OPTIMIZATION AND CONTROL OF A DISTRICT HEATING NETWORK

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Abstract: The short term optimization and control of a district heating network is a crucial point for Energy Industries. In this article, a model, well suited to industrial issues is presented and then used to determine the optimal schedule of the network. As consumers demands are imperfectly predicted, it is necessary to have a closed loop strategy to robustly control the network. The control law is based on the schedule planning (open loop control) and on predictive control. The control method has been validated on a benchmark network created by 'EDF' (Electricité de France).

Keywords: District heating, models, benchmark examples, power systems, optimization problems, predictive control.

1. INTRODUCTION

In a more and more open and competitive market, short term optimal control of energetic systems (from few hours to very few days) has emerged as a crucial stake for Energy Industries. Consumers' demands have to be satisfied with the lowest costs, and the lowest rate of polluting emissions. Hence, it leads to an operation problem where technical, economical and environmental constraints have to be simultaneously dealt with. In particular, these difficulties are increased for the short term optimal scheduling of district heating networks, as propagation delays can not be neglected.

The expertise of 'Electricité de France' for electric power plants operation and network management can be of great help in other energy fields, and especially in district heating networks. That is why new research areas are investigated in collaboration with Supélec: modelling, design, optimization and control of "multi energy, multi domain networks".

Most studies assume that demands are perfectly known as in (Benonysson, *et al.*, 1995; Zhao, *et al.*, 1998). As a result, the minimization of operational costs gives an ideal control law, which is a reference trajectory, but not a closed loop control. In (Nielsen and Madsen, 2002), an interesting closed loop control is proposed, concerning district heating networks with one production plant. The heat losses in pipes are considered (they increase with the supply temperature). All in all, results show that the optimal management for this kind of network is to keep the supply temperature as low as possible, under the restriction that consumers' constraints are fulfilled. This approach fails when hypothesis are not verified:

- If production costs are time varying, (for example for cogeneration units), it can be better to produce

more energy than requested when costs are low, and to use the network as a thermal storage system.
- If there are several production units with different production costs in the network, the optimal supply temperatures are very difficult to compute.

Therefore, defining the reference inputs which lead to an optimal control of the network is a tough task in the general case. In this article, a new control strategy is defined, which aims to be applicable for a large kind of networks and to be robust toward load prediction errors and model uncertainties. The control strategy is based on the predictive control depicted in (Clarke, *et al*., 1987; Maciejowski, 2002).

A new district heating model is depicted in section 2. This model appears to be well suited to industrial issues and remains tractable for optimization and control purposes. The proposed control strategy is given in section 3 as well as simulation results, which have been obtained on a benchmark network designed by ’Electricité de France’. A discussion about the method is presented in section 4. Finally, concluding remarks and forthcoming works are drawn in section 5.

2. MODELLING OF A DISTRICT HEATING NETWORK FOR OPTIMIZATION

The model, developed for simulation purposes, and related examples of simulation are fully given in (Sandou, *et al.*, 2004). Some results are here called up to establish a model well suited to optimization and control issues. The time range is discretized using a sampling period of one hour. Take note that many variables are time dependent. However, when there is no risk of misunderstanding, the time interval subscript n is omitted to make reading easier.

2.1. Production model

The model of a production site k can be expressed by a relation between the thermal power Q_n^k (MW) given to the primary network by the producer during time interval $[n\text{-}1,n]$ and the corresponding production costs:

$$c^k_{prod,n}\left(Q^k_n\right) = a_{2,n}\left(Q^k_n\right)^2 + a_{1,n}Q^k_n + a_{0,n} \tag{1}$$

Note that the coefficients of this quadratic are time dependent: for example, it arises in cogeneration sites when the price of the sold electricity is time dependent; see (Ravn and Rygaard, 1994). Maintenance costs are added by way of a penalization on power increments which is expressed by the following equation:

$$c^k_{main,n}\left(Q^k_{n-1}, Q^k_n\right) = \lambda\left(Q^k_n - Q^k_{n-1}\right)^2 \tag{2}$$

The total thermal power Q_n^k (W) given to the primary network by production site k during time interval $[n\text{-}1,n]$ is expressed by:

$$Q^k_n = c_p m_{s,n}\left(T^k_{s,n} - T^k_{r,n}\right) \tag{3}$$

where c_p (J.kg^{-1}.K^{-1}) is the specific heat of water, m_s (kg.s^{-1}) is the mass flow in the primary network, T_s (K) is the supply temperature and T_r (K) is the return temperature of the primary network.

2.2. Energy supply network model

Pipes model. The pressure at the end of the pipe H_{out} (m) can be related to the pressure at the beginning of the pipe H_{in} and the mass flow m_p, using the following expression:

$$H_{out} = H_{in} - Z_p m_p^{\ 2} \tag{4}$$

where Z_p (m.kg^{-2}.s^2) represents the mechanical effect due to friction. As the fluid in the primary network is liquid, this coefficient is supposed to be independent of the temperature. For a pipe with a valve, an additional variable is introduced: the opening degree of the valve $d \in [0,1]$ (with 0 for a completely closed valve, and 1 for a completely open one). The corresponding friction coefficient of the pipe is then Z/d .

As district pipes lengths are about several kilometres, the propagation times can not be neglected. It is assumed that this delay is constant for each pipe. The temperature at the end of a pipe on time interval $[n\text{-}1,n]$ is then:

$$T^{out}_n = (1-\rho)T^{in}_{n-\tau} \tag{5}$$

where τ is the constant time delay, and ρ the thermal loss coefficient of the pipe. Note that this value depends on the discretization step.

Nodes model. A node is modelled by two equations: the mass flow balance and the energy balance, as for simulation models (Sandou, *et al*., 2004).

Pumps model. In order to compensate for mechanical losses described by equation (4), pumps are installed in the network. The pressure due to the pump is modelled by:

$$\Delta H = a_2\left(m\frac{\omega_0}{\omega}\right)^2 + a_1\left(m\frac{\omega_0}{\omega}\right) + a_0 \tag{6}$$

with m the mass flow through the pump, ω_0 (rad.s^{-1}) the nominal rotation speed of the pump and ω the rotation speed. Pumping costs can be neglected, compared with production costs.

2.3. Consumers model

The secondary network of a consumer is connected to the primary network by way of a heat exchanger. The notations are those of figure 1. The following equation (7) is the classical heat transfer equation for a counter flow heat exchanger with S (m^2) the surface of the heat exchanger, and e (J.kg^{-1}.K^{-1}.m^{-2}) its efficiency:

$$Q_c = eS\frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln(T_{h,in} - T_{c,out}) - \ln(T_{h,out} - T_{c,in})} \quad (7)$$

Assuming no thermal energy loss between primary and secondary networks, the thermal power given by the primary network can be also expressed by:

$$Q_c = c_p m_h (T_{h,in} - T_{h,out}) \quad (8)$$

Further, note that the thermal power received by the secondary network is as well:

$$Q_c = c_p m_c (T_{c,out} - T_{c,in}) \quad (9)$$

Assuming that m_c and $T_{c,out}$ are given data, and that mass flow m_h is determined by the opening of the valve, then $T_{c,in}$, Q_c and $T_{h,out}$ can be computed from $T_{h,in}$. Q_c is an increasing function of m_h. Therefore the maximal thermal power which can be given to a consumer is obtained for $m_h = m_s$. It is assumed that there is a local regulation, which is not of interest in this study, so that the consumer can choose the value of m_h, by controlling the opening degree of the valve. Consequently, the given power is finally:

$$Q_c = \min(Q_{dem}, Q_{\max}) \quad (10)$$

where Q_{dem} is the heat demand of the consumer, and Q_{max} is the maximum power that can be given by the primary network. Q_{max} is computed by solving the system made of equations (7), (8) and (9), in the particular case $m_h = m_s$.

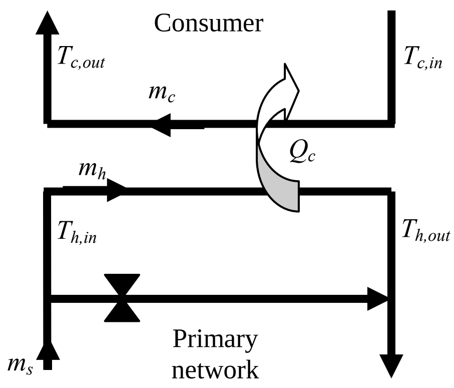

Fig 1. Notations for consumers modelling

3. DISTRICT HEATING CONTROL

Considering constant rotation speeds of pumps, the input controls of the district heating network are produced powers and the opening degrees of valves.

3.1. Open loop control

If consumers' demands are supposed to be known on time interval [1:N], the optimal control of the district heating network, supplied by K power plants and controlled by V valves, can be computed as the solution of the following non linear optimization problem:

$$\min_{\substack{\{Q_n^k, d_n^v\} \\ n\in[1:N], k\in[1:K], v\in[1:V]}} \sum_{k=1}^{K}\sum_{n=1}^{N}\begin{pmatrix} c_{prod,n}^k(Q_n^k) \\ + c_{main,n}^k(Q_{n-1}^k, Q_n^k)\end{pmatrix} \quad (11)$$

Constraints are minimal and maximal bounds for each variable, consumers' demands which have to be fulfilled for each time period and bounds on district network temperatures, mass flows and pressures. Note that variable bounds can also be time dependent, for example for a waste incinerator production site.

The violation of constraints is checked in two steps. First, mass flows and pressures have to be computed by solving the non linear and algebraic system made of mass flow balances, equations (4) and equations (6). Although it might be possible to find the analytic expression of the system solution for a relatively small network, it will be inextricable for bigger networks. Since the control strategy has to be applicable for all kinds of networks, a Newton Raphson method has been used for the resolution of the algebraic system. Secondly, equations (3), (5), (7), (8), (9) and (10) are simulated to compute power deliveries. The concatenation of these equations is related to the state equations of a non linear discrete system. The optimization problem is solved with the Matlab™ optimization toolbox.

3.2. Closed loop control

The control strategy is based on predictive method. The general scheme is depicted on figure 2. Considering load predictions, the optimization problem of section 3.1 is solved on time interval [m:m+N]. As consumers' demands are imperfectly predicted, the open loop control can not be directly applied to the district heating network. The first values (control values at time m) are applied to the system, with an extra amount of power supply to

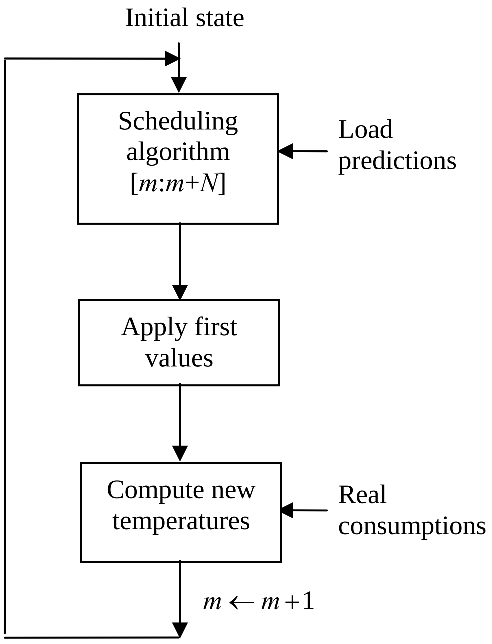

Fig 2. Control strategy

counterbalance error predictions and model uncertainties. This strategy is based on storage tank effect, which will be described now. The district heating system is simulated, with the true consumers' demands, leading to a new temperature map, which is the initial state of the network for the optimization problem on the next time interval: [m+1:m+1+N]. If loads have been overestimated, or if control is increased as for our strategy, the extra amount of power supply will make the district heating network act as a storage tank. Thus, the increase in production costs over the whole time interval (150 hours) used to obtain a robust behaviour will be kept reasonable.

The choice of the value for the extra amount of energy can be difficult. On one hand, the higher the extra amount value is, the more robust towards error predictions the control strategy will be. But, on the other hand, as heat losses increase with temperature

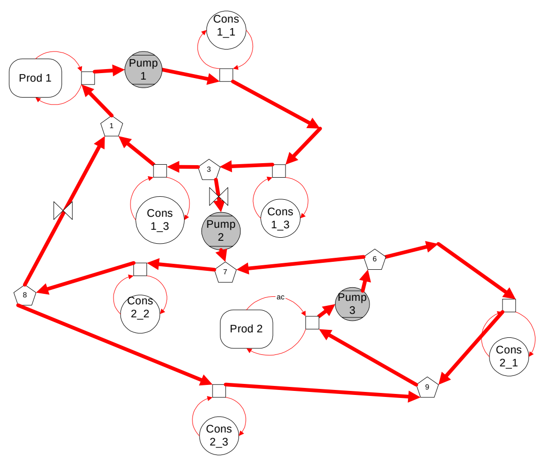

Fig 3. District heating network

(equation 5), a high value will increase operation costs. Thus, this value should be related to the variance of load prediction and model uncertainties. The prediction of consumers' demands are not of interest in this study, see for example (Nielsen and Madsen, 2000).

3.3. Numerical results

The considered district heating network is depicted on figure 3. It is a part of a more general benchmark network which has been defined in collaboration with 'Electricité de France' in the plan "Modelling, simulation and control of complex heating networks", see (Sandou, *et al.*, 2004).

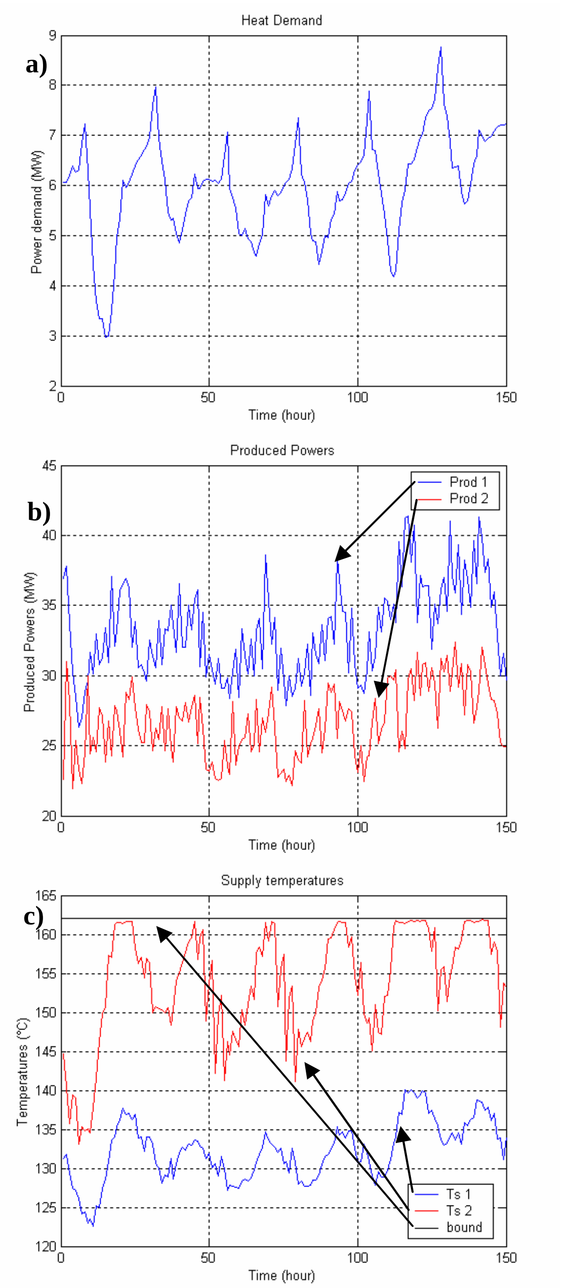

Fig 4. Simulation example. a) Load demand shape. b) Produced powers. c) Supply temperatures

The control strategy has been implemented for this district heating network with Matlab™ 6.1 and its optimization toolbox 2.1.1. The length of the predictive horizon *N* was taken equal to 12 hours. To obtain a satisfying behaviour, this value has to be greater than the highest loop time delay that is observed in the district network. The simulation length is 150 hours. A simulation example is given by figure 4.

It was assumed that all consumers were blocks of flats, so that consumers' consumptions have the shape represented on figure 4a. It was also assumed that all heat loads have been overestimated. This assumption is a worst case situation (in the usual case prediction errors can partially compensate each other). Figure 4b represents produced powers. Both production sites are heat only units. For this kind of units, production costs are constant. Hence, in this particular case, due to heat losses, using the district network as a storage tank is not interesting in terms of economical profit. That is why the shapes of produced powers are similar to demand loads. However produced powers are less smooth than heat demands. Delays imply a mixing of heat demands when they are observed from power plants. The effect of time delays can also be observed: produced power peaks appear before heat demand peaks. Supply temperatures (temperatures of primary network water after producer 1 and producer 2) are given by figure 4c. As expected, the control strategy leads to acceptable supply temperatures, kept lower than the requested limit.

The computation time is about 4 minutes for the solution of the scheduling problem (equation 11) on a Pentium IV, 2.5 GHz. The control strategy can be implemented in an on-line frame. Fine profile of computation time shows that the resolution of the algebraic system (Newton-Raphson method), which has to be done for each constraints evaluation, is time consuming. However, it is observed that the limiting aspect is not the total length of the network or the number of pipes, but mainly the number of loops in the primary network.

4. DISCUSSION

4.1. Objective function

The proposed method can be applied for generic and multi looped district heating networks, with several production sites. In addition, production sites are in fact made of several production units (steam boilers, hot water boilers and turbo alternators for cogeneration sites) which are brought together in secondary production networks. Such production sites can include heat storage tanks. The optimization of such production sites is referred to the so called "thermal unit commitment" issue, which is a huge mixed integer programming problem and has to be solved with one of the classical methods listed in (Sen and Kothari, 1998). Thus, the cost function used for the optimization problem (equation 11) is actually an estimated one. The establishment of such a globally estimated objective function is a tough task, which depends on the topology of each production site.

The scheduling algorithm can be viewed as an economic dispatch, where time delays have been taken into account. The unit commitment problem has then to be solved for each production site. If this solution leads to production costs which are quite different from the estimated costs, the optimization problem (11) may be solved again with an updated estimated objective function. This strategy could be viewed as a two level optimization and control approach.

4.2. On-line measurements

The control strategy assumes that on-line measurements of real consumptions are available, which may not be true in practice. However, a part of the system state can be obtained from temperature sensors. A local non linear estimator may have to be designed to estimate real consumptions and all the useful temperatures in the district heating network.

4.3. Infeasibility

After several iterations of the control procedure, the control sequence may lead to the infeasibility of the optimization problem (11). This is mainly due to error predictions and has been especially observed when some of heat loads are strongly underestimated. That is why an extra amount of power supply has been added to the optimal scheduling.

By definition, the short term optimization of the network is a limit scheduling: the network manager tries to produce as less thermal power as possible, while satisfying consumers' demands. Some of consumers are installed in a cascading way. If the first consumers take more power than they were expected to, the demands of the following consumers may not be fulfilled, as there is not enough energy in the network anymore. The frequency of appearance of such a problem is mainly due to the manager policy and to the level of security margin he has decided. Thus, it can be remarked that the infeasibility of the optimization problem is closely related to the classical margin notion of Automatic Control.

Nevertheless, whatever the strategy the manager may choose, such infeasibility problems can occur. A strategy has to be defined so as to compute relevant control values in such cases. When infeasibility of consumers' demands has been detected:

- it is possible to try to satisfy consumers' demands "as better as possible". For example, consumers' constraints can be relaxed and expressed as penalization terms in the objective function.
- it could be interesting to define a control law so as to reach again feasibility as soon as possible. Such a strategy can be viewed as a disturbance rejection, where the predictive consumption is a deterministic input of the discrete system, and the prediction error is a disturbance input.

5. CONCLUSION

The optimization and control of a district heating network is a very complex problem which includes technical, economical and environmental aspects. The difficulty is enhanced by the fact that time delays can not be neglected in the distribution network. In this paper a model of district heating network is defined for optimization and control purposes. This model is versatile and could be used to model many kinds of heating networks. Under the assumption of constant propagation times, a new control strategy is presented, which can be applied to various kinds of district heating network (multi supply points, cogeneration or heat-only networks, multi looped networks…). It is based on a scheduling algorithm (the open loop control is the result of the optimization algorithm) and on the predictive horizon principle. In order to counterbalance load prediction errors and model uncertainties, an extra amount of power is produced. The distribution network acts then as a storage tank, leading to a slightly increase in production costs, but also to a more robust control strategy.

The method has been tested on the district heating network depicted on figure 3, which is a benchmark network designed by EDF ('Electricté de France') and Supélec. Computation time keeps reasonably small, despite the solution of algebraic non linear systems of equations by way of a Newton Raphson method: an iteration of the scheduling algorithm is made in less than 4 minutes.

Several research axes are now investigated. The control method has to be coupled with a "unit commitment" solution algorithm, to compute the scheduling of production sites. This may be an opportunity of updating the estimated cost function.

The control strategy, which is based on an optimization algorithm, can lead to some cases of infeasibility. This can be mainly related to prediction errors and may occur in practice. The main point is now to define an efficient strategy to deal with these cases which takes into account the Automatic Control notions of robustness and disturbance rejection.

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