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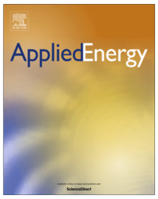

Optimal control of a wind–PV-hybrid powered heat pump water heater ☆

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HIGHLIGHTS

- Optimal control of a wind–PV-hybrid powered heat pump water heater is modelled.
- Daily energy cost saving of around 70.74% is shown.
- Saved energy is due to proposed optima control intervention with time-of-use.
- Potential of a daily energy saving of about up to 51.23% is shown.
- The optimal photovoltaic and wind energy feed-into the grid is modelled.

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ABSTRACT

This paper develops an optimal control (OC) model of a heat pump water heater (HPWH) supplied by a wind generator–photovoltaic-grid system. The objective function is energy cost minimization, taking into account the time-of-use electricity tariff, which is an important control parameter. The control variables are the supply switch to the HPWH and the power from the grid, while the hot water temperature inside the tank is the state variable. The model meets both the HPWH's technical and operational constraints in providing hot water at a desired temperature and achieves load shifting. This problem is solved using a mixed integer linear program. The results show a 70.7% cost reduction upon implementation of this intervention. A case study is done and the OC shows significant potential in both energy and cost saving in comparison to the digital thermostat controller used in most of the HPWHs on the market. The economic analysis is presented in this paper as well.

1. Introduction

The energy consumption in buildings account for about 42% of global energy production, especially in developed countries [1]; 60.51% of this energy goes for space heating while 23.60% goes for water heating at domestic[1] level. Therefore, in order to reduce the high energy consumption, energy-efficient equipment, such as heat pump water heaters (HPWH), needs to be employed for demand side management (DSM) at domestic level. HPWHs are devices that drive heat energy from a cooler surrounding medium to a much warmer place using a working fluid (refrigerant). The refrigerant absorbs the ambient energy of the surrounding medium in the evaporator and passes through the compressor, where it gains extra heat energy through an increase in pressure as a result of compression. This hot working fluid then circulates through the heat exchanger (condenser), where thermal energy is transferred to the water and the process is repeated. The past two decades have seen major advances in HPWH technology [2–4], which has led to its wider application and improved coefficient of performance (COP). Essen and Yuksel [5] extensively investigated both ground-sourced and air-sourced HPWHs and made an economic analysis. Various authors [6–11] have developed models and investigated ways of improving the COP of the HPWH; however, most of them agree that optimal control (OC), system design, sizing and integration remain technological challenges.

The problem of DSM requires a multi-directional approach; the HPWHs alone might not achieve significant energy savings, hence the need to integrate them with distributed renewable energy sources (DREs) such as wind and photovoltaic (PV) power in buildings [12,13]. On/off-site DRE integration into buildings and small communities is a promising technology for DSM. Various hybrid DREs are presented in [14–20], though much of the success achieved so far is in the sizing and system design. More effort

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[1] http://www.dti.gov.uk/energy/inform/.

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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}	heat pump water heater power demand (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)
$p(t)$	time-of-use electricity price (R/kW h)
N	total number of sampling intervals
t_s and k	sampling time (h) 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 (l/h)
q_{loss}	conventional loss in (W/m^2)
Δx	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)
η_t	turbine coupling gearbox efficiency (%)
η_g	wind generator efficiency (%)
ρ	air density factor of the wind generator
C_p	Betz limit
A_w	wind generator rotor sweeping area (m^2)
V_N	rated wind speed (m/s)
V_r	wind speed (m/s)
P_{wr}	rated wind turbine power output (kW)
V_i	cut-in wind speed (m/s)
V_c	cut-off wind speed (m/s)
NPV	net present value
PV	present value
m	project life period (years)
r	interest rate or discount rate
n	time in years before the future cash flow occurs
MILP	mixed integer linear program
TOU	time-of-use electricity tariff
Eskom	South African power utility company

and research are required to integrate these DREs optimally into energy-efficient household loads (e.g. heat pumps) to realize net-zero energy buildings [21], cost-effective billing and positive-energy buildings [22]. Therefore, future optimal energy-mixing will rely on the successful implementation of OC techniques [23–25].

The main problem of digital thermostat control systems used in HPWHs and some tank hot water heaters (geysers) on the market, is the dependency of its operation on temperature set-points only and does not change its assumed operating state between the intervals. Digital thermostat actuation occurs upon hitting the lower/upper set-point, which prolongs the operation time and consumes lots of energy. This control system is unable to optimally control either demand prediction or load-shifting to avoid operation during peak time-of-use (TOU) electricity tariff periods, that could save energy and cost. Most geysers in South Africa are fitted with a thermostat control system actuating only every lapse of thermostat dead-band interval below the set-point, operating continuously even in periods when there is no demand for hot water. Moreover, this hot water generating equipment accounting for 23.60% energy consumption in the building is rarely integrated into DREs.

Therefore, this paper proposes a first attempt at optimal control system application in HPWHs that is superior to digital thermostat control limitations. A further novelty is in the successful optimal integration of the DREs, such as wind into the supply of heat pumps, which has not yet been explored in literature. This DRE-HPWH model meets both the technical and operational constraints, deals with excess energy feed-in and provides the desired hot water temperature optimally under the TOU tariff. In comparison to the digital thermostat control system, this paper's OC technology can effectively predict within the control horizon with known hot water demand, an optimal hot water temperature without necessarily reaching the set-points. This in turn minimizes the energy required to raise the water temperature till set-point. This model has the potential to achieve practical net-zero energy building with cost-effective consumption. An addition contribution is that unlike many previous works that evaluated the techno-economic benefit [26–32], i.e., the objective functions are performances over a year, or multiple years, this paper proposes operational performances that are evaluated over a much shorter period, such as a day, 24 h. A short period enables end-users to monitor their daily energy usage rather than accumulative annual totals effectively. The daily savings eventually accumulate into savings over weeks, months, seasons and years. The end-user effectively assesses and can understand energy consumption trends and its cost implications on a daily basis. This is a major difference in this paper.

This paper is structured as follows: Sections 2 and 3 present the mathematical model formulation and Section 4 the simulation results and discussion. The last part, Section 5, is the conclusion.

2. Mathematical model formulation

2.1. Schematic model layout

The optimal switching strategy schematic diagram of the heat pump shown in Fig. 1 comprises the wind generator $P_w(t)$, PV modules $P_{pv}(t)$, grid $P_g(t)$ and an air-sourced heat pump with tank-wrapped condenser $P_{hp}(t)$. The switch $u(t)$ controls the power supply to the HPWH. The excess renewable power is fed into the grid. The grid power $P_g(t)$ accepts power from renewable power sources as well as it supplements the heat pump whenever their combined output fails to meet the demand.

The TOU electricity tariff is one of the important control parameters in the optimal switching strategy of the HPWH, especially in the peak period. $T(t)$ is the state variable, viz the temperature of the water inside the storage tank. The hot water demand $W_D(t)$ is the flow rate in liters/hour taken from the case study. The desired hot water temperature is predetermined at between T_{low} and T_{up}, which are the lower and upper temperature set-point respectively. However, these limits may vary from one individual to another. The control variables in this paper are the grid power $P_g(t)$ and heat pump supply switch $u(t)$.

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