Control-oriented model for air-based BIPV/T systems

A M Sigounis, E D Rounis, A K Athienitis and C Vallianos

Concordia University, 1455 De Maisonneuve Blvd. W., Montreal, Quebec, Canada

sigounisan@gmail.com, efstratios.rounis@gmail.com, aathieni@encs.concordia.ca, hvallianos@gmail.com

Abstract. This study presents the development of a control-oriented model for Building Integrated Photovoltaic Thermal (BIPV/T) systems. Model-based control strategies could optimize their coupled operation with the building Heating Ventilation and Air-Conditioning (HVAC) system and maximize the heat utilization. Two transient simulation models (1st order and 2nd order) are developed using Python, validated with experimental data and compared to each other. Finally, simulation results are presented where the range of possible outlet air temperatures for different mass flow rates are identified.

1. Introduction

BIPV/T systems are hybrid systems which generate useful heat in addition to electricity. By circulating a fluid under the PV surface, part of the normally waste heat can be recovered while simultaneously cooling the PV. Increased PV temperatures can lead to decreased electrical output and shorter life expectancy. [1] The main objective of this paper is the development of a transient control-oriented model for an air-based BIPV/T system which will be utilized to control the airflow within the channel through a variable speed fan.

There are multiple integration options with the building HVAC system, including, but not limited to, assisting an air-source heat pump (ASHP), enhancing the performance of a heat recovery ventilator (HRV) and preconditioning the fresh air supply [1]. A control algorithm is required to regulate the BIPV/T flow rate accordingly, depending on the supply air temperature and flow requirements, and the respective environmental conditions.

The vast majority of BIPV/T models follow a steady-state approach. Candanedo et al. [2] compared a steady-state and transient BIPV/T model, which considered the thermal capacity effects of the PV module. The transient model was found to follow the experimental results closely, without the extreme instantaneous fluctuations of the steady-state model. The damping effect of the thermal capacitance can be crucial for a control algorithm to provide stable operation during rapid environmental changes (wind gusts, instantaneous shading). To the authors’ best knowledge only a limited number of studies have focused on heat management of BIPV/T collectors. These studies used rule-based control strategies applied on generic steady-state models. The present study builds upon the work of Candanedo et al [2] introducing additionally the thermal capacitance of the materials comprising the rear side of the channel in the transient model. This model will be calibrated in real time and will enable model-predictive control of BIPV/T systems integrated with heat pumps and other HVAC systems so as to enhance energy efficiency by operating at an optimal flow rate that is a function of outdoor weather conditions, sensed outlet air temperature and actual system time constants.

2. Development of the model
2.1. Experimental set up

Two different transient models were developed, based on monitored data from a series of experiments carried out in the Concordia University Solar Simulator (Figure 1).

The Solar Simulator and Environmental Chamber (SSEC) is an indoor experimental facility consisting of a lamp field with a ventilated artificial sky, a linear variable speed fan which can replicate the wind effect and a test platform whereupon the test subjects are placed. [3] A BIPV/T prototype with channel dimensions 2.09m x 0.49m x 0.06m was tested. The top of the channel consists of polycrystalline cells incorporated in a 4mm glass with a packing factor of 85.5%. The rest of the area was covered by Polyethylene Terephthalate. The bottom of the channel consists of 51mm XPS insulation in between two aluminum sheets. Thermocouples were installed on the back side of the PV, middle of the channel and top and bottom of the insulation. The air flow rate, irradiation and air velocity on top of the channel were controlled in the experiments with ranges of (0.033–0.067 kg/s), (807–1058W/m²) and (1.53–3.2 m/s) respectively.

2.2. Mathematical models

The two models considered are shown in Figure 2. The models are identical except in one respect: The 2nd order model takes in to account the capacitance of the PV and the insulation while the 1st order model only considers the capacitance of the PV. In each time step, the models require the solution of the previous time step with a fully-explicit finite difference scheme. The temperatures of the surfaces (PV, insulation board) are assumed to be uniform inside the control volume and no edge effects are considered. The models were implemented in the Python programming language.

The parameters in the models were assigned their theoretical values derived from [2], [6]. The total thermal resistance of the PV and insulation are \( R_{pv}=0.004 \text{ m}^2\text{K}/\text{W} \) and \( R_{ins}=1.76 \text{ m}^2\text{K}/\text{W} \) respectively while the capacitances are \( C_{pv}=7578.5 \text{ J/m}^2\text{K} \) and \( C_{ins}=17502 \text{ J/m}^2\text{K} \). The expressions for wind-driven convective heat transfer coefficient and Nusselt number for the air channel were proposed by Palyvos [4] and Candanedo et al. [5] respectively. The combination of these coefficients has been found to accurately predict temperatures of the different surfaces of BIPV/T systems based on outdoor and full-scale system monitoring [1].

2.3. Comparison of the models

Table 1 demonstrates the mean absolute error (MAE) and the root means square error (RMSE) of the two models considered. The 2nd order model showed improved accuracy in terms of predicting the outlet temperature and its fluctuations without requiring more processing time. Figure 3 shows the measured and simulated (2nd order model) outlet temperature.

3. Simulation

A simulation was performed using the 2nd order model assuming a BIPV/T system with a 6.53m long

| Model      | MAE  | RMSE |
|------------|------|------|
| 1st order  | 0.413| 0.549|
| 2nd order  | 0.392| 0.519|
The analysis was realized using EnergyPlus weather data (epw file) for a cold sunny day in February in Montreal, Canada. The fan velocity within the channel varied in the range of 0.4 to 2.0 m/s. Figure 4 illustrates the different outlet temperatures obtained for different fan speeds (different mass flow rates). Higher mass flow rates lead to lower outlet temperatures but higher heat recovery. A maximum ΔT of 13.02°C was achieved at 1:00 pm at the lowest mass flow rate (0.031 kg/s). Determining the limitations of the system and its operating range is the basis of model-based control strategies.

4. Conclusion
This paper presented a brief description of the development of a control-oriented model for a BIPV/T system. Two transient models were developed and compared. The 2nd order model accurately followed monitored results and temperature fluctuations and shows great potential for implementation in model-based control. Finally, a simulation using the selected model was performed where the range of possible BIPV/T outlet temperatures for different mass flow rates are identified. Future steps of this research focus on implementing a Model Predictive Control (MPC) strategy with the developed model. The MPC strategy will determine the optimal use of the BIPV/T outlet air based on the needs of the house, the weather conditions and the BIPV/T operation range. Improved supply of fresh air can be achieved with the BIPV/T mitigating the additional required consumption while the energy flexibility of the building can improve as the gained heat is optimally managed.

Acknowledgements
This work was supported by a NSERC/Hydro Quebec Industrial Research Chair and a NSERC Masters scholarship.

References
[1] Rounis E D, Athienitis A and Stathopoulos T 2021 Review of air-based PV/T and BIPV/T systems - Performance and modelling. Renewable Energy 163 1729-53
[2] Candanedo L M, Athienitis A K, Candanedo J A, O’Brien W and Chen Y 2010 Transient and Steady State Models for Open-Loop Air-Based BIPV/T Systems. ASHRAE Transactions 116 600-12
[3] Tingting Y and Athienitis A 2014 A study of design options for a building integrated photovoltaic/thermal (BIPV/T) system with glazed air collector and multiple inlets. Solar Energy 104 82-92
[4] Palyvos J 2008 A survey of wind convection coefficient correlations for building envelope energy systems’ modeling. Applied Thermal Engineering 28 801–08
[5] Candanedo L M, Athienitis A and Park K-W 2011 Convective Heat Transfer Coefficients in a Building-Intergrated Photovoltaic/Thermal System. Solar Energy Engineering 133
[6] American Society of Heating, Refrigerating and Air-Conditioning Engineers 2017 2017 ASHRAE handbook: Fundamentals. Atlanta, GA: American Society of Heating, Refrigeration and Air-Conditioning Engineers.