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Simulation Model of a Smart Grid with an Integrated Large Heat Source

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Abstract: The purpose of this research is to improve an existing simulation model to provide a tool for effectively dealing with heating requirements in Intelligent Cities and Smart Grid Systems. The goal is to show that existing, large heating sources can become a valuable part of such systems and be connected as heat sources and not just electricity power producers. The first part of this article involves a Requirements Analysis and the design of the structure to be modeled. The second part shows the simulation experiments and results. The results provide valuable information regarding the possibility of using large heating sources and address their role in Intelligent Cities and Smart Grids.

Keywords: Energy, heat, intelligent cities, modeling, simulation model, smart grid.

1. INTRODUCTION

Just a few decades ago, the large majority of countries built large power and heating plants on the outskirts of their big cities. Today, building large heat sources is in decline. One reason is the trend of using more ecological resources – e.g. solar, wind or waste incinerators, which are more local and therefore, also smaller resources. (Nuclear energy is a special case - and, considering the constant increase in demand for electrical energy, an important source of energy but this is not analysed in this article). Other reasons are that a new and modern era requires one to take account of saving energy and reducing ecological footprints. New buildings are constructed as low-energy, passive – or, even with energy surpluses (Stephan, Crawford and de Myttenaere, 2013). Also, new industrial technology has more care for low energy consumption. These and other aspects, such as new, advanced technologies and high-quality communication technologies allow the creation of intelligent units like Smart Grids in the electricity (Moura et al., 2013; Smart Grids European Technology Platform, 2013) and in the heat production and distribution industry (Johansson, 2012), or Intelligent Cities (Intelligent Cities Expo, 2013).

Despite these trends, there are some good reasons why central sources should be taken into account and strive to make them work more effectively and to integrate them into new concepts. These are the fundamental reasons:

- These sources are already built and considerable costs have been invested
- These sources are able delivery high power, so they are able to produce electricity for a large part of the region and provide heat in the form of steam or hot water for the surrounding cities – for houses and industry
- They produce energy more efficiently than conventional local sources, which use the same fuels

New and modern techniques, however, may find applications for existing and, at first sight, apparently unsuitable systems.

Large heating plants are able to produce a large amount of heat, but consumption of heat is decreasing while, on the contrary, the demand for electricity is growing. Nevertheless, these old systems are often rated for heat production and are often unable to efficiently produce electricity without much residual heat. These limitations must be taken into account in the design of systems that seek to exploit these resources in a modern environment. The aim of this paper is not to dramatically rebuild existing systems, since the costs associated with this would often outweigh the price of building new facilities, but to design an appropriate way to use the existing possibilities. It is the task of making these sources part of units like Smart Grids and to teach them to be able to use the weaknesses of large sources to improve themselves and moreover, due to the incorporated modern elements, to contribute to the more efficient operation of these old, large sources. If this succeeds, the set target will be met.

The integration of large heat sources into a network of other sources of heat and electricity involves a number of complications. For the proper integration of sources and verification of the operability of the grid, it was important to build an appropriate model, which would allow the modelling and simulation of the processes in such a system. The model can be used in the analysis of system behaviour, the design of the control system, for testing control algorithms and also – for when the system is managed as a whole. Based on this, a model arose in previous years and for the purposes of the present research, this model was modified and modernized. The details of the model and its modification will be described in the following paragraphs.

The theoretical debate in this paper will conclude with a practical example of using a model of a central heating system with one large source in an Intelligent Heat Supply System. Simulation results confirm that the use of large heat sources, assuming good quality information from the consumption point of view, and a good model may be useful for Advanced Smart Grid Systems and production planning.

2. CENTRAL HEATING SYSTEMS

A central heating system (district heating and industrial heat) is a system for distributing heat generated in a centralized location for residential and commercial heating requirements like interior space heating, water heating or heat for technological industrial processes. The heat is often obtained from a cogeneration plant which burns fossil fuels - but increasingly, also biomass, although heat-only boiler stations, geothermal heating and central solar heating are also used, as well as nuclear power (Wiki, 2013).

Fig. 1. Coal heating plant in the Czech Republic [UE, 2013]

2.1 Heat distribution

The heat is distributed via a network of insulated pipes to customers. District Heating Systems consist of Feed (Supply) and Return lines. Usually, the pipes are installed underground but there are also some aboveground pipe systems. The common medium used for heat distribution is water or steam. The steam is often used for industrial purposes. The main disadvantage of the steam is a higher heat loss due to high temperature (Wiki, 2013).

A common District Heating System can be divided into several blocks:

- Production
- The primary circuit (Transmission),
- The secondary circuit (Distribution)

The output of the production is steam; this medium is transmitted as is (only for industrial needs in modern systems) or immediately transformed into hot water (approx. 120 °C), in the heating plant. Heat exchangers are spread throughout the supplied city location, which then form the basis of secondary networks for the supply of individual objects. A simple schematic is shown in Fig. 2.

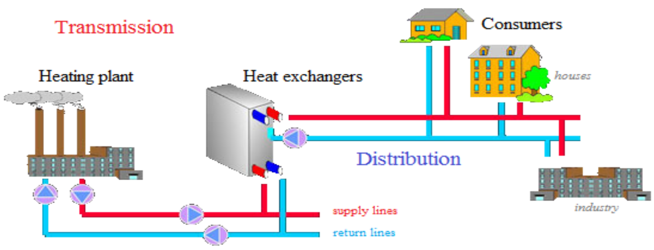

Fig. 2. Heat transmission and distribution system [DBDH, 2013]

2.2 Cogeneration

Cogeneration (i.e. combined heat and electricity production) is an effective way of utilizing fuels in the energy sector. Cogeneration makes possible the production of heat while simultaneously producing electricity. This combination helps to maximize energy efficiency in production, often reaching an 80-90% utilization level of the primary fuel, as compared to around 30-50% in a traditional power plant. The reason is that it is possible to use the waste heat generated by electricity production in an interlinked heating system. The heat produced by cogeneration is used to heat the adjacent district heating system, while the electricity is transferred and sold on the electricity market.

However, it is not possible to separate the physical processes of producing heat and power in a cogeneration production facility, energy companies will want to synchronize high heat load production with high electricity spot prices whenever possible. This can be done by using large storage tanks where the heat is buffered during hours with high spot prices, which is then distributed to the district heat system as the heat load demand increases. However, such storage tanks are expensive to build and maintain, and they have limited operational dynamics. An alternative is to use the actual buildings connected to the district heat system, in order to utilize their thermal inertia by the use of Active Load Control (Johansson, Wernstedt and Davidsson, 2012). Active Load Control, as a modern trend in the energy sector, is a prerequisite to Smart Heat Grid systems.

2.3 Local example

An example of a centralized heating system could be the United Energy heating plant in Komorany – Most (Czech Republic), see. Fig. 1. This example of a heating plant was not chosen randomly. The practical part of this paper will show a simulation experiment based on the model of Komorany plant and its operational data. The Komorany heating plant began to be built in 1943 and started operation in 1951 (UE, 2013). Over the years, the heating plant has been modernized and it is still a major producer of heat for the surrounding city (Most) and an important source of electricity in the Czech Republic. Energy is generated from brown coal combustion in ten modern fluidized bed boilers. The boiler has an installed capacity of 974 MWt for steam production while the installed capacity for heat production is 505.89 MWt and the heating plant annually produces more than 2,000 TJ of thermal energy (UE, 2013).

The Komorany heating plant has become a modern energy company with a high-quality cogeneration source operating with high efficiency. Such a source can become a quality component of Smart Heat Grids.

3. SMART HEAT GRID

The basic ideas of Smart Grid Systems were designed for electricity supply, but many points of this concept can be applied to the supply of thermal energy. In this case, it is assumed that the system consists of a set of consumers, the set of sources and - unlike electric power, by a system of accumulators because thermal energy can be stored in limited quantities and for a limited time for later use through heat accumulation, while on the other hand, electricity in large quantities is difficult to accumulate.

There is no operational information link between the energy company and their customers in a traditional district heating system. The whole system is purely demand-driven in the sense that the production unit can only react to the aggregated demand of the customers. However, the control systems in each consumer substation operate solely on very local parameters - which typically lead to volatile demand profiles with peak loads during mornings and evenings - which is not desirable from either the technical/financial or environmental point of view. Smart Heat Grid technology turns all this around by providing a platform for operational interaction between the energy company and their consumers. An energy company can only react to the heat demand without doing anything about it in a typical district heating system. On the other hand, in a Smart Heat Grid, the energy company takes control of the heat demand (Johansson, 2012).

Thermal energy is mainly used for these purposes, which form the set of customers:

- Heating buildings that people need for housing, employment, education, trade, governance and other social activities. The heat consumption is limited by the time and location of the smart grid. The amount of the consumed heat is very variable depending on local conditions, especially the climate.
- The preparation of hot water in similar places as above. The energy requirement for this purpose is rather stable and is less dependent on changes in weather conditions than the energy required for heating.
- So-called “Technological Heat” in manufacturing production companies. This energy requirement depends on the production technology and production quantity. While production technology in large intervals is unchanged, production volumes can fluctuate significantly in short time intervals.

In general, it can be concluded that the required amount of thermal energy is a dynamic variable and depends on many local conditions. Moreover, it is a quantity which has a significantly stochastic character because, in addition to climatic influences that have a stochastic nature, it is also affected by people´s behaviour and this cannot be definitively deterministically predicted.

The most common energy sources are:

- Solar energy produced by heating a suitable heat transfer fluid in solar panels
- Wind energy
- Local heating plants with biomass or fossil fuels
- Electric power generated in smart grids - surpluses that are not used for their own use
- Thermal energy from central heating systems
- The stored heat from the above-mentioned reservoirs of heat (thermal energy accumulators)
- Waste heat from technological and manufacturing processes

4. MODELS AND THEIR USE

From the above brief summary of the elements that can occur and be used in a Smart Heat Grid, it is obvious that a Smart Heat Grid can be very diverse, and considering the various possibilities of interconnections between elements, also highly variable. This entails high demands on the range of functions and the flexibility of the management. Management methods thus significantly affect the operational efficiency of a Smart Heat Grid itself, as well as any interlinked systems (in this case, especially central heating systems). Managing such a complex and flexible system often uses the technique of creating and using a simulation model of the controlled system, which allows:

- Analysis of the basic characteristics and behaviour of the controlled system
- Simulation of different management strategies always related to the specific conditions in which the system operates
- Checking the scope of control actions (i.e. "what-if" analysis). In a given situation, this enables the most appropriate actions for achieving the best possible values of the objective function (the objective function used can be different and depends on the controlling goals).
- Prediction of the behaviour of the controlled system in the near future when something occurs in the predicted course of the factors that significantly affect the system – e.g. outdoor temperatures, sunshine, wind direction and its force, or respectively, other meteorological data in the area. Prediction Control actions are very closely related with the prediction of the behaviour of the controlled system. These actions must also take into account the time delay between the heat energy production and consumption due to the different positions of heat source and heat consumer.

This paper describes the particular relationship and interconnection between a Smart Heat Grid and a central heating system which supplies heat to a larger area than just one Smart Heat Grid. From this perspective, it is possible to speak about two parts of a simulation model. One part describes the Smart Heat Grid, while the second deals with the central heating system. Both, of course, closely cooperate and interact. The model of the Smart Heat Grid determines the heat demands in time, while the central heat system model must be able to react to these demands within the scope of their supply of heat to a wider area. It is expected that the heat demands for a Smart Heat Grid will be much more variable, with greater changes in speed and varying levels of dependence on external factors than the "classic" areas supplied within a central heating system.

The following section describes the simulation model of the distribution and consumption of thermal energy, which will form the basis for both - for the Smart Heat Grid simulation model, as well as the central heating system simulation model.

The Central Heating System model was developed in more detail in the past and now the ability to connect a Smart Heat Grid model has been added. The data exchange between the two parts of the model is then formed on the one hand (a Smart Heat Grid) as a time function of heat demands, while on other (the central heating system) as a time function of heat supplies in the form of the basic parameters of the heating medium (i.e. temperature and flow rate) on the main exchange station for a Smart Heat Grid.

5. SIMULATION MODEL

Simulation is one of the few methods which can be effectively used for the analysis of large and complex systems. It is characteristic to create a model of the system for simulation purposes, usually an abstract model and today, almost exclusively, a computer model. Experiments are performed using this model and the results are then applied to the original system (Vasek and Dolinay, 2011).

5.1 Heat distribution and consumption

There are many different approaches for simulation models and the operational optimization of heating networks and heat-load modelling (Navratil et al., 2012). Data-mining combined with a physical model of the heating network seems most appropriate (Vasek et al., 2011).

In the framework of national project, the development of a discrete computer model was started at our university several years ago. The model was developed in cooperation with power plant representatives in the Czech Republic. The model was designed as a discrete entity, with a number of freely usable parameters (Vasek and Dolinay, 2011). The identification of parts of the model utilizes real data measured in heat distribution systems to set up the internal structures of the model for subsequent use in prediction. For the model, the distribution network of the chosen location must be simplified and the model trained on the real measured data (Vasek and Dolinay 2010). One of the fundamental tasks of heat distribution management is to answer the questions: “When and how much, heat energy should be produced and what temperature to set-up for hot water supply”. This task could be applied to traditional district heating systems as well as to more complex systems like Smart Heat Grid systems. Traditional heat consumers – e.g. houses and apartment buildings mainly consume energy depending on the outdoor temperature and time of day. On the other hand, Smart Heat Grids demand energy depending on many other factors, and are also better able to meet suppliers´ requirements. The ability of the model to identify its parameters in situations where part of the connected consumers is a Smart Heat Grid is greatly reduced. The number of requirements may show signs of stochastic behaviour, like responding to immediate electricity prices, energy supply from wind farms, etc. However, in the practical experiment in Chapter 6, this model, in simplified form, was tested - used to predict the behaviour of a large heat source interlinked with a Smart Heat Grid.

5.2 Model description

The distribution network can be presented as a set of heat energy sources (supply heating stations) and heat consumers which are cross-linked through piping. For modelling purposes, the pipes and heat consumers are concentrated in sections, which are connected in nodes. A section starts and ends in a node and can be divided into several elements of the distribution net (e.g. pipe lines and heat consumers). Each element has its own constant characteristics from the flow and heat transfer point of view. Simulation time runs in discrete time intervals of a constant length - designated as Δt. The time interval Δt is identical to the sampling time interval for data measured and Δt_j determines the simulation step j.

Let us consider the "discrete flow quantum" DFQ of fluid (water) as the basic “moving” element (or “transaction” in simulation terminology). The DFQ flows through the network, gradually losing energy, depending on its current position. The volume of the quanta is determined by the quantity of water entering the distribution network for the time interval Δt in the given simulation step. The amount of heat energy in DFQ is based on the water´s quantity and temperature (Vasek and Dolinay, 2010). The model uses two closely connected processes: mass flow and heat transfer.

5.2.1 Flow modelling

To monitor the flow quantum passing through the distribution network, it is necessary to respect the fundamental physical laws applicable to fluid flow and heat energy transfer – the Law of Mass and Energy Conservation and the Law of Continuity. Based on these laws, the rules for describing the mass flow in network nodes and in interconnecting pipes were defined.

According to these rules, the mass flow in the distribution network is then modelled. In each simulation step, indexed j, each flow quantum, indexed i and denoted ${}^jDFQ_i$ in the network is monitored. For illustration sake, the ${}^jDFQ_i$ in the pipe is shown in Fig. 3 (Vasek and Dolinay, 2010),

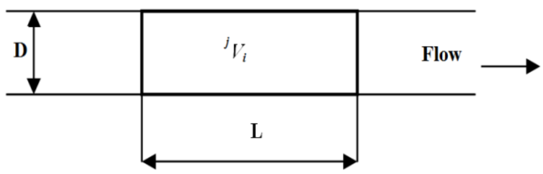

Fig. 3 Discreet Flow Quantum ${}^jDFQ_i$

where:

- D, is pipe diameter in the current ${}^jDFQ_i$ location,
- L, is the current ${}^jDFQ_i$ length, and
- ${}^jV_i$, is the ${}^jDFQ_i$ volume.

5.2.2 Heat transfer modelling

For each flow quantum which is in the distribution network at a given time, its heat balance is calculated in every simulation step. The heat balance is based on the Law of the Preservation of Thermal Energy. As mentioned above, the time interval Δt may have a length of a few minutes, so it was considered appropriate to model the temperature T of DFQ according to the formulas for a cooled object. The valid differential equation for this is:

$$\frac{dT}{dt} = K * (T - T_{ext}) \qquad (1)$$

where:

- K is the constant describing the thermal characteristics for the particular element of the distribution network and the heating medium (e.g. K for the pipe line depends on the pipe wall material, its insulation, its diameter, and the velocity and specific capacity of the heating medium - hot water),
- T is the current temperature *DFQ* in the particular simulation step *j*,
- T_{ext} is the current outside temperature.

Resolving Equation (1), leads to obtaining Eq. (2):

$$T_1 = exp\ (-K*t) * (T_0 - T_{ext}) + T_{ext} \qquad (2)$$

Where:

T_0 and T_1 are the water temperature at the beginning and end of the time interval Δt

The amount of heat ΔQ, transferred in a given time interval, is then the function of the heat capacity c_p, volume V, density ρ of the heated water and the temperature difference T_0 and T_{ext}, i.e.:

$$\Delta Q = c_p * V * (T_0 - T_{ext}) * (1 - \exp(-K * \Delta t)) \qquad (3)$$

A detailed description of the model´s uses and applicability is described by Vasek and Dolinay (2013).

6. SIMULATION EXPERIMENT

The following simulation experiment shows the virtual situation. The behaviour of a large heat source – see. Chapter 2.3, is affected by a Smart Heat Grid as a significant energy consumer. This grid is expected to have a nominal power corresponding to 10 % of the average consumption capacity of the supplied locality. Grid energy requirements may vary considerably. Under optimum conditions, the Smart Heat Grid has the ability to be fully passive – i.e. it does not require any heat supply from external sources.

6.1 The system identification

The example shows the identification of the system based on the measured data. The structure of heat consumption in the Smart Heat Grid is known and the behaviour monitored. Then, the system behaviour in cases where consumption of the grid is minimal will be presented. The sample data is from the beginning of the heating season. It is on an autumn day and the outdoor temperature is still high enough and the bulk of consumption is given by the consumption of hot water. The simulated course – i.e. the minimum demands of a Smart Heat Grid is caused by the sunny day, which made full use of solar energy in the Smart Heat Grid. Solar water heaters provided a sufficient supply of hot water for day and evening use. Some figures have a hidden y-axis – the data presented herein is subject to being a trade secret of the company which provided measured data.

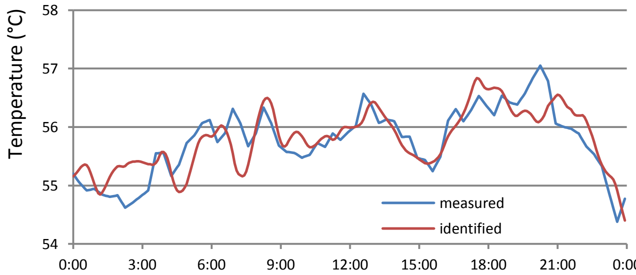

Fig. 4 Measured and calculated temperature of the returned water

Figure 4 shows the results. In the identification process, the model parameters are sought in relation to the input data and an effort is made to get output with minimum deviations from the measured data. The output is the temperature of returned water, (Vasek and Dolinay, 2011). The figure shows a good match between the data obtained and measured. The obtained results have, on average, a deviation of about 0.27 °C and a maximum deviation of 0.95 ° C.

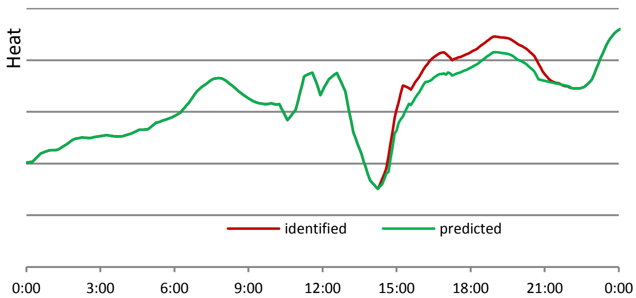

Fig. 5 Heat consumption

Figure 5 shows the amount of heat consumed during the monitored period. The red line shows the values obtained as a result of the identification process and show consumption in place of appliance - in this case, the consumption of the heat exchangers in the modelled area. The green line shows the predicted course of the fall in consumption due to reducing demand in the Smart Heat Grid and will be applied in the subsequent prediction. See the description of the experiment at the beginning of this chapter for details.

6.2 Prediction of the heat consumption

The heating water temperature at the source output is shown in Fig. 6. (green line). The step changes in the course of the day are part of the applied strategy of the quality-quantitative management of energy supply. The purpose of these step increases is to raise the amount of energy for a time of increased consumption. For example, the increase at 12 AM provides heat energy for the evening rush-hour. In the afternoon, the system operates with an average time delay of about 4 hours - which clarifies the actions at 12 AM. The evening rush-hour usually starts at about 5 PM and culminates around 9 PM. This behaviour is partly evident in the measured values of mass flow, as shown in Fig 7. (blue line). Figures 6, 8 and 9 show the prediction results for the situation presented above - see Fig. 5.

Two situations were simulated. The first, (Experiment 1) where, regardless of the change in consumption patterns control action (heating water temperature) was applied from the reference day and the behaviour of mass flow and return water temperature monitored. The second experiment (Experiment 2) responded to the prediction of heat consumption and reduction of the heating water temperature.

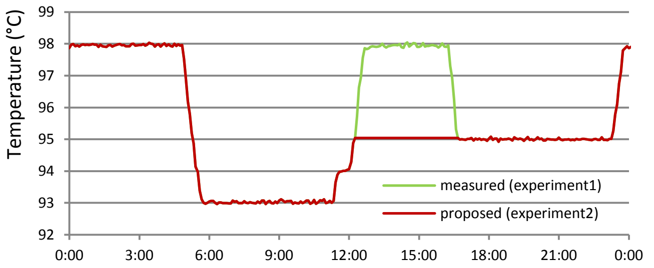

Fig. 6 Applied heating water temperature

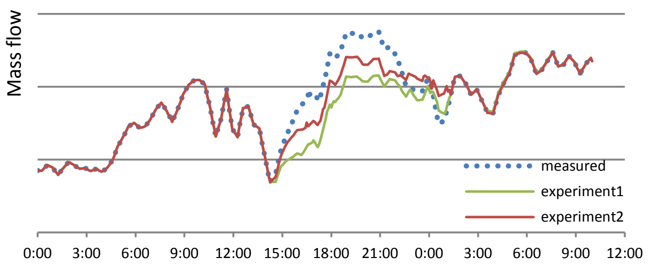

Fig. 7 Predicted mass flow

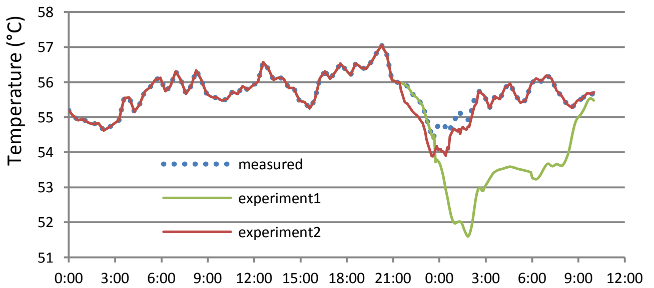

Fig. 8 Predicted return water temperature

7. CONCLUSIONS

Smart Heat Grids are becoming an important element of modern ways in heating systems, but at the same time, there are numbers of existing heating plants with combined production which are able to produce huge amounts of heat. This article wanted to point out the suitability of the combination of modern trends with existing ones and show that the interconnection can be beneficial for both systems. It is also important to prepare the simulation apparatus to provide better production management tools for the supply and consumption of heat energy. One of these tools can be the simulation model developed at our university and presented herein in this article.

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