MODELLING AND SIMULATION OF BUILDING ENERGY SYSTEMS USING INTELLIGENT TECHNIQUES

Ph.D. THESIS

by

V. S. K. V. HARISH

ALTERNATE HYDRO ENERGY CENTRE
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE-247667 (INDIA)

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ABSTRACT

Driven by the rising population, expanding economy and a quest for improved quality of life, energy consumption has increased manifold during last decade**.** This has led to an increased demand-supply gap of energy resulting in restricted supply of electricity to the consumers. Adequate regulatory as well as technical actions and measures are being adopted, to reduce this gap, both at the supply and demand side. Demand-side measures like developing energy efficient (EE) appliances and equipment, promoting energy conservation (EC) techniques, use of renewable energy sources, energy efficient building design and control as well as distributed generation are emerging as an effective solution to meet the demand growth and to mitigate the demand-supply gap.

End-use power consumption is categorized into residential, commercial, industrial, transportation, municipal and other service sectors. Despite of the fact that buildings account for 30% to 40% of the world's energy use, but have not been identified as a service sector in many countries. Thus, it is considerably difficult to gather information about building energy consumption. Different control techniques together with intelligent building technology are used to improve EE of buildings. Building energy control systems (BECS) are basic entities in building energy management for attaining energy efficiency and sustainability. Building energy systems (BESs) are defined as systems responsible for consumption of energy in the buildings. BECS aim to ensure operational performance of the BESs along with safety and comfort of the occupants.

The most significant part in design of BECS is modelling. In almost all energy control projects, it is crucial to have precise models of the energy systems. These can be any physical equipment or machinery or process or a combination of them. Based on literature survey of energy modelling and control of buildings, following gaps have been identified:

- **Modelling structure and accuracy**: Reported research in development of building energy models (BEMs) and BECS have dealt mainly with network topology or structure. Environmental and energy monitoring equipment, used to improve the prediction accuracy of BES models, increases modelling and calibration costs. Reported strategies for energy control of BESs lack modelling accuracy as majority of the energy models assume single-layered building construction elements (BCEs).

- **Parameter selection and influence**: More research is needed on the influence of parameters like solar radiation, wind, and occupancy, etc. on BEMs. An integrated BEM with combined interaction of temperature, heat, relative humidity with active occupancy schedule has not been reported. Effects of the BES modelling parameters on net energy consumption has not been researched.

- **Modelling performance**: Techniques used in modelling lack computational efficiency and majority of the developed models are predicted models. Dynamic response of models developed by researchers lacks accuracy. Models which are accurate to a fair degree require a large computer memory and processing time.

- **Energy modelling and control**: Impact of BES modelling performance and simulation and control strategies for changing the occupants comfort level on net energy consumption pattern of buildings needs more research. Not much research has been reported in controllability and stability studies of BEMs.

- **Optimization techniques**: For development of BEMs, different optimization algorithms like the conventional Gauss–Newton and Genetic algorithms have been majorly used. Utilization of hybrid algorithms to combine strengths of individual optimization techniques has not been reported. Effect of hybrid algorithms for solving a multi-objective optimization problem and their resulting indoor occupant comfort implications in the buildings still needs to be investigated.

Development of a reliable BEM that could effectively map the hygro-thermal dynamics of a building space is a fundamental challenge. To pursue such an objective, a model is developed by formulating energy transfer equations for all the elements of BESs like building envelope and space, PID-controlled HVAC system, and active occupancy schedule. Parameters influencing transfer of energy through the BES model are categorized as:

- **Environmental parameters**: Outdoor air temperature and humidity, wind speed and direction, solar radiation, and sol-air temperature.

- **Building envelope parameters**: Thermo-physical properties of construction materials, orientation, planning, and design specifications.

- **Occupancy factors**: Causal heat gains (internal heat loads), functional use of building, and occupancy schedule.

- **Plant parameters**: Plant heat rate, number of ventilated air changes per hour, mass flow rate and temperature of cooling water, and valve signal.

A benchmark white box BES model, based on first principles of building energy physics, is developed. Fourier's conduction equations of thermal energy transfer through the building envelope are formulated as finite difference (FiD) equations and solved using Crank-Nicholson (CN) scheme. Each multi-layer BCE is divided into 20 equally spaced sub-divisional planes, developed in both time and space domain. Building space is modelled for both sensible and latent heat transfer processes. State space approach is used to model the building envelope elements such as walls, doors, and windows, etc. Causal heat gains accounting for heat emitted from occupants, lights and other equipment are also modelled. A simple PID controlled HVAC system model has been developed. Simulations are performed for a single-zone building space with thermos-physical properties of BCEs chosen as per ASHRAE handbook of fundamentals, 2013.

Daily, weekly and monthly energy consumed by HVAC and lighting systems of the BES model are computed under no control scenario. Response of BES model for step excitations of outdoor air temperature, relative humidity and HVAC system's heat rate are analyzed. Computational performance of the BES model is studied in terms of settling time, peak time and rise time. In order to develop building energy control and comfort management (BEC-CM) strategies, order of the developed BES model is reduced by using a nonlinear time invariant optimization technique.

The optimization technique assists in estimating the parameters of the reduced order model which is a thermal resistor-capacitor network of second order (3R2C). Step responses of both standard and 3R2C model are compared and sum-squared error of both the responses are minimized to estimate the parameters of 3R2C model. 3R2C model is subjected to step response inputs of outdoor temperature, outdoor relative humidity and HVAC plant load. BES model is simulated for light, medium and heavy BCEs of different thermal capacities. This enables the optimization technique to be utilized for parameter identification and model order reduction of a BES model, regardless of buildings' functionality.

Accuracy of optimal 3R2C model is validated by comparing step responses of optimal 3R2C model with that of the models with two different parameter configurations available in literature named as model-I and model-II. Model-I is a 3R2C model with the three resistances being outside conductive resistance, wall conduction resistance and inside conductive resistance and the two capacitances being equal to half of the total thermal capacitance of the multi-layer slab. Model-II is a 3R2C model with the three resistances and the two capacitances distributed equally and evenly.

Stability and controllability analysis is carried out to check and analyze the feasibility of the BES model to any desired control strategy. Input-to-state interaction of the state space BES model is explored to characterize the extent to which state trajectories can be controlled by the input signals of outdoor environmental conditions such as wind speed and direction, solar radiation and indoor environmental conditions such as building space air temperature and relative humidity. Conditions, that enable the BES model's state trajectory to be driven towards origin, are derived over a finite interval of time. This enabled BES model to steer the state trajectory to any final state in finite time via a suitable input signal.

A control algorithm, as an engineered solution for BEC-CM, is developed. A multi-objective optimization (MOO) routine is developed to compute optimal set-point level of HVAC and lighting systems with a view to balance energy consumption and occupants' comfort. Occupants' comfort is evaluated for indoor air quality as CO_2 concentration, thermal and visual comfort. A hybrid GA-PSO algorithm has been developed to solve the MOO problem, enabling optimal control for smart energy and comfort management in buildings. Hybrid GA-PSO utilizes the merits of individual algorithm. Functions and operations of GA like mutation, traditional or classical crossover, and multiple-crossover and of PSO are used to develop a hybrid GA-PSO algorithm. Fuzzy probability is used for selection of these operators.

On the basis of occupants' defined set-point values for building space air temperature, CO_2 concentration and indoor illumination levels, GA-PSO based BEC-CM strategy enables better regulation of the indoor level parameters. This leads to improved overall comfort value by 19% under low or zero occupancy periods and by 17% under full occupancy periods of time. Also, application of the developed strategy reduces the daily, weekly and monthly consumption of energy by HVAC and lighting systems of the building by 22%, 27% and 29%, respectively. Thus, two-fold objective of improved comfort and decreased energy consumption is achieved. This shall lead to reduced demand of electricity on the power grid both during peak and off-peak periods of a day.

Contributions made through this thesis are summarized as follows:

- An integrated BES model consisting of multi-layered BCEs, building space, HVAC and lighting systems is developed using first principles of building energy physics in MATLAB/Simulink. For operating hours of 8 hours per day and assuming that 2 lamps are switched on at all time of the day, daily, weekly and monthly energy consumed by the BES was 16.8 *kWh*, 41.9 *kWh*, and 139.67 *kWh*, respectively.

- Order of the developed BES model is reduced by a nonlinear time invariant optimization technique. Sum-squared error of step responses of benchmark and optimal 3R2C model are minimized to estimate the parameters of 3R2C model. Validations are performed for low, medium and heavy thermal capacity BCEs. Response of the optimal model followed closely the response of numerical model as compared to the responses of other 3R2C models with normally used typical configurations of BES modelling. The overall accuracy of the reduced order BES model was achieved up to 90%.

- Stability of each element of BES model was assessed using root-locus method. Controllability analysis of the BES model was carried out using RIDE theory. A basic PI controlled HVAC system was found to be stable and controllable for controlling building space air temperature. There was negligible impact of thermal mass of building on the stability of building space air temperature.

- A hybrid GA-PSO based BEC-CM strategy has been developed for smart energy and comfort management in buildings. Developed control strategy of improved comfort and decreased energy consumption is achieved. Maximum comfort of occupants' was achieved at building space air temperature of *23.8°C*, lighting of *783.14 lux* level and CO_2 concentration of *683.25 ppm* with overall energy consumption of *44.85 kWh*. A significant reduction of 23.8% of energy was achieved as compared to PID controlled HVAC system.

- Under summer conditions with set-point temperature, illumination and CO_2 concentration at *20°C*, *440 lux* and *950 ppm*, respectively BES consumed minimum energy of *33.09 kWh* at minimum occupants' comfort of *91.91%*. For winter season with different set-point levels, BES consumed *23.01 kWh* at minimum occupants' comfort of *89.83%*.

- Overall occupants' comfort was improved by 19% under low or zero occupancy periods and by 17% under full occupancy periods of time. Daily, weekly and monthly consumption of energy by HVAC and lighting systems of the building was reduced by 22%, 27% and 29%, respectively compared to PID controlled HVAC system.