water. These factors have made Sub-Saharan Africa to be the most energy insecure region in the world with the average urban and rural electrification standing at 59% and 17% respectively [2], while over 40% of the population do not have safe clean

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http://dx.doi.org/10.1016/j.apenergy.2017.05.033
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Please cite this article in press as: Wanjiru EM et al. Model predictive control of heat pump water heater-instantaneous shower powered with integrated renewable-grid energy systems. Appl Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.05.033

Nomenclature

A_c	area of photovoltaic (PV) array (m^2)
A_{hp}, A_{is}	surface area of HPWH's, instantaneous shower's storage (m^2)
A_w	sweeping area of turbine rotor (m^2)
COP	coefficient of performance
C_p	power coefficient of wind turbine
c_w	specific heat capacity of water (J/kg °C)
D_{tot}, D_{is}	HPWH, instantaneous shower water demand (kg/h)
Δx	thickness of insulation material (m)
h	coefficient of surface heat transfer (W/m^2 K)
η_g, η_t	generator, gearbox efficiency
η_{is}	efficiency of instantaneous shower's heating element
η_{pv}	efficiency of photovoltaic generator
I_{pv}	solar irradiation on photovoltaic array (kW h/m^2)
J	objective function
k	coefficient of thermal conductivity (W/m K)
m_{hp}, m_{is}	mass of water inside HPWH, instantaneous shower (kg)
N	total number of samples during the 24-h operating cycle
ρ_a	density of air (kg/m^3)
p_e	price of electricity using TOU tariff (*currency*/kW h)
P_g	grid power (kW)
P_{hp}, P_{is}	power rating of HPWH, instantaneous shower (kW)
P_l	domestic load (kW)
p_{off}, p_{peak}	off-peak, peak electricity price in the TOU tariff (*currency*/kW h)
P_{pv}, P_w	photovoltaic, wind power (kW)
Q_d, Q_l	thermal power loss due to water flow, standby losses (W)
R_{hp}, R_{is}	thermal resistance of insulating material (m^2 K/W)
TOU	time-of-use tariff
T_a	ambient temperature (°C)
T_{hp}, T_{is}	temperature of water inside HPWH, instantaneous shower (°C)
T_{hp}^{in}, T_{is}^{in}	temperature of incoming water to HPWH, instantaneous shower (°C)
t_s and j	sampling period (h) and jth sampling interval
u_{hp}, u_{is}	status of HPWH's, instantaneous shower's switch
V_c, V_i, V_N	cut out, cut in, rated wind speed (m/s)
ω	weighting factor
Rand (R)	South African currency ((1 Rand = 0.075 USD), as at 02 May 2017)

water. This is despite renewable energy having the potential to increase the energy capacity through micro grids, combined heat and power systems and production of bio fuels. Tapping into this potential would increase electrification, improve grid quality, also lower the cost of electricity which eventually would lead to improved quality of life. In South Africa, access to electricity increased from 35% to 84% between 1990 and 2011. The increased demand led to a very narrow reserve margin in the grid eventually causing power shortages (black outs) and load shedding from 2008, with huge negative economic ramifications [3]. In addition, electricity is mainly generated from coal leading to a very high carbon footprint, and the government is considering introduction of carbon tax [4]. To deal with these challenges, the government introduced both supply and demand side management initiatives. In supply side, the government sought to increase the generation capacity through building of new coal power stations, return to service of some coal power stations and explore co-generation and renewable energy options [5]. The existing coal power plants have become outdated, while the coal reserves are dwindling, making construction of new plants not only environmentally hazardous but also prohibitively expensive to implement. Therefore, the only viable option in supply side is co-generation and renewable energy options. The demand side management (DSM) measures introduced sought to reduce the demand for power by up to 5000 MW by 2025 [3]. DSM seeks to reduce the gap between supply and demand through improving energy efficiency (EE) as well as load management (LM) [6]. LM is tailored to reduce the demand for electricity during peak period by offering incentives to shift load to off-peak periods. This is normally done through the use of time-of-use tariffs or demand response programs [7]. Following the above reasons, this study seeks to consider a more grid independent system using available renewable energy sources while also ensuring EE takes place.

Energy efficiency and DSM have also become very attractive research topics [8]. Areas of interests and applications have been in industrial systems [9–14], power systems [15–18], building energy systems [19–21], and the eventual measurement and verification [22]. Water heating is one of the most important energy intensive components in the building energy systems. In a typical South African residence, water heating leads to 40–60% of total energy consumption [23] There is therefore a huge potential for EE and energy conservation measures for water heating especially in South Africa. One such way is through the use of efficient technologies such as HPWHs [24]. They have a high coefficient of performance making them a suitable alternative to electric storage water heaters (geysers) in reducing the monthly peak electricity demand charges. Despite their superiority and government intervention, their market penetration is still low standing at about 16% [25]. Coupled with high investment cost, there are technological challenges in HPWH's optimal operation, sizing and integration [26].

HPWHs are not only ideal in enhancing EE for domestic hot water systems [24], but have also been proven to be economically feasible [27]. Further, it is possible to shift the load using HPWHs increasing the prospect of integrating it with renewable energy sources [28]. Various control algorithms aiming to reduce energy consumption and its associated cost have been developed. A feed forward artificial neural network (ANN) was desined to control HPWHs [29]. However, of the control algorithms tested, including proportional-integral-derivative (PID) controllers, predictive control algorithms proved to be most effective [30]. Use of renewable energy systems to power HPWHs and other domestic loads has a huge potential to save more energy, cost and reducing greenhouse gas emissions [31]. Various open looop predictive control algorithms for controlling HPWHs with distributed renewable energy systems have been designed. An optimal control model operating a HPWH powered using grid tied photovoltaic (PV) and diesel generator integrated system was developed for application in areas with intermittent power supply [26]. An optimal power dispatch model of a grid tied photovoltaic system was used to power HPWH. The cost of grid energy was structured as a time-of-use (TOU) tariff and the model not only showed the potential to save energy but also the ability to use the energy stored in the battery in case of either power black out or during peak time [32]. In addition, an optimal controller was designed to operate a HPWH powered using integrated wind generator-photovoltaic-grid system. This controller led to energy and cost savings from renewable energy systems. The grid was designed such that it could accept power back from renewable energy systems whenever it was not required [33]. The optimal control model was advanced by incorporating a

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