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Optimal control of heat pump water heater-instantaneous shower using integrated renewable-grid energy systems

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ABSTRACT

Developing countries are grappling with energy and water insecurity, impelling governments to encourage end-users to conserve and efficiently consume these vital resources. With water heating being among the largest energy users in residential buildings, it is imperative that the efficiency and conservation of both energy and water are achieved. Heat pump water heaters (HPWHs) are a superior choice in efficiently providing domestic hot water. However, there are still challenges in their optimal operation and high initial cost in developing nations. 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 cold water has to be poured away. This paper introduces an optimal control strategy of a hybrid HPWH and instantaneous shower powered using integrated renewable energy systems. This strategy has the potential to save 23.4% and 19 l of energy and water in a day respectively, while also promising lower energy and water bills to the end users. Further economic benefit can be achieved through the sale of excess renewable energy back to the grid through an appropriate feed-in tariff.

1. Introduction

Renewable energy is increasingly being adopted by many countries in the world with the aim of reducing over-reliance on fossil fuels. However, remote areas in many developing nations, such as Africa and most islands developing nations are not connected to the grid. They are therefore relying on fossil fuel generators despite their high potential for renewable energy [1]. The negative environmental effect of fossil fuels, coupled with high fuel importation transport cost and dis-economies of scale in electricity production lead to exorbitantly high energy cost and long term financial risks for the economy [2]. Furthermore, increasing population is straining the existing energy infrastructure through increasing energy demand. By 2020, energy use by developing nations will grow at an average annual rate of 3.2% surpassing 1.1% in the developed countries [3]. Renewable energy technologies are a sustainable solution to providing cheaper and cleaner energy in these areas. For instance, in Maldives islands, hybrid solar and wind electricity generation systems have been proven to be financially feasible for supplementing the fossil fuel based grid [4]. Adoption of these hybrid renewable energy systems is faced with the challenge of designing an optimal energy management system that satisfies the load while considering the intermittent nature of renewable energy sources and variations in power demand [5].

Domestic water heating is the fourth largest energy user in commercial buildings, after heating, air conditioning, and lighting, and third largest in residential buildings [6]. Studies from various parts of the world reveal that domestic water heating, when compared with total energy consumption in buildings, is responsible for 18% in the USA [7], 25% in UK [8], 26% in Spain [3], 30% in Australia [9] and 20% in Brazil [10]. This has led to increased effort in improving energy efficiency of domestic hot water systems, whose level determines the energy saving potential [11]. Heat pumps offer economically attractive choices as they recoup heat from various industrial, commercial and residential applications [12]. Heat pump water heaters (HPWHs) operate on the principle of the refrigerant cycle converting one unit of electrical energy to produce three units of thermal energy [13]. Despite the superiority, improvement of its performance, reliability, and environmental impact have been a concern [12], while optimal operation and integration of the technologies remains a challenge [14]. These challenges, coupled with high initial investment cost especially in developing countries have hindered their uptake. For instance, in South Africa the market penetration of HPWH is 16% [15].

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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 = 0.074 USD), as at 17 August 2016)

Various studies have looked at ways to achieve energy efficiency using HPWHs. Kreuder and Spataru [16] showed that heat pumps can indeed be used to enhance energy efficiency in homes while Aste et al. [17] showed their economic feasibility. Further, various control algorithms have shown their potential in reducing the delivered energy and its cost but predictive control algorithm was the most effective [18]. Integration of distributed renewable energy provides a huge potential in powering HPWHs further increasing the energy savings [19]. Therefore, an optimal control model of a grid tied photovoltaic (PV) and diesel generator integrated system applicable in areas with intermittent power supply was used to power HPWHs [14]. In another study, an optimal power dispatch model of a grid tied photovoltaic system was used to power HPWH. The model showed energy savings potential and ability to use the stored energy in the battery in case of power black out, or during peak time [20]. An optimal controller for the HPWH powered using integrated wind generator-photovoltaic-grid system led to energy savings further improving the energy efficiency of the HPWH while feeding back excess power back to the grid through a suitable feed-in tariff [21]. This study was advanced by incorporating a fuel cell which improved the reliability of the intermittent renewable power supplies. The optimal control strategy showed the possibility of integrating renewable energy systems and energy efficient systems [22]. Despite the superiority of HPWHs to other water heating technologies, they have a slow rate of heating water. Consequently, in cases with high demand for hot water, HPWHs are unable to supply it. Further, since HPWHs are normally centrally located in the house, energy and water losses associated with the hot water conveyance to the consumption point occur as the cold water in the pipe is wasted while waiting for hot water at the point of use. Upon finishing with the use, the remaining water in the pipe quickly cools down [23]. To address these challenges, instantaneous water heaters, placed at the consumption point, can be used [24]. Although previous studies have mainly concentrated on energy demand management, the demand management of energy-water nexus gaining more attention in developing nations [25], with instantaneous heaters proposed as a suitable option [26].

This paper introduces a novel and economical optimal control strategy that ensures both energy and water are efficiently consumed by using HPWH and instantaneous shower to conveniently meet domestic hot water demand. The shower end use is selected in this study as it is one of the most hot water intensive end uses in homes. The control model uses integrated wind-photovoltaic renewable energy to power the hot water devices, needing grid power whenever they are insufficient. However, whenever renewable energy is in excess, it is sold back to the grid through an appropriate feed-in tariff. Therefore, the aim of the controls is to optimally operate both hot water devices, maximizing the use of renewable energy effectively ensuring the customer incurs the least cost of electricity. The controls further minimize water loss during conveyance to the shower.

2. Controller formulation

2.1. Schematic layout

Fig. 1 shows the schematic diagram of the water heating system comprising of the HPWH and the instantaneous shower. The water heating devices are powered using photovoltaic solar, P_{pv}, and wind generator, P_w, while grid, P_g, acts as a back whenever the renewable sources are insufficient. The HPWH, centrally located in the house, meets the total hot water demand. The instantaneous shower is placed in the shower to act as back up whenever the water from the HPWH is not at the required temperature. Switches u_{hp} and u_{is} control the power flow to HPWH and instantaneous shower respectively. The grid supplements power from the renewable sources as well as accepting excess power back.

2.2. Wind energy

Wind energy is one of the integrated renewable energy system used to power the hot water devices. Whenever there is excess wind energy than that required by the hot water devices, it is fed back to the grid using an appropriate feed-in tariff. The power output of a typical wind turbine is proportional to the cubed wind speed as long as this speed is between the cut in wind speed, V_i and rated wind speed, V_N. For a simplified model of a wind generator, the power output, P_w, at the rated wind speed is [27],

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