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Optimal power dispatch of a grid tied-battery-photovoltaic system supplying heat pump water heaters ☆

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ABSTRACT

The aim of this paper is to develop an optimal scheduling strategy model for a grid-tied photovoltaic (PV) system to power a heat pump water heater (HPWH). The system is composed of PV modules that are grid-tied and a backup battery. The PV is capable of supplying power simultaneously to the HPWH and domestic load, whilst the grid and the battery are complementary sources. The objective function of this model is energy cost. The time-of-use (TOU) electricity tariff is taken into account in the optimal scheduling model. The control variables are the power flows within the branches of the system. The optimal control strategy of this grid-tied PV system can be implemented to reduce the energy cost while meeting the technical and operational constraints. This model has shown to have more economic benefits than solar thermal heaters, because of the possibility to turn the dwelling into net-zero energy or positive-energy buildings with the attractiveness of the feed-in tariff. A case study is done based on 3 × 16 kW HPWH installed at a Pretoria hotel in South Africa. Simulations are run for a year on selected seasonal date using the actual HPWH demand. The optimal control results show how the battery status of charge and TOU affect the power scheduling strategy of the HPWH. The energy and cost savings are presented in this paper as well.

1. Introduction

Heat pump water heaters (HPWH) have gained wide usage [1] in offering economical means of heat recovery from the environment for industrial and domestic applications. The most predominant usage [2,3] of the HPWH is for water and space heating. Heat pumps have low energy consumption, approximately two thirds [4] less than resistive element water heaters owing to its coefficient of performance (COP). Hawlader et al. [5] developed a detailed mathematical model for most of the parameters of the heat pump system. Research work to improve the technical and operational efficiency of HPWH has been extensively presented in [6–10]. While Yin et al. [11] presented a novel design of photovoltaic (PV)/thermal energy for an energy-efficiency building, various authors [12–15] looked into different PV/thermal energy design configurations and optimisation of the COP of the HPWH to achieve the required thermal comfort, both for water and space heating. However technological challenges, as mentioned by Chua et al. [1] on initial costs, system designing and integration of the heat pumps still exit. In this research paper, the heat pump is used in demand side management (DSM) as an efficient means of providing the thermal energy requirements of the building.

The integration of distributed renewable energy sources (DRE) into buildings provides huge potential in overall energy saving and management. These DRE can either be on/off site powering the entire building (zero energy buildings) or grid connected which are referred to as net-zero energy buildings (NZEBs). The energy consumed in buildings [16,17] accounts for 40% of global energy production. Therefore, most countries are encouraging and implementing regulatory measures at national level [18] to achieve NZEBs. Most researchers [19–21] have provided various methodologies and approaches for calculation of NZEBs. These formulations and methodologies, however, lead to different interpretation of energy savings in the building. Marszal et al. [18] pointed out that a practical integration of DRE with the grid to achieve the NZEBs is still a big challenge.

The hybrid photovoltaic (PV) system in [22] presented a model for load shifting and maximum demand control using the HPWH as the major correction equipment. Several renewable hybrid system designs to power small loads in urban and rural communities are presented in [23–27] where the authors outlined the need for optimal designing, sizing and control. The optimisation and maximum

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Nomenclature

P_i	control variable, which is the power in the *i*-th branch (kW)
"*min*" and "*max*"	minimum and maximum of the variable
R	South African Rands (ZAR)
p	TOU electricity price (R/kW h)
N	total number of sampling intervals
t_s and k	sampling time (hour) and *k*th sampling interval
ω	weighting factor
p_c	photovoltaic feed-in tariff (R/kW h)
P_{hp}	heat pump water heater power demand (kW)
COP	coefficient of performance
P_{dl}	domestic appliances power demand (kW)
P_{pv}	photovoltaic power output (kW)
$B_c(t)$	battery capacity at every given time *t* in (kW h)
η_c	battery charging efficiency
η_d	battery discharging efficiency
$B_c(0)$	initial status of charge of the battery
SOE	battery status of energy (kW h)
B_c^{max}	maximum battery rated capacity in (A h)
η_i	inverter efficiency
NERSA	National Energy Regulator of South Africa
REFIT	Renewable Energy Feed-in Tariff for South Africa
REPA	Renewable Energy Purchasing Agency
MINLP	Mixed Integer Nonlinear Program

power tracking of solar PV are intensively explained in [28–30]. The optimal energy scheduling for a practical application in NZEBs still seems infeasible owing to constraints on technology, integration and operations, as mentioned in [18]. Most of the work in finding solutions for NZEBs at building design stage, carbon emissions and energy balance was done by [31,32].

Despite all the above success in optimal designs and control, little research has been done on a grid-tied PV system to power HPWH and they remain uneconomical [4] in most developing countries (e.g., South Africa), with only 16% market penetration. Nevertheless, nowadays heat pumps are slowly becoming attractive for usage in hot water generation and DSM because of success in design and system integration, which is lowering the initial costs. There is still low application of renewable energy such as biomass, wind and solar to power energy-efficient loads such as HPWHs. The proper integration of these sources and using HPWH could reduce the power utility's maximum demand and improve the security of the supply. Most countries at policy level are beginning to introduce attractive feed-in and rebate systems for using greener energy and energy-efficient load like heat pumps. These policies encourage building owner to turn their dwelling into zero/positive energy buildings. Some work has been done in this regard, Ikegami et al. [33] attempted to develop an optimal control (OC) model on an ideal HPWH for using it as a DSM correction tool.

However, this paper reports on a first attempt to design a greener, practical and economically attractive optimal control model for a grid-tied PV system [34] that considers the time-of-use (TOU) electricity tariff to supply the HPWH. In this model the battery is not charged by the PV as per usual case, instead it is being used as a storage of cheaper-to-purchase (off-peak) grid energy and make it available during peak demand. The model present an optimal control breakthrough in the integration of renewable resources to power the HPWH and the possibility of turning dwelling into energy/cost-positive building. The other contribution is the application of Mixed Integer Non-Linear Programming (MINLP) to this complex nonlinear engineering problem. The scheduling strategy of our model can be adopted by building owners intending to achieve net-zero or positive-energy buildings. It provides a practical model for energy savings through integration of DRE to the grid, with the battery being charged by the grid during off-peak in order to minimise cost. The OC used the cheaper stored energy and the PV to power the HPWH whenever sufficient, the excess PV power was sold to the grid. The feed-in of PV energy to the grid could as well qualify the building owner to the prevailing rebate and incentives on renewable energy trade-off.

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

2. Mathematical formulation

2.1. Schematic model layout

The optimal control (OC) strategy schematic layout in Fig. 1 consist of 5 sub-models: the power utility grid 230/400V, PV modules with grid-interactive inverter, battery with inverter/charger, heat pump water heater (HPWH) and the domestic load. The grid can supply power $P_1(t)$ directly through a switch $u_1(t)$ the HPWH, while $P_2(t)$ is for charging the battery and $P_5(t)$ supplies the domestic load. The battery is used to store off-peak cheaper energy from the grid through $P_2(t)$, this off-peak stored energy is made available during peak demand to supplement the loads. The battery supplies $P_3(t)$, $P_4(t)$ to the HPWH and domestic load respectively. The PV modules can supply power to all the loads and at the same time feed-into the grid, $P_7(t)$ supplies the HPWH, $P_6(t)$ supplies the domestic load and $P_8(t)$ is the excess power from the PV which is sold to the grid. The proposed model is controlled by an energy management systems, which are not shown in the schematic layout. The power flows $P_1(t)$, $P_2(t)$, $P_3(t)$, $P_4(t)$, $P_5(t)$, $P_6(t)$, $P_7(t)$, $P_8(t)$ and the switch $u_1(t)$ in Fig. 1 are the control variables in this model.

Here the grid act as the excess PV power storage system, unlike using the PV power to charge the battery. The selling of PV power to the grid attracts rebates and other incentives in most countries in addition to the revenue generation. The battery is charged during the cheapest TOU tariff and make usage of this cheaper-to-buy stored energy during the peak demand. The weighting factor was incorporated in the objective function as factor for selling of excess PV power to the grid, based on the desired effects of each client. The formulation of optimal control of the HPWH was achieved using the operation constraints and objective function.

2.2. Sub-models

1. *Heat pump*
   The heat pump is modelled as a fixed load at a discrete time interval with respect to the power demand. The power demand of the heat pump is taken to be proportional to the thermal load requirements and inversely proportion to its COP. Though in [5] mathematical model of heat pump is presented, however, in this study the HPWH is modelled as a fixed load and regarded as an input data based on annual demand profile taken from a case study in South Africa. The grid can supply $P_1(k)$ to the HPWH direct through a switch $u_1(k)$, this supply route has a continuous and binary variable which is a nonlinear constraint. The HPWH is mainly supplied by the solar PV $P_7(k)$ and battery $P_3(k)$ whenever available. In this paper, for simplicity we denoted $P_i(k)t_s = P_i(k)$, with $i = 1,\dots,9$ being the number of