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Utilisation of Excess Energy in the Sizing of Photovoltaic-Thermal System (PVT) using Design Space Approach

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Photovoltaic-thermal system (PVT) is a renewable energy based cogeneration system and it converts solar radiation simultaneously into thermal or electrical energy. The design space, a collection of all feasible system sizes, is developed based on the principles of Pinch Analysis to design isolated energy systems. The design space for a PVT system is governed by the electrical demand, the thermal demand, the load temperature of the thermal demand, and the boiling point of working fluid. However, it is observed that a PVT system generates excess electrical energy, especially during noon where the solar radiation is high. This excess energy can be used for some other useful work when battery is in danger of overcharging. In this paper, the impact of using of this battery excess energy on sizing of overall PVT system is presented. The comparative analysis of PVT system with the battery excess energy dumped into the storage tank or use of an auxiliary heater for the domestic hot water system are carried out in this paper. The analysis suggests that the supply of excess energy in auxiliary heater is beneficial.

1. Introduction

A photovoltaic-thermal hybrid system (PVT) is a renewable energy based cogeneration technology that utilizes solar energy to produce simultaneously low temperature heat and electricity. It is an integrated system formed by applying thermal absorber on back of photovoltaic cells to produce both electrical and thermal energy. It represents, in principle, one of the most efficient ways to use solar energy to meet simultaneously the thermal as well as the electrical energy demands. Many researchers have analysed performance of PVT system by experimenting various PVT panel configurations like channel type with parabolic reflector (Garg and Agarwal, 1995), sheet and tube type (Zondag et al., 2002), booster reflectors (Tripanagnostopoulos et al., 2002), two absorber type (Bakker et al., 2002), polymer channel absorber (Sandnes and Rekstad, 2002), single-crystalline silicon with flat solar radiation reflectors (Kostić et al., 2010), a single glazed flat plate PVT with heat exchanger (Dupeyrat et al., 2011), unglazed box type prototype PVT collector (Thakare et al., 2013), etc. Integration of photovoltaic power for running a heat and water system was presented by Martínez-Patiño et al. (2012).

To improve system performance, most of the earlier investigations directed towards maintaining an optimum collector flow rate or developing improved PVT collector design. As solar radiation becomes high during noon, it is observed that a PVT system generates excess electrical energy. It results in overcharging of battery. To avoid this, excess electrical energy needs to be dumped in some dumped load. Hence, when the battery is in danger of overcharging, it is possible to use this excess energy for some other useful work. The primary objective of this paper is to present analysis of PVT system sizing with this excess available energy dumped into storage tank or utilized through an auxiliary heater. No such study is reported in the literature.

A sizing technique, called design space approach, is selected to analyse the impact of battery excess energy on PVT sizing. The design space approach, developed based on the principles of pinch analysis, was initially applied to sizing solar water heating (SWH) system (Kulkarni et al., 2007), pressurized water systems (Kulkarni et al., 2008) and impact of water replenishments on SWH system (Kulkarni et al., 2009). Afterwards, Arun et al. (2008) presented sizing of PV systems and uncertainties associated with solar insolation (Arun et al., 2009a) and demand (Arun et al., 2009b). The design space approach was also

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extended for sizing of wind-battery systems (Roy et al., 2009) and its assessment considering resource uncertainty (Roy et al., 2010). The design space technique also applied for isolated renewable hybrid system by Sreeraj et al. (2010). In this paper, the design space approach for sizing of a PVT system (Krishna Priya et al., 2013) is extended to analyze impact of excess energy on PVT system sizing.

2. Mathematical model

The schematic of a PVT based cogeneration system is shown in Figure 1. The component of PVT system includes PVT collector, storage tank, battery bank, charge controller and inverter. A solar energy absorbed by PVT panel supplies both electrical and thermal energy. The electrical subsystem converts solar radiation into electrical power with the help of PV. It then converts the generated DC power to AC and supplies the electrical load. A battery serves the purpose of electrical storage. It handles any discrepancy between electricity generation and demand. A charge controller takes care of battery limits during over charging and deep discharging. The thermal subsystem of the system has a well insulated storage tank. It is used to serve the thermal demand at desired load temperature.

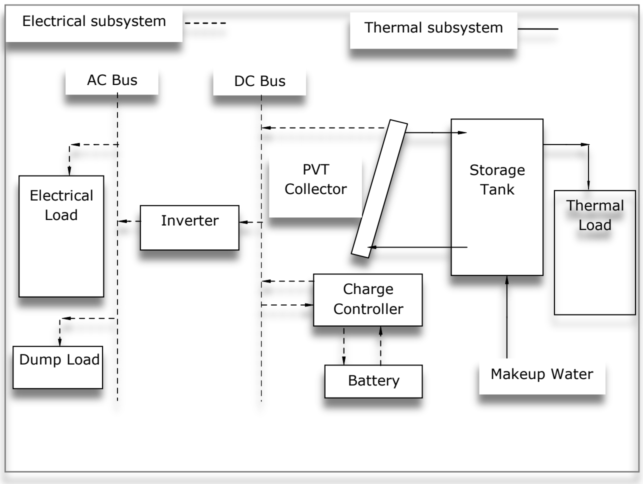

Figure 1: Layout of PVT based cogeneration system

PVT panel model, proposed by Zondag et al. (2002), is adopted in this paper. This mathematical model was developed for a PVT panel made up of conventional PV laminate of multi-crystalline silicone cell and absorber of a conventional sheet and tube type glaze collector. The model predicts basic thermal energy (Q_u) generation as:

$$Q_u = A_{pv} F_r((\tau_\alpha - \tau\eta_{el})I_T - U_L(T_{sti} - T_a)) \quad (1)$$

where A_{pv} is the area of PVT collector, η_{el} the electrical efficiency of the cells, F_r is the heat removal factor of the collector, and U_L is the loss coefficient of the collector. T_{sti} and T_a are the initial storage tank and ambient temperatures respectively. τ_α and τ represent the transmission absorption factor and transmission factor of glass and I_T is the solar radiation incident on the panel. The mean plate temperature (T_{pm}) was corrected using the relations given in Eq(2). T_{pm} is a function of useful thermal output, collector area, heat transfer coefficient across cell and absorber (h_{ca}) and mass flow rate ($\dot{m}$). C_p is the specific heat capacity of water. Hourly useful thermal output and electrical efficiency of the PVT collector are determined as the T_{pm} converged to a constant value.

$$T_{pm} = T_{in} + \frac{Q_u}{2\dot{m}C_p} + \frac{Q_u}{h_{ca}A_{pv}} \quad 2.1\ (2)$$

The electrical efficiency η_{el} is computed using the following expression where β is the cell efficiency temperature coefficient.

$$\eta_{el} = \eta_{ref}(1 - \beta(T - T_{ref})) \quad (3)$$

By multiplying the value of the electrical efficiency with insolation and panel area, the electrical output can be obtained. The model was further used to analyze the PVT system behaviour for given demands.

3. Generation of design space

Being renewable cogeneration system, PVT is having two subsystems, namely the electrical and thermal subsystems (Figure 1). The change in energy stored in the thermal storage tank is the difference between energy generated by the collector and the energy supplied to the load as well as the storage losses. The energy balance for the thermal subsystem can be formulated as:

$$\rho C_P V_{st} \frac{dT_{st}}{dt} = Q_u^+ + q_{ls} - q_{stl} \tag{4}$$

To obtain the final storage temperature at the end of a time step, Eq(4) can be solved. In order to find Q_u, the model explained earlier is used. The '+' sign in the Eq(4) indicates that hot water from collector array enters the storage tank for positive solar useful heat gain. The demand met by solar energy (q_{ls}) to meet the load at a mass flow rate $\dot{m}_{st}$ is assumed to be constant over a time step *t* and is calculated based on the initial temperature of the storage tank (T_{st}). Storage heat losses (q_{stl}) and energy drawn from the storage tank to meet the load are estimated using the following equations:

$$q_{ls} = \dot{m}_{st} C_p (T_{st} - T_a) \tag{5}$$

$$q_{stl} = U_{st} A_{st} (T_{st} - T_a) \tag{6}$$

U_{st} is the storage loss coefficient of the storage tank. The surface area (A_{st}) of the cylindrical storage tank is assumed to be related to the storage volume (V_{st}) by following relation with equal height to diameter ratio (Kulkarni et al., 2009).

$$A_{st} = 5.54 (V_{st})^{2/3} \tag{7}$$

Substituting Eqs (1), (5), and (6) in Eq(8), the final temperature of the storage tank may be expressed as.

$$T_{stf} = \left\{ T_{sti} - \left(Q_u^+ + q_{ls} - q_{stl} \right) \frac{\Delta t}{\rho C_P V_{st}} \right\} \tag{8}$$

The transient behaviour of temperature profile is neglected to assure appropriate design of the system. It is assumed that the temperature profile reaches a steady-state condition. This implies that the net gain or loss of the stored thermal energy for the storage tank over a given time horizon of analysis is zero.

The methodology of design space generation for PVT system (Krishna Priya et al., 2013) is presented here in brief for domestic hot water system. For a given demands, by varying the collector area and the storage volume, design space for the thermal subsystem can be obtained. For a PVT collector, Eq(8) predicts the temperature profile of the storage tank as a function of collector area (A_{pv}) and storage volume (V_{st}). To meet the load demands constraints imposed includes the storage tank (T_{st}) should never fall below the load temperature (T_L), 'T_{st}' must remain below the saturated temperature (T_{sat}) and due to a steady state assumption, 'T_{st}' at beginning and end of the cycle needs to be same.

An illustrative example of PVT system sizing for one day using design space approach is presented. The PVT system considered is unity solar fraction system as no auxiliary heater is used. The solar insolation and ambient temperature data for March 15 for a rural location near Mumbai (19º17'N, 72º48'E) has been used for calculations (Krishna Priya et al., 2013). The electrical load pattern is adapted from Arun et al. (2008) and the thermal load pattern is adapted from Pillai and Banerjee (2007). The thermal load is 180 L/d at 60 °C. The parameter values used for the calculation of thermal system are referred from Zondag et al. (2002). It is seen that for any feasible collector area, there is a maximum and a minimum thermal storage volumes. It is due to the fact that for unity solar fraction system, the storage tank temperature should not go below the load temperature. Also, for a given collector area, the minimum volume is searched such that the temperature profile always remains below the maximum allowed saturation temperature limit.

For the electrical subsystem, the net electrical energy generated is proportional to the rate of change of energy stored (dQ_B/dt) in the battery bank. The change in storage energy level can be represented as the difference between the electrical energy generated by the PVT collector (P), the energy required by the load (D) and the excess energy (P_{du}) which is to be dumped at the instant of battery overcharging. The net energy flow across the electrical storage is accounted considering the efficiencies for the power conversion during charging and discharging processes. Hence, the energy balance on the electrical subsystem can be formulated as

$$\frac{dQ_B}{dt} = \left(P(t) - P_{du}(t) - D(t)\right) \cdot f(t) \tag{9}$$

where *f(t)* is the charging or discharging efficiency of the battery.
The constraint in electrical subsystem includes, the battery returns to its initial state of charge at the end of each cycle and the battery energy level is always a positive. Then the battery rating (B_r) is the maximum amount of energy that the battery has to store or supply. So, Battery rating is calculated as,

$$B_r = max \frac{Q_B(t)}{DOD} \tag{10}$$

where DOD is the depth of discharge of the battery.
The sizing curve on the thermal side is drawn by considering load temperature as well as limiting storage temperature constraint. The size of electrical storage can be found using any generic search method. The constraints of positive battery energy level and steady state operation are to be met for the energy balance Eq (9) of the electrical side. The values used for electrical subsystem calculation include the reference cell efficiency of 9.7 % at 25 °C and battery charging and discharging efficiency of 86 %. The DOD of battery is assumed to be of 50 %. The feasible design points for the PVT system can be defined by collector area, storage volume and battery size. The complete design space for a base case PVT system with thermal and electrical storage is given in Figure 2. In Figure 2, for the particular collector area, the curves 'Vst-max' and 'Vst-min' represent the maximum and the minimum storage volume require to satisfy the load temperature constraints for the given thermal demand. The 'Vst-100' line represent the storage volume require to meet the saturation temperature constrain for the particular collector area. The electrical limits line in Figure 5 shows the PVT collector area and corresponding storage volume needed to satisfy both electrical and thermal demands. The point 'a' in the figure shows the minimum storage volume requires 19 m^3 and corresponding collector area of 68 m^2 to supply the given thermal and electrical demands. The shaded portion in Figure 2 includes all possible designs of the system and may be called as the design space for unity solar fraction. A detailed illustration of design space approach for unity solar fraction PVT system for one day and annual performance has presented by Krishna Priya et al. (2013).

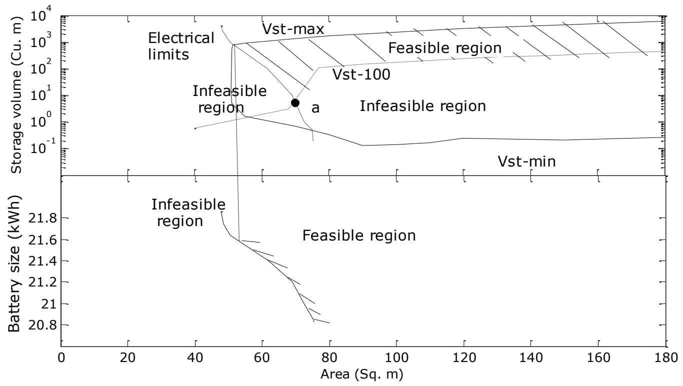

Figure 2: Design space for base case PVT system

4. Utilization of battery excess energy

The design space for a PVT system is governed by the electrical demand, the thermal demand, the load temperature of the thermal demand, and the boiling point of working fluid. However, it is observed that a PVT system generates excess electrical energy, especially during high solar radiation. This excess electrical energy needs to be dumped in some dumped load to restrict battery from overcharging. The excess energy can be utilised to satisfy thermal demand and reduce overall size of the system. Excess electrical energy can be used to heat the storage tank or as auxiliary heater before supplying hot water to the thermal load.

4.1 Excess electrical energy given to storage tank

To minimize the wastage due to dumped energy, this excess electrical energy may be used to heat water in the storage tank. The design space for such a system is discussed in this section. Addition of excess energy in storage tank increases the boundary of maximum storage volume. The minimum storage volume boundary has been lowered in this case. As the energy supplied has increased, the system can now better handle the fluctuations in temperature at lower volumes. It should also be noted that the boundary imposed by the boiling of water has also shifted up similar to the maximum storage volume boundary.

In electrical subsystem of PVT system, the boundary imposed by electrical load shifts to the right. It means the minimum area needed to meet the electrical load increases. This is due to increase in temperature of the supply water. It resulted in decrease in electrical efficiency of panel hence larger area for the panel is required to supply the same electrical load. The design space for battery excess energy added to storage tank is shown in Figure 3. The point ‘b’ in the figure shows the minimum storage volume requires 24 m^3 and corresponding collector area of 72 m^2. An increment of 26.32 % in storage volume and 5.88% in collector area are observed due to supply of excess energy to the storage tank. In this case, addition of excess energy in storage tank found to be ineffective, as for a given electrical and thermal load, both the minimum panel size and the minimum storage volume are increased.

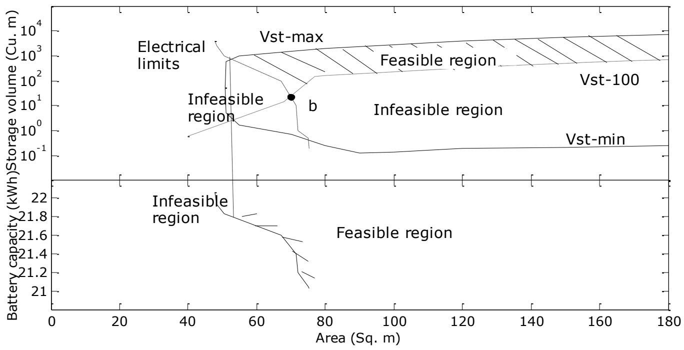

Figure 3: Design space when excess electrical energy of the PVT system is supplied to storage tank

4.2 Battery excess energy given to auxiliary heater

In this case, excess electrical energy, generated by the PVT panel, is supplied to an auxiliary heater. When the excess electrical energy is generated and it cannot be stored in the battery, auxiliary heater can utilise it heat water just before supplying it to the thermal load. Auxiliary heater can be used to meet the temperature requirement of the load and the storage tank temperature can be slightly lower. The maximum storage volume boundary obtained in this case is slightly lower than the boundary obtained when excess energy is added to the storage tank. As additional energy is not supplied to the storage tank, lower storage volume boundary remains same as the base case. It should also be noted that the boundary imposed by the boiling of water has also remained at original position similar to the minimum storage volume boundary. In electrical subsystem of PVT system, the boundary imposed by electrical load remains unchanged. It means the minimum area needed to meet the electrical load as same as in base case. This was due to less fluctuation in storage tank temperature as compare to excess energy given to the storage tank. The design space for such a system is shown in Figure 4. The point ‘c’ in the figure shows minimum storage volume requires 21 m^3 and corresponding collector area of 68 m^2. An increment of 10.52 % in storage volume was observed by giving excess energy to an auxiliary heater.

Conclusions

The methodology of design space approach for sizing of PVT system in view of utilization excess electrical energy generated during noon is presented in this paper. The comparative analysis is carried out for PVT system with the battery excess energy dumped into the storage tank and use of an auxiliary heater. Supply of excess energy in auxiliary heater found beneficial, as for a given electrical and thermal demand, the storage volume has now been lowered as compared to dumping of excess energy in storage tank. The option of battery excess energy supplied to auxiliary heater serves the thermal demand more efficiently. Present research is restricted to unity solar fraction system, i.e., entire load is met with solar energy only. The future research direction will be sizing of PVT system by varying solar fraction (through hybridization with grid) and selection of optimal size of auxiliary heater to meet the thermal demand.

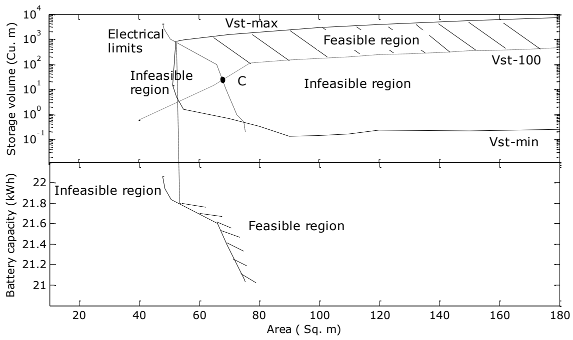

Figure 4: Design space when excess electrical energy is supplied to the auxiliary heater

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