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Residential fuel cell energy systems performance optimization using ''soft computing'' techniques

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Abstract

Stationary residential and commercial fuel cell cogeneration systems have received increasing attention by the general public due to their great potential to supply both thermal and electrical loads to the dwellings. The reported number of field demonstration trials with grid connected and off-grid applications are under way and valuable and unique data are collected to describe the system's performance. While the single electricity mode of operation is relatively easy to introduce, it is characterized with relatively low efficiency performance (20–35%). The combined heat and power generation mode is more attractive due to higher efficiency +60%, better resources and fuel utilization, and the advantage of using a compact one box/single fuel approach for supplying all energy needs of the dwellings. While commercial fuel cell cogeneration applications are easy to adopt in combined mode of operation, due to the relatively stable base power/heat load throughout the day, the residential fuel cell cogeneration systems face a different environment with uneven load, usually two peaks in the morning and in the evening and the fact that the triple load: space, water and power occur at almost the same time. In most of the cases, the fuel cell system is not able to satisfy the triple demand and additional back up heater/burner is used. The developed ''soft computing'' control strategy for FC integrated systems would be able to optimize the combined system operation while satisfying combination of demands. The simulation results showed that by employing a generic fuzzy logic control strategy the management of the power supply and thermal loads could be done appropriately in an optimal way, satisfying homeowners' power and comfort needs.

Keywords: Integrated energy systems; Fuel cells; Fuzzy logic; Control strategy; Stochastic model

1. Introduction

The end of the 20th century has been characterized by the rapid development of environmentally friendly technologies. Global warming combined with public awareness concerning the impact of greenhouse gasses on the environment has triggered the search for new high efficiency heat and power generation technologies for total building energy supply. The idea for distributed power generation—namely, the notion of power sources near the end-user—is gaining momentum and supporters. Although an attractive strategy, it is obvious that improving the efficiency of current systems alone will not be sufficient to meet the Kyoto targets.

Commercial and residential buildings in North America are responsible for almost one-third of total greenhouse gas emissions and substantial efforts are needed to lower this value. Currently, in both commercial and residential sectors the buildings are being built with a high level of insulation, which significantly lowers the space-heating loads; at the same time, the increased number of high efficiency, low power consumed appliances have been increased. Recent constructions are built with 50% less heating loads in comparison to the 1970s. This progress has provided opportunities for new innovative approaches to be applied to the mechanical system design. The new, already commercialized combined oil and gas-fired heating systems are able to supply both space- and water-heating loads by employing a single energy generator, which significantly reduces the size of the overall system, lowers greenhouse gases and increases efficiency up to +90% for condensing units. Currently, the R&D efforts are aimed towards development of distributed advanced integrated energy systems for total, on-site building energy supply.

The newly developed stationary fuel cell systems comprise a single energy generator that will supply both power and space- and water-heating needs of a single-family house. Stationary residential and commercial fuel cell cogeneration systems are the first fuel cell systems that will be introduced to general public. The reported number of field trials with grid connected and off-grid applications are under way and valuable and unique data are collected to describe the systems performance. While the single electricity mode of operation is

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relatively easy to introduce it is characterized with relatively low efficiency performance in order of 30–40%. The combined heat and power generation mode is more attractive with efficiency of +60%, better resources and fuel utilization, and the advantage of using a compact one box/single fuel approach for supplying all energy needs of the dwellings. While commercial fuel cell cogeneration applications are easy to adopt in combined mode of operation, due to the relatively stable base power/heat load throughout the day, the residential fuel cell cogeneration systems face a different environment with uneven load, usually two peaks in the morning and in the evening and the fact that the triple load: space, water and power occur at almost the same time with no or little dephase. In most of the cases, the fuel cell system is not able to satisfy the triple demand and additional back up heater/burner is used. The experience with residential integrated heating systems that supplies both space- and water-heating loads from one energy generator showed that even with two modes of operation there are instances when despite the employment of powerful burner the system is not able to satisfy both loads at the same time. Usually, in these cases a priority control strategy is used in combined mode of operation that sacrifices one of the demands usually space-heating until the other demand is satisfied.

2. Integrated space- and water-heating systems (ISWHS)

The advanced building technologies challenge the heating industry to develop more efficient and sophisticated heating systems to meet the lower heating loads and increased demand of a comfortable living environment. The heating systems, from the beginning, are appointed to satisfy two main requirements. First, they have to be able to supply enough heat during the heating season; under no circumstances should the temperature inside the dwelling drop below a fixed value determined by the room thermostat. Second, the system must be able to supply hot water on continuous basis while maintaining a consistent, acceptable temperature level for tap hot water determined by the storage water tank thermostat setting. However, these two requirements must be satisfied in a near-stochastic environment characterized by random external/internal influences and impacts. The outdoor conditions defined by the random variations of outdoor temperature, wind speed/direction and solar radiation have a significant role on the building's thermal losses and greatly influence the heating systems' behavior. New building technologies provide a high level of insulation that diminished, to a certain degree, the impact of outdoor temperature and wind on the building's thermal losses. Furthermore, the new low-emissivity double and triple glass windows have significantly increase solar gains, greatly affecting the heating system's operational performance. Due to the above factors, the magnitudes of water- and space-heating loads are converging. This has opened an opportunity for new approaches to be applied to the mechanical systems' design. Although integrated space- and water-heating systems are a relatively new approach to heating dwellings, they have already begun to gain popular acceptance on the market. In comparison to the existing conventional arrangement (gas/oil-fired furnace and gas/electric water storage tank), the new systems employ a single gas or oil-fired energy generator capable of satisfying both the single and combined energy heating demands. Thus, there are possibilities for achieving major efficiency gains and pollutant reductions in a cost-effective fashion. The basic concept of the integrated system is shown in Fig. 1. The system's generator is equipped with a

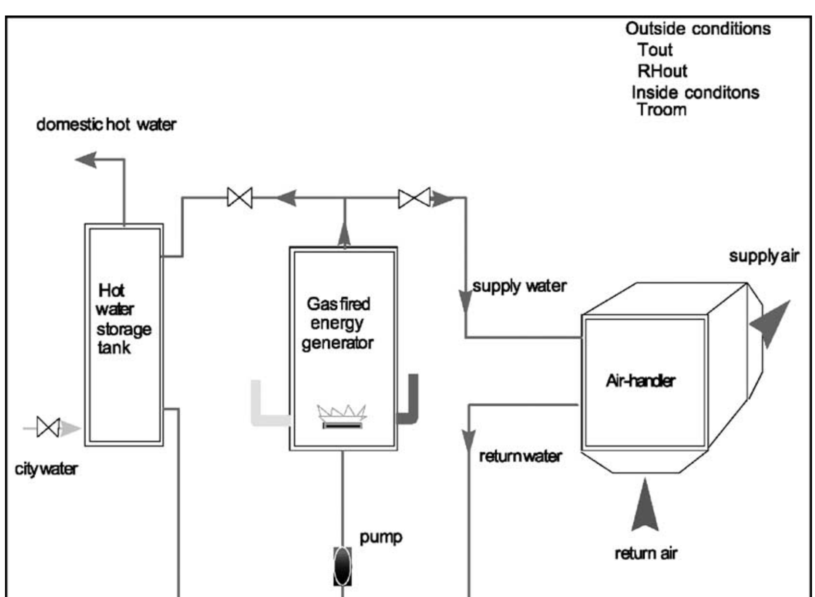

Fig. 1. Integrated space- and water-heating system.

powerful burner sized to restore the system status in a very short time interval. A water pump is responsible for moving the hot water from the hot water storage tank through the air-handler, radiators or underfloor radiant system back to the storage tank at any time whenever a demand for space-heating exist. The delivered heat is utilized across the fan-coil by running the blower motor, and the heated air is distributed through the house. Whenever there is a call for domestic hot water, the demand is satisfied by drawing water directly from the hot water storage tank. The ISWHS can has a potential for seasonal efficiencies of over 90+% for the condensing units and emission reductions of more than 30%, when compared to conventional systems. However, even if the heating system is based on a hot water generator, be it a boiler or a hot water heater, the realized efficiency is often much less than designed. This is mainly due to the wrong integration, a lack of forcing function below the flue gas due point and an adequate control strategy. Other papers [4,8] have discussed some of the detailed experiments performed on ISWHS under a variety of conditions and fuel properties. They have shown the impact of proper design and integration on emissions of incomplete combustion during the transient combustion conditions at start up and shut down.

Further efficiency gain, emission reductions and improved comfort delivery can be achieved by applying an appropriate control strategy. The developed advanced control strategy for ISWHS employs Fuzzy Logic and Neural Networks techniques for optimal performance. The premise has been that the heating systems perform in a stochastic environment defined by changing weather patterns, variable internal gains and the occupant's distinct habits. The input information is evaluated by fuzzy logic membership functions and appropriate action is taken by firing the knowledge base rules. The output is generated after evaluation of the set of rules with a certain degree of truth. The neural network module is used to learn and consequently recognize the occupant's pattern of hot water usage and thermostat setback. The detailed description of the learning base control is published [1,2,7] as the effect of the new AI controls lead to efficiency improvements in order of 5–6% with emission reductions of ∼15%.

3. Residential fuel cell cogeneration systems

The idea for distributed power generation—namely, the notion of power sources near the end-user—is gaining momentum and supporters. With the advent of deregulation in the electricity industry, there will be enormous opportunities in distributed power technology. Although, an attractive strategy, it is obvious that the newly developed technologies should have higher overall efficiency and lower greenhouse gas emissions. Currently, one of the most attractive options is a fuel cell based system. Fuel cells were originally developed for the aerospace industry to generate electricity for space vehicles. In recent years, due to advantages in material technologies they have become the focus of worldwide R&D activities. Fuel cells have the potential to produce electricity at a relatively high efficiency, compared to conventional power plants, while they limit greenhouse and other emissions. As fuel cells convert chemical energy directly into electrical energy, their efficiency is not limited by the Carnot cycle; thus, efficiencies of 50+% are potentially achievable that is approximately twice that of conventional power generation. When utilized in a cogeneration application by recovering the available thermal output, overall utilization efficiency of 75–85% is realistic. There are currently several types of fuel cells in different stages of development: phosphoric acid (PA), proton exchange membrane (PEM), solid oxide (SO), molten carbonate (MC), etc. After a detailed examination and evaluation of the existing FC technologies, the most attractive to the buildings sector applications appeared to be PEM and SOFC. The stability and high temperature operation of the solid oxide allows internal reforming to take place and to have even greater level of fuel flexibility than other types of FC. The high-grade residual heat is available for utilization to supply space- and water-heating loads of the house and cooling during the summer. A sketch of integrated residential fuel cell is presented in Fig. 2.

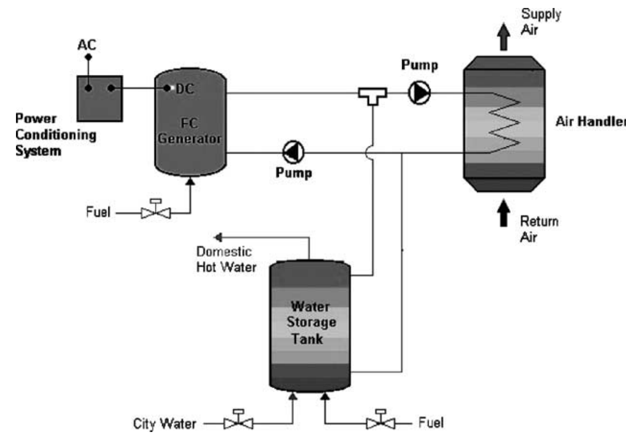

Fig. 2. SOFC generation system.

The generation system will produce 5 kW_{el} and 6–12 kW_{th}, which will satisfy the average North American home energy usage and store the excess electricity to cover the peak demand. New Canadian homes have an average of 14 kW space- and water-heating demands. The fuel cell high-grade residual heat is utilized across the air to water heat exchanger and stored as hot water in a water storage tank. Whenever there is a call for space-heating, the hot water is moved from the storage tank through an air-handler device in a similar manner as in the integrated heating system. The storage tank has an additional gas burner, in case of shortage of enough heat to satisfy the demand.

4. Integrated system modelling

Integrated heating systems are designed to satisfy buildings' thermal loads. However, these requirements must be satisfied in a near-stochastic environment characterized by random external and internal influences and impacts. Currently, most of the new residential/commercial buildings are being built with increasingly low energy requirements, so that the magnitudes of water- and space-heating loads are converging. Despite these new technologies, the building stock in North America remains very diversified and is presently characterized by a mix of low and very efficient dwellings. The integrated energy systems must perform equally well when installed in new, renovated and old buildings stock.

There have been a number of attempts to model the energy behavior of integrated systems. Most of them are based on the deterministic approach and except for a hand full of useful results, have failed to give a realistic picture of the actual system performance. Combined space- and water-heating of dwellings is a complex process; therefore, one approach is to be studied, modeled and controlled on stochastic base by in depth analysis and probabilistic assessment of outside influences and performance data.

By employing a stochastic approach the integrated heating system can be described as the following:

- it consists of elements with different properties and characteristics;
- it is under random external and internal impacts;
- capable of accumulating heat to different degrees;
- the space- and water-heating loads vary during the hours, days, months and years.

The performed system analysis showed that in order to create an adequate generic mathematical model, the following parameters describing the outside conditions and building envelope should be considered:

- outdoor temperature, wind speed/direction, and solar radiation;
- design, structural and thermal characteristics of building envelope;
- thermal and hydraulic characteristics of the integrated heating system
- homeowners' usage pattern.

5. Stochastic mathematical model

The performance of integrated energy systems is modelled by using a stochastic differential Eq. (1) defined by: the stochastic nature of the outside conditions, non-linearity of the system operators and the wide variety of the building envelopes and integrated system parameters

$$\dot{Y} = \alpha Y(t) + \beta X(t) \qquad (1)$$

Where: $X(t)$ is the input vector of the external influences, flows and energy input; $Y(t)$ the output vector of heat and power generated; $\alpha,\beta : 3 \times 3$ matrixes of building envelope characteristics and system's design and operational parameters.

The integrated system performance is determined by a variety of parameters with different nature. The analyzed set of parameters is divided into three groups—technical, controlled and maintained. The analysis showed that these groups correlate with each other and system performance and sensitivity greatly depends on their adjustment [3].

The technical parameters are defined at the design stage and include the physical size of the generation and distribution system—storage volume, gas input rate, heat exchangers, etc. and the design and thermal characteristics of the building.

The controlled parameters are appointed to compensate for the influence of the technical parameters and maintain conditions over the system performance—they are presented by mass flow rates, temperature set points, thermostat and aquastat settings, controls, etc.

The elements of the α,β matrices are generated as random sets with known distribution, include the technical and control parameters subsets and maintain conditions. The mass flow rates among the fuel cell and the air-handler unit, and the external storage tank are determined by built-in control conditions for different system designs.

The simulation program is built using a modular structure. Separate modules generate the following: outdoor conditions, random parameters' values and a numerical method for solving the system equations, and a post-processing multiple solutions evaluation to probabilistic characteristics (if is necessary). This approach reduces the complexity of the stochastic system and accelerates the solution. The modeled integrated system consists of a fuel cell, air-handler and external water storage tank. The two subsystems are coupled to the generator via water to water and water to air heat exchangers. The frequency of burner operation and water pump is controlled through a control procedure modeling the room thermostat set point and aquastat operation.

Usually, two possible approaches are employed to solve the stochastic differential equations system: either Focker–Plank–Kolmogorov's technique or by a multiple solution as a system of normal differential equation with random coefficients and post-processing conversion of the results to probabilistic characteristics. The model shows a reasonable agreement with the real data performance results with RSME of $\pm 5\%$.

6. Fuzzy logic control strategy

The developed fuzzy logic control strategy targets three of the integrated system's devices: the variable fuel cell energy output rate, the air-handler blower-motor operation and the water-storage tank aquastat settings.

The fuzzy logic fuel cell strategy controls the energy output in conjunction with the current-storage tank water temperature and room thermostat temperature differential. It

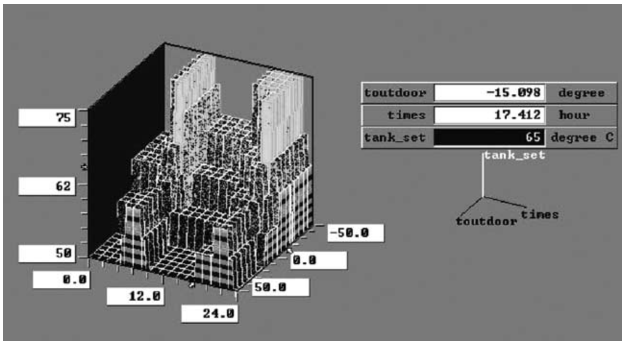

Fig. 3. Combined mode of operation simulation.

minimizes the cycling and extends the operation length of each cycle and, as a result, increases the overall efficiency while dramatically lowering the emissions [5,6]. The additional burner is a conventional two-stage burner and, despite the design limitations, the new control improves the burner efficiency, resulting in savings in the range of 3–5% and lowers the pollutant emissions by 10–15%.

The air-handler blower motor operation determines the heat utilization across the heating coil and the effectiveness of heat distribution around the house. The variable commutated programmable blower motor speed is controlled in relation with the outside temperature, room thermostat differential and mode of operation. By being aware of the status of the other system devices and the heating load, the optimal blower motor operation is set to enhance comfort while avoiding the overshooting and undershooting often seen with conventional control strategies. It is also reduces the temperature level required, and further increases efficiency.

Once the pattern of the house is established, the third loop manages the setting of the heat generator aquastat depending on the time of the day and the outside conditions. The variable aquastat settings improve the system performance by lowering the stand-by heat losses and adjusting the current water temperature according to the outdoor conditions and the occupants' usage pattern.

Subject to the environment and the occupant's habits, the developed overall fuzzy logic control strategy is able to set the system at optimal performance and efficiency mode, thus increasing its ability to satisfy the demands under a range of loads and requirements. The developed fuzzy logic approach to control the overall operation of the integrated energy system would result in improving system efficiency in the order of 8–10% and reduce pollutants by 25–30% (Fig. 3).

7. Conclusions

The paper describes a dynamic simulation tool for modeling the integrated energy systems' performance. Compared to the traditional HVAC models, it differs due to the stochastic approach and focus on probabilistic estimation of the output. By applying this concept, it is possible to evaluate the system performance under different outdoor conditions, impacts and, as a result, eliminate bad or unsuitable systems early in the design or installation stages. It could be also used as a simulation tool for testing different control strategies aimed to optimize efficiency and overall integrated heating systems' performance. Due to its stochastic nature, the model is being applied in the evaluation of the integrated systems' fuzzy logic control strategy [2,4,7]. The computer simulation results have been compared with the data from laboratory trials and have showed exceptional agreement with the lab trials

To reduce overall cost, it is becoming increasingly attractive to integrate space-heating, water-heating, ventilation and power generation into one system. Most North American homes are now being built using warm air distribution systems, to allow rapid thermal response as required, not to mention ventilation, air conditioning and even air cleaning. The developed integrated heating systems are already commercialized and are enjoying a successful ride at the market place. By employing the fuel cell cogeneration systems, significant savings can be achieved both in terms of cost and reduction of greenhouse gas emissions. The developed ''soft computing'' control strategy allows additional intelligence to be introduced into the system operation, further increasing the efficiency and lowering greenhouse gasses and other emissions.

The potential for new distributed generation technologies in North American household is significant over the next decade. Care must be taken to ensure that these systems achieve their potential for high efficiencies, reliability and low greenhouse gas emissions.

Acknowledgements

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