Improving heat energy measurement in district heating substations using an adaptive algorithm

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Abstract: Heat measurement errors cause revenue discrepancies in the district heating industry. Some of these errors are static and can be estimated using standard error analysis, but the largest error source is the dynamic load such systems are subject to, as in the case of warm water tapping. The frequency at which heat meters estimate and update the energy is either constant or depends on the flow rate. The heat meter power consumption is basically proportional to their estimation frequency. Since the heat meters most often are battery powered this is a sever limiting factor to the introduction of heat metering improvements in the industry. Heat meters with a flow rate dependent estimation frequency are usually based on volume-flow meters. They are widely used in district heating due to their lower estimation frequency which prolongs their battery life. Such meters are clearly inaccurate especially at low flow rates.

An adaptive algorithm that adjusts its estimation frequency depending on the flow rate, is presented in this paper. This algorithm reduces the heat measurement error due to the dynamics of the system while keeping the battery life relatively long. The adaptive algorithm has been implemented and tested against traditional heat meters in a Simulink model of a district heating substation.

Keywords: district heating, heat meter, sensors, measurement, heat.

1 Introduction

District heating is a technology used to deliver heat energy from a central production facility to city districts or whole cities through a distribution network. This technology was introduced in the USA around 1870-80 [1]. Water is commonly used as an energy carrier in these networks. The transfer of heat energy between the district heating network and a building occurs in a district heating substation through heat exchangers. It is at these substations that heat meters are located.

The energy consumption can be divided into space heating and tap water usage. The tap water consumption varies as users consume hot water when they, for example, take a hot shower or wash hands.

A typical heat meter consists of a set of two resistive temperature sensors, usually Pt-500 sensors, a flow meter and an integrating unit, which estimates the energy consumed by the household [1].

The frequency at which heat meters estimate and update the energy is either constant or depends on the flow rate. Heat meters are often battery operated and their power consumption is basically proportional to their estimation frequency. Heat meters with a flow rate dependent estimation frequency are usually based on volume-flow meters, such as turbine or ultrasonic flow meters. Their lower energy estimation frequency prolongs their battery life. They are therefore widely used in district heating.

A modern substation responds well to sudden changes of the heat demand or dynamic loads. However, the metering of the transferred heat has not evolved to address such variations. The measurement error in traditional heat meters based on volume-flow meters is proportional to the frequency and amplitude of the tap water load. A low tap water load results in a higher measurement error [2]. Based on simulation experiments heat measurement errors of more than 10% is easily obtained for normal operating conditions [2].

To reduce this large error an approach of flow rate adapted heat estimations frequency is proposed. A solution based on an adaptive algorithm is presented to increase the heat measurement accuracy while keeping the battery life relatively long.

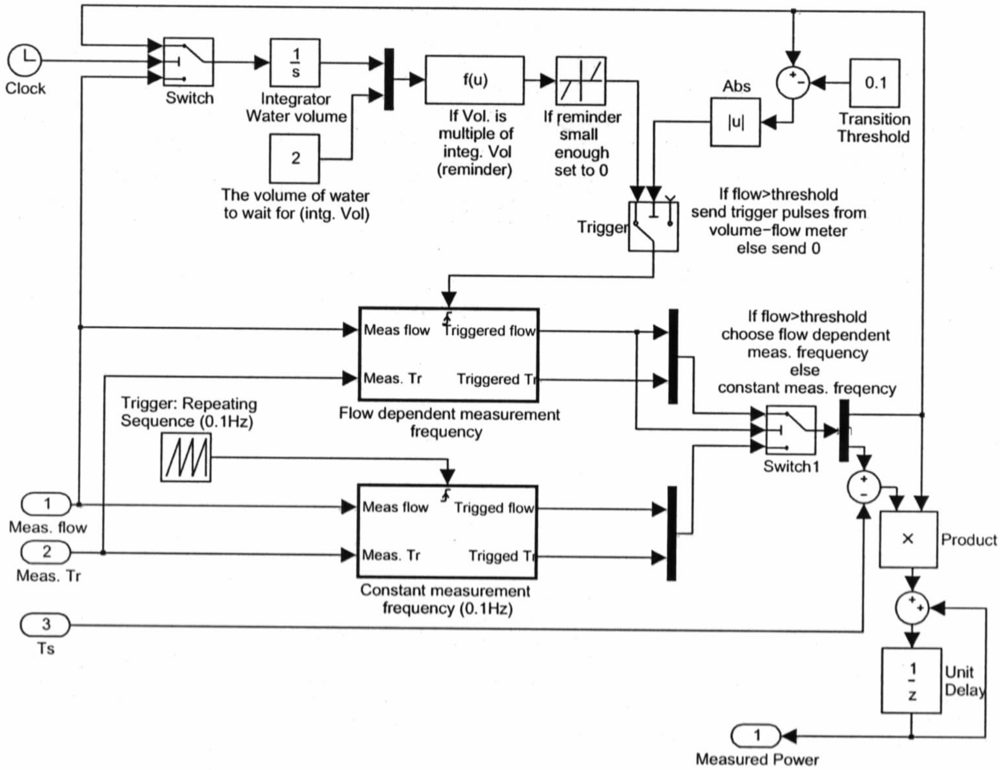

Figure 1: Simulink model of the adaptive algorithm

2 Theory

The district heating substation, connects the district heating network and house, while isolating their circuits. The district heating circuit is referred to as the primary circuit while the household circuits are the secondary circuits. A heat meter measures how much energy was transfered from the primary circuit to the secondary circuits. It is commonly comprised of a flow meter, two resistive temperature sensors and a computing unit. The temperature sensors measure the supply and return temperatures of the primary circuit. The flow meter measures the flow rate of the primary circuit.

The heat energy Q [J] consumed by the household during a period of time $\Delta t = t_2 - t_1$ is given by the following continuous time integral [1]

$$\begin{aligned} Q &= \int_{t_1}^{t_2} \dot{m} \overline{c_p(T_r,T_s)} \Delta T dt \\ &= \int_{t_1}^{t_2} V k(T_r,T_s) \Delta T dt, \end{aligned} \qquad (1)$$

where ΔT is the difference between the return and supply temperatures of the primary circuit T_r and T_s respectively. The average specific heat capacity $\overline{c_p(T_r,T_s)}$ at T_r and T_s. $\dot{m}$ is the mass flow rate in the primary circuit, which can be expressed as the product of the volumetric flow rate V and $\rho(T_r)$, the fluid density at T_r. The specific heat coefficient $k(T_r,T_s)$ is given by the product of the fluid density $\rho(T_r)$, and the average specific heat capacity $\overline{c_p(T_r,T_s)}$.

Modern heat meters do not compute continuous events, they use the following discrete approximation of equation (1) to compute the heat energy consumed by the household

$$Q = \sum_{i=0}^{N} k_i V_i \Delta T_i \Delta t_i, \qquad (2)$$

where $\Delta t_i = t_{i+1} - t_i$ is the time elapsed between two consecutive measurements, k_i, V_i, k_i and ΔT_i are measured at t_i.

2.1 Traditional heat meters based on volume-flow meters

This method has its origin in old turbine flow meters. Such flow meters are powered by the flow. The turbine drive a mechanism that provides a pulse after a certain amount of fluid has passed by.

The flow rate dependent heat measurement is triggered by a series of pulses from the flow meter. The flow meter emits a pulse when a fixed volume of water has passed through it. The time between two consecutive pulses is often called *the integration time* and is flow dependent. When a pulse is emitted, the integration unit measures the return and supply temperatures and the integration time [1].

The heat integrator computes the heat energy consumed for each iteration i with the average flow rate during the integration time V_i, temperature difference ΔT_i and the heat coefficient $k_i(T_{r_i}, T_{s_i})$. The obtained value is then accumulated onto the total heat energy consumed according to equation (2).

The measurement error in such heat meters depends on many factors [2]. The largest source of error originates from the fbw meter. It only enables us to estimate an average fbw rate under the integration time. The real fbw rate may drastically vary during the integration time without being detected by the heat meter.

2.2 Adaptive algorithm

The measurement error of heat meters based on volume-fbw meters dependents on the frequency and amount of tap water demand as mentioned in [2].

Under normal fbw rates, the estimation frequency of traditional heat meters based on volume-fbw meters is fast enough to obtain an acceptable heat measurement accuracy, since it is proportional to the fbw rate [2]. The problem occurs at low fbw rates, when the time between tow fbw meter pulses is longer. The measurement frequency in this case is too slow to cope with fast and short heat energy changes in the system. Heat meters with a constant estimation frequency are not affected in the same way by low primary fbw rates since their measurement frequency can be set to be high enough to avoid this problem, but again at the cost of the battery's life expectancy.

A new adaptive algorithm is proposed to deal with the heat measurement problem encountered at low primary fbw rates.

The new algorithm measures the heat energy with a fbw rate dependent estimation frequency at high fbw rates in the primary circuit. But if the fbw rate drops below a certain transition threshold the heat meter measures the energy with a constant estimation frequency. This implies that the sampling frequency at low fbw rates will be higher than the one in heat meters with a fbw rate dependent estimation frequency.

The adaptive algorithm is a hybrid algorithm that adjusts its estimation frequency depending on the fbw rate. It combines two existing heat measurement algorithms to give a higher accuracy measurement. A Simulink implementation of the adaptive algorithm is shown in figure 1.

3 Simulation experiments

Simulink models of the adaptive algorithm and a traditional heat meter with fbw dependent estimation frequency were made using the theory presented in section 2.2 and in paper [2] respectively. Both models were used as part of a larger Simulink model of a district heating substation [3].

The temperature sensors and the fbw meter have been modeled separately with their associated bias and random uncertainties. Random uncertainties have been modeled by adding a Gaussian distribution with mean 0 and variance 1 [4].

The response time due to material coatings and encapsulation around resistive temperature sensors has been modeled using the following first order transfer function [5]

$$G(s) = \frac{1}{\tau s + 1}, \quad (3)$$

where τ is the time constant [6]. We have used $\tau = 2$ seconds in this simulation.

The battery power consumption have been estimated by adding one power unit each time a heat measurement is taken.

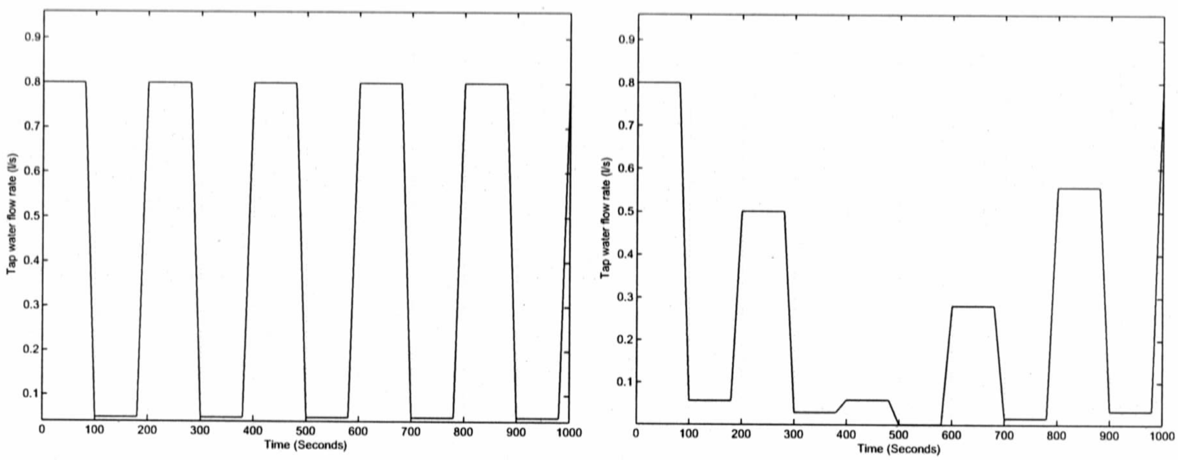

Figure 2: Tap water load in simulation 1 and 2

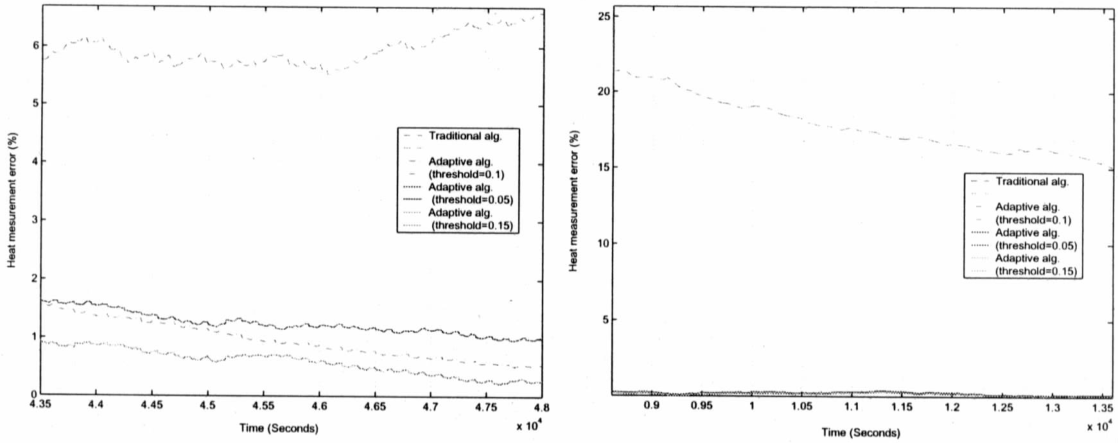

Figure 3: Heat measurement error in simulation 1 and 2.

3.1 Simulations

The aim of the simulations is to compare the accuracy of the adaptive algorithm to the traditional heat meter with fbw dependent estimation frequency subject to different tap water loads. The impact of the transition threshold's selection on the heat measurement error of the adaptive algorithm has also been investigated in these simulations.

The adaptive algorithm used in the two simulations was run with transition thresholds of 0.05 l/s, 0.1 l/s and 0.15 l/s corresponding to a low, normal and high primary fbw rates respectively.

Heat measurements occurs with a frequency 0.1 Hz if the fbw rate in the primary circuit is below the transition threshold in both simulations. The above measurement frequency was chosen to ensure a good sampling frequency at low primary fbw rates.

Rectangular pulses with a duration of 100 s occurring every 200 s were used to simulate the tap water usage in both simulations. Different tap water fbw rate amplitudes were used in both simulations to emphasize the impact of the dynamics of the tap water load on the measurement error. Graphs of the tap water load used in both simulations are shown in figure 2.

- **Simulation 1:**
  The amplitude of the tap water fbw rate was fixed to 0.8 l/s as shown in figure 2.
- **Simulation 2:**
  The amplitude of the tap water fbw rate was random between 0 to 0.8 l/s as shown in figure 2.

4 Results

The relative heat measurement error of the adaptive algorithm at given transition thresholds and the traditional heat-meter are plotted in figure 3 for both simulations.

Both plots in figure 3 show that the adaptive algorithm has a lower measurement error than the traditional one. The heat measurement error is especially lower in simulation 2 when a random tap water fbw rate is used. This is mostly due to the dynamics of the tap water load are high when the primary fbw rate lies under the transition threshold. The heat meter measures then the heat energy every 10 seconds which gives a more accurate value than in the traditional way.

Both graphs show that the higher the threshold is the more accurate heat energy measurement. This is because if the transition threshold is high the primary fbw rate lies more often below the threshold and the adaptive algorithm will measure the heat energy at a fixed sampling frequency of 0.1 Hz. The battery energy consumption in the other hand grows when the threshold increases because periodic heat measurements at static time periods are more energy consuming than fbw triggered heat measurements. A more accurate heat energy measurement is however obtained when the threshold is increased.

5 Conclusion

It have been shown that by adapting the heat energy estimation frequency to the fbw rate clearly will reduce the heat measurement error. Still maintaining a relative low power consumption at the meter it self. The power consumption is however always higher in the adaptive algorithm than in the traditional one. A more accurate heat energy measurement is obtained if we increase the threshold at the cost of higher power consumption. A balance between what we could accept as accurate heat measurement and a low power consumption can be established.

This opens up for future improvements where a new adaptive algorithm will be based both measurements error and heat meter battry life time. Thus an optimised life time economy of the system can be obtained.

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