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Optimal power control of grid tied PV-battery-diesel system powering heat pump water heaters

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Abstract

This paper develops an optimal control strategy for power dispatch of the grid tied photovoltaic (PV) - battery-diesel system to power heat pump water heaters (HPWH). The system comprises of the PV modules, grid, battery, HPWH, diesel generator (DG) and other domestic appliances. The PV can simultaneously feed-in the excess power to the grid and supply the loads. The battery is used as storage of cheaper-to-buy off peak grid energy dependent on the time-of-use (TOU) electricity tariff whilst the DG is a backup power source. The objective function of model is to minimize energy and fuel cost while maximizing PV energy trade-off for incentives. The TOU is an important control parameter in the model. The power flows from each source are the control variables. The optimal control showed a great potential for the realization of a practical net zero-energy building and as well as for demand side management, since the model meets both technical and operational constraints. A case study is done based on 3x16kW HPWH installed at Pretoria hotel in South Africa. Simulations run over year on selected seasonal dates using the actual measured demand of the HPWH. The optimal control problem is solved using mixed integer nonlinear program and the results show how TOU affects the power dispatch to the HPWH. The energy and cost savings are presented in this paper.

Keywords: Heat pump water heater; Optimal control; Photovoltaic; Net zero-energy building; Diesel generator; Mixed integer nonlinear program

1. Introduction

The optimal sizing and integration of the heat pump water heaters (HPWH) with other sources of energy, such as solar thermal collectors [1] have contributed to the improvement the heat pumps coefficient of performance (COP). The application of HPWH for space and water heating is on the rise

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[2] owing to the advances in the HPWH researches. The initial investment cost in most developing countries are still uneconomical due to various technological challenges, for example in South Africa the market penetration of HPWH is 16%[3]. HPWH consumes one unit of electrical energy to produce three units of thermal energy when compared to the storage tank water heaters (geysers) which uses one unit of electrical energy to generate one unit of thermal energy. In order to achieve the net zero-energy building and to effectively integrate the distributed energy resources (DRE), there is need to increase the application of energy efficient equipment such as HPWHs.

There have been efforts by various authors [4] [5] [6] [7] to design and evaluate DREs systems. Despite these successes, a practical integration of the DREs in buildings to realize net zero-energy still remains a challenge as mentioned in [8] and [9]. The major problems lie on optimal control and sizing many have employed software such as HOMER to simulate these systems. However, there is few research in the designing of optimal control strategy for higher control/supervisory level and real time control techniques in dynamic scheduling. In [10] attempts on ideal model for optimal control of a hybrid PV system to power HPWH for DSM are presented. In our previous researches [11] and [12] we give a practical optimal control strategy to power HPWHs with DREs without a battery. This paper is a continuation of our previous works and the contribution of this paper are: inclusive of the new battery usage model for the storage of cheaper-to-purchase off-peak grid energy and application of mixed nonlinear program for this optimal control problem in order to achieve a net zero-energy building.

This paper is structured as follows: Section 2 is the mathematical model while Section 3 comprises simulation results and conclusion.

Nomenclature

P_i	Control variables which are the power flow in *i-th* branch of the hybrid system
$p(t)$	Electricity buying price [R/kWh] based on TOU tariff.
$p_s(t)$	PV feed-in tariff [R/kWh].
C_f	Fuel cost [Rands/litre]
SOE	Battery status of energy [kWh]
B_c	Battery capacity [kW]
$P_{hp,j}$	Power consumption of the heat pump during hour t
$P_{ld,j}$	Power consumption of the domestic load during hour t

2. **Mathematical model formulation**

The optimal control (OC) strategy schematic layout in Fig.1 consist of the utility power grid, PV modules, battery, diesel generator (DG), HPWH and domestic load. The grid can supply power $P_1(t)$ directly through a switch $u_1(t)$ to the HPWH, while $P_2(t)$ is for charging the battery and P_3 (t) supplies the domestic load. The battery is used to store off-peak cheaper energy from the grid; this off-peak stored energy is made available during peak demand to supplement the HPWH. The battery supplies $P_7(t)$ to the

HPWH. The PV modules can supply power to all the loads and at the same time feed into the grid, $P_5(t)$ supplies the HPWH, P_6 (t) supplies the domestic load and P_4 (t) is the excess power from the PV which is sold to the grid.

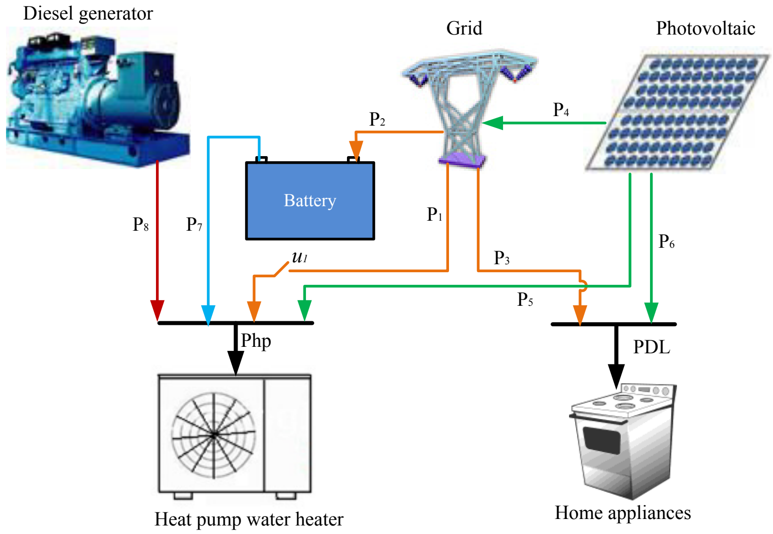

Fig.1. Schematic layout of power flows

In this model, the excess PV energy is sold to the grid, which attracts incentives on renewable energy trade-off in addition to the income generation. In contrast to most battery model found in literature, this paper proposes a new battery connection model which is charged using the cheaper-to-buy off-peak energy and makes it available in peak demand periods. However, the selling of excess PV power to the grid is weighted in the objective function and is dependent on the desired effects of the individual customer.

3. **Objective function**

The objective function is expressed in a discrete-time domain to minimise energy and fuel cost while maximising the solar energy sales to the grid. The battery was deliberately undersized to store just enough cheaper-to-buy off peak grid energy and make it available to the HPWH during peak periods. The DG acts as a backup power during peak demand or load shedding when solar power is unavailable. The weighting factor ω_k is adjusted based on the desired effects (i.e. savings on energy) of the customer.

$$\min J = t_s\left(\omega_1 \sum_{j=1}^{N} p(t)\big(P_1(j)+P_2(j)+P_3(j)\big)+\omega_2 \sum_{j=1}^{N} Cf(aP_8^2(j)+bP_8(j)+c)-\omega_3 p_s \sum_{j=1}^{N} P_4(j)\right), \qquad (1)$$

where; $p(t)$ is the time of use electricity tariff in [R/kWh], C_f is the fuel cost of the DG [R/litre], p_s is feed-in tariff of renewable energy from solar PV in [R/kWh], t_s is the sampling time (h), $P_i(j)$ are the power flows at j^{th} sampling interval, $i=1,2,...8$ with i being the power flow within the i^{th} branch of the hybrid system, $N=24$ is the sampling interval and ω_k is a weighting factor where $k=1,2,...3$, a and b

are the generator coefficient of fuel consumption. For simplicity we denoted $t_s P_i(j) = P_i(j)$. η_c And η_d are the battery charging and discharging efficiency respectively.

3.1 Control variables and constraints

The control variables: $u_1(j)$, $P_1(j)$, $P_2(j)$ $P_3(j)$, $P_4(j)$, $P_5(j)$, $P_6(j)$ $P_7(j)$ $P_8(j)$ and a state variables $SOE(j)$ $(1 \le j \le N)$

$$u_1(j)P_1(j) + P_5(j) + P_7(j) + P_8(j) = P_{hp}(j)\,, \tag{2}$$

$$P_3(j) + P_6(j) = P_{dl}(j)\,, \tag{3}$$

$$0 \le P_4(j) + P_5(j) + P_6(j) \le P_{PV}(j)\,, \tag{4}$$

$$0 \le P_8(j) \le P_{DG}\,, \tag{5}$$

$$B_c(j) = B_c(0) + \eta_c \sum_{j=1}^{N} P_2(j) - \eta_d \sum_{j=1}^{N} P_7(j)\,, \tag{6}$$

$$P_i^{\min} \le P_i \le P_i^{\max}\,, \tag{7}$$

The objective function is given by equation (1) and the problem is a nonlinear optimal switching control, therefore, the *mixed integer nonlinear program* (MINLP) function in MATLAB *Opti* package was used.

3.2 Case study

A case study was done based on 3 x16kW HPWH installed at the Pretoria Hotel in South Africa. The energy consumption of the HPWH was measured at hourly intervals for a year. The input data on the PV power generation were adopted from the measured data from our on-going research [4] on a tilted roof-top mounted PV modules. The diesel generator power output is 9.7 kW and the battery capacity is 3x165A-h . In this study, the recent Eskom Megaflex Active Energy-TOU tariff was used

4. Results and discussion

The optimal control results in Fig.2 shows the power scheduling to the HPWH and the domestic loads for the month of December only from the case study. The TOU electricity tariff legend in Fig.2 (c) applies to all figures in this paper. Four months were selected along the year from the case study to represent each prevailing season in South Africa which depicts the actual thermal requirement from the HPWH, the result are shown in table 1. In Fig.2 (a), the battery P_7 supplied most of the load demand from midnight to the beginning of morning peak period. The direct grid supply P_1 in Fig.2 (b) to the HPWH only came in for few hours after midnight and at the end of evening standard TOU period. The optimal switching avoided the peak period in order to minimize the usage of expensive energy from the grid instead the strategy opted for the cheaper-to-buy stored energy in the battery.

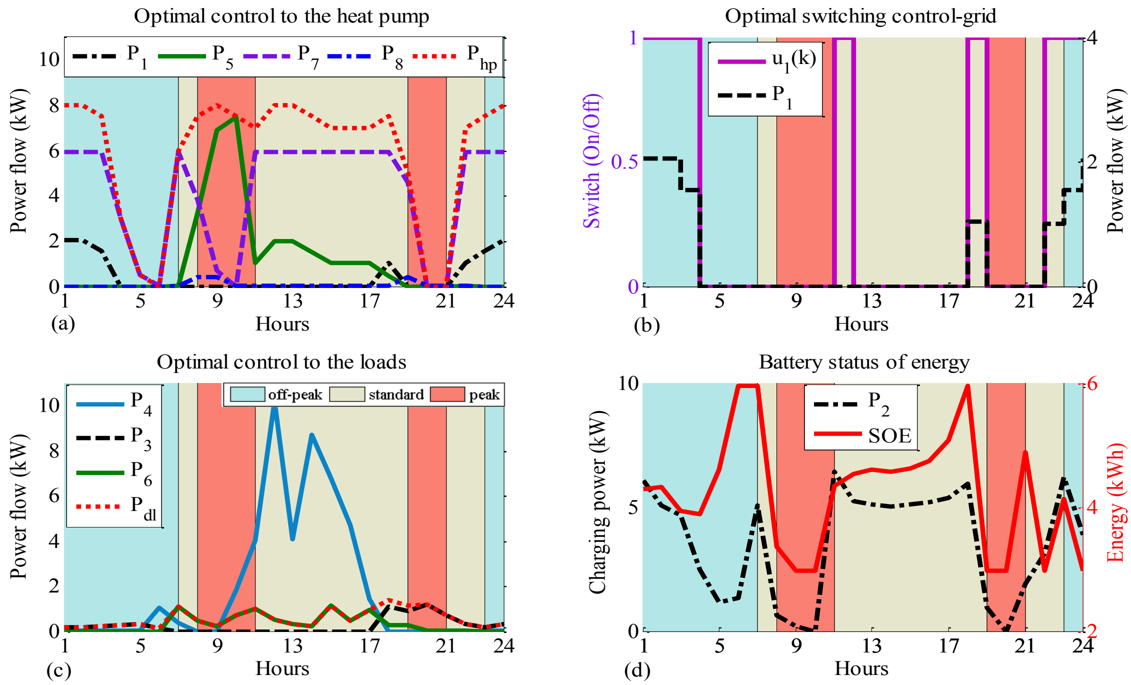

Fig.2 (a) HPWH; (b) OC from the grid to HPWH; (c) domestic load and solar sales ; (d) Battery SOE

It is observed in Fig.2 (b) and (d) that as peak period approached there was no battery charging activity, P_7 declined and at the same time the battery was not being charged . P_2 sharply declined avoiding storage of expensive energy, subsequently the battery state of energy dropped in the peak period. Though, it's observed that the grid started charging the battery in the standard TOU tariff which is relatively cheaper energy. Whilst much of the peak demand was met by the PV supply P_5, with the excess power in Fig.2(c) P_4 being sold to the grid. The DG in Fig.2 (a) P_8 came in to assist the PV only during the morning and evening peak period. The weighting factor was set in such a way to have maximum benefit to the building owner. It's observed that the load uses much of the cheaper stored grid energy and solar energy.

The daily energy and cost savings are present in table 1. The baseline line cost is the prevailing situation in the case study where the grid meets all the demand. However, our model presents a huge energy saving as well as cost saving. Strictly speaking the model is cost-positive in certain months because the revenue from the solar energy sales can offset the energy bills due to the utility (e.g. in December). The energy saved in this model is the undelivered (not-served) energy to the load from the grid. The maximum cost saving were in the month of March with 68.09%.

The economical analysis was done with the following assumptions:

• A discount factor of 5.9% was used to reflect the time value of money and the 5.9% is indicative of the inflation rate in South Africa

• Solar sales and the cost savings are based on the average of all the months tested in the case study, and then the costs/revenue of that day were annualized to reflect an average amount per annum

• It's assumed that the solar sales, cost savings, operations and maintenance costs will remain constant throughout the period. Though it is expected that there would be an increase in all these factors, it cannot be reliably estimated at this time. Increases in solar sales and costs would reduce the payback period. The detailed economical analysis of payback period is shown in the Appendix A Table 2 and Table 3.

Table1. Daily optimal energy and cost savings

Month	Baseline cost (R/day)	Optimal cost (R/day)	Solar sales (R/day)	Baseline energy (kWh)	Energy saved (kWh)	Cost savings (%)
December	140.52	62.79	170.02	155.95	80.01	55.32
March	113.94	36.36	251.22	96.76	98.56	68.09
June	253.97	129.48	13.96	274.85	95.69	49.02
August	190.19	79.33	174.32	184.11	114.06	58.29

5. **Conclusion**

The model has a potential to save energy up to 114.06 *kWh* daily with a maximum cost saving of 68.09%. The optimal control can be adopted to realize practical net zero-energy buildings in urban and rural communities. The benefit using the battery as storage of cheaper-to-buy grid energy in a dynamics pricing system contributed further to the reduction of energy, unlike the conventional models where the battery stores PV energy. The model enables a building owner to tradeoff the solar energy in return for incentives which are common policy in most countries which promotes the generation of renewable energy. The payback period is 5 years 9 months owing to huge solar sales.

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APPENDIX A – ECONOMICAL ANALYSIS AND PAYBACK PERIOD

Table 2. Discounted payback period

Years	0	1	2	3	4	5	6	7	8
Diesel generator	(45,000.00)								
Solar modules	(115,000.00)								
Battery	(8,760.00)								
Controllers	(35,000.00)								
Inverters and accesories	(45,484.00)								
Installation cost	(25,000.00)								
Maintainance cost		(10,000.00)	(10,000.00)	(10,000.00)	(10,000.00)	(10,000.00)	(10,000.00)	(10,000.00)	(10,000.00)
Operation cost		(23,725.00)	(23,725.00)	(23,725.00)	(23,725.00)	(23,725.00)	(23,725.00)	(23,725.00)	(23,725.00)
Solar sales		55,618.70	55,618.70	55,618.70	55,618.70	55,618.70	55,618.70	55,618.70	55,618.70
Cost Savings		35,647.73	35,647.73	35,647.73	35,647.73	35,647.73	35,647.73	35,647.73	35,647.73
	(274,244.00)	57,541.43	57,541.43	57,541.43	57,541.43	57,541.43	57,541.43	57,541.43	57,541.43
Discount factor @ 5.9%	1	0.944287063	0.891678058	0.842000055	0.795089759	0.750792973	0.70896409	0.66946562	0.63216772
Discounted cashflows	(274,244.00)	54,335.62	51,308.43	48,449.88	45,750.60	43,201.70	40,794.80	38,522.01	36,375.83

Discounted Payback Period	Years	Discounted cashflows	Cumulative cashflows
	0	(274,244.00)	(274,244.00)
	1	54,335.62	(219,908.38)
	2	51,308.43	(168,599.95)
	3	48,449.88	(120,150.07)
	4	45,750.60	(74,399.47)
	5	43,201.70	(31,197.77)
	6	40,794.80	9,597.03
	7	38,522.01	48,119.04
	8	36,375.83	84,494.87
Payback is	5 years plus 9 months	9.176983393	

Table 3. Annualised baseline and optimal costs

	Baseline costs	Optimal	Solar sales	
	140.52	62.79	170.02	
	113.94	36.36	251.22	
	253.97	129.48	13.96	
	190.19	79.33	174.32	
Average	174.655	76.99	152.38	97.665 (Savings =Baseline cost-Optimal cost)
Annualised benefits			55,618.70	35647.725