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Report Title: Nonlinear Optimisation in CHP Applications

Report No. 1

1   Introduction

At the Fraunhofer Institute UMSICHT a nonlinear model has been developed facilitating the dynamic optimisation[1] of combined heat and power production systems. The strategy called "dynamic supply temperature optimisation" is a very promising approach to use the DH-network itself as a large heat storage causing no additional investment cost.

The pipeline system of a district heating system has a huge potential for the storage of energy. Especially for the application of renewable energies the optimal use of these storage capabilities will increase the overall efficiency. In particular for CHP systems with fixed heat and power coupling (back pressure turbines), this approach could enable a reduction of operating heating plants and the displacement of expensive peak power plants. It will reduce electrical power peaks and enables a better utilisation of tariffs.

The supply temperature optimisation aims at finding the operating point at which the power requirements (heat and electrical energy) of the consumers can be covered with minimum operating cost. In order to determine the optimal values of the variables, the system performance as well as the technical and contractual restrictions have been considered in the mathematical optimisation model. These are e.g. the energy purchase contracts, the characteristics of the energy conversion plants, the power requirement of the consumers and the dynamic behaviour of the DH network. These connections have been described by equations and inequations, in which optimisation variables and model coefficients are linked together. On the basis of configuration and calculation data an optimisation model has been formulated under application of modern optimisation procedures. As results of these optimisation model the optimal courses of the supply temperatures of the individual suppliers, the electrical and thermal input powers as well as the storage powers etc. can be received.

2   Scientific and technical objectives

Since the volume of the DH-network of a CHP system is often more than 50.000 m³, the pipeline system in particular enables the storage of heat without additional investment costs. In a DH-network a time of some minutes to several hours passes between the input of heat at the production

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[1] In this context not the dynamic programming but the optimisation over a certain time period is meant

plant and the output of this heat at particular consumer stations. In other words, after increasing the heat input there is a time period in which the heat is stored in the DH-network. The maximal storage time depends upon the distance between the production plant and the consumer and the velocity of the DH-water. Therefore, the characteristics of the energy supply system's operation have to be considered to evaluate the potential for heat storage processes.
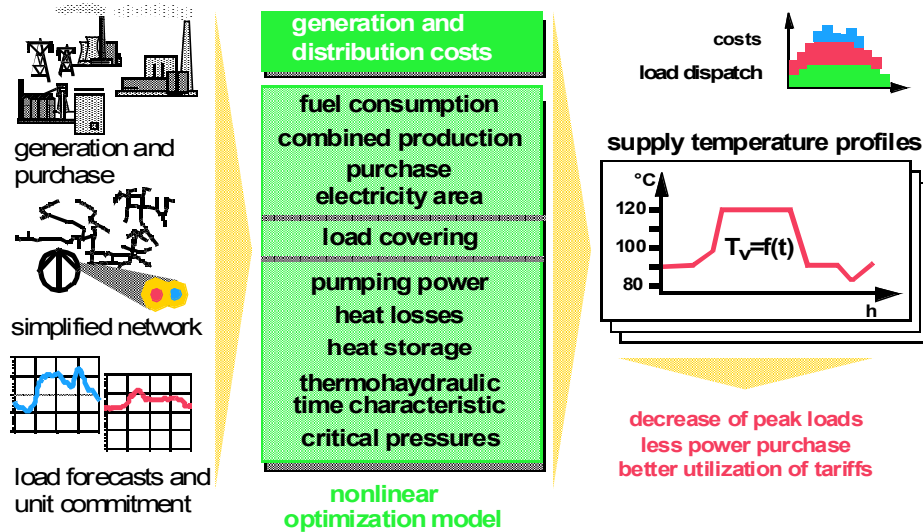

Fig. 2-1: Heat storage optimisation model

In order to determine the optimisation potential of heat storage processes in the DH-network of a DH or CHP system, an algorithm for the dynamic optimisation has been developed. As input data, the technical and economical structure of the energy production facilities, the energy purchase as well as the DH-network including heat accumulators and the prognoses of the thermal and electrical power requirements of the consumers is needed (see figure above). This prognoses data must be provided for the time period considered for the optimisation.

Based on this data an appropriate optimisation model has to be generated which enables the consideration of the dynamic thermo-hydraulic behaviour of DH and CHP systems due to dynamic energy production, distribution and demand. The dynamic pumping power requirement along with the heat loss has to be modelled. Special consideration must be taken towards a suitable mathematical formulation for the complex dynamic processes in the transport system since this is essential when modelling the heat storage processes in the DH-system. The unit commitment, the load dispatch as well as the operation of the bypasses and especially the supply temperatures in all heat production plants must be considered to facilitate the full potential of the energy supply system due to its optimisation by the heat storage processes.

2.1   *Mathematical model*

In the mathematical model Fraunhofer UMSICHT distinguishes between energy supply and DH network. The energy supply consists of systems for the energy conversion, the contracts for the external supply of heat and electrical power as well as the electricity network. They have to be set up in such a way that the supply temperature is declared as optimisation variable. The DH-network is the most important part of the mathematical model. In this model the thermo-hydraulically dynamic behaviour of the DH network has to be modelled. This submodel is based on methods of the thermo-hydraulic network simulation.

The mathematical model is based on the separation of the optimisation period into equidistant time steps with the time increment Δt. The time steps are chronologically numbered. The starting point of the optimisation period is the first time step. To get a clearer formulation of the model the first time step is defined as zero point of the time axis. Based on this discrete representation the model is divided into three sections for the description of the thermo-hydraulical dynamic behaviour of the DH network:

- steady state hydraulic model
- steady state thermal model
- dynamic thermal model.

Due to the assumption of a quasi steady state hydraulic behaviour of the system the steady state hydraulic model has to be set up for each time step. The steady state thermal model serves for the definition of a clear starting point for the dynamic optimisation.

Due to the convective heat transport and the large delay times in some pipes a dynamic thermal model has to be developed for these components, which describes the delay time characteristic of the network. For the other components of the DH network the delay time behaviour can be neglected.

For each element of the DH-network a adequate nonlinear model has been developed. All separate elements are set up to an overall system of linear and nonlinear restrictions. It can be distinguished between:

- Power plants (Heating unit, CHP Unit of different types)   ⇒   linear
- Heat exchanger   ⇒   nonlinear
- Valves   ⇒   nonlinear
- Pumps   ⇒   nonlinear
- Pipes   ⇒   nonlinear
- Consumer   ⇒   linear
- Purchase contracts   ⇒   linear

To make this system solvable the equations have to be continuously differentiable. For example the massflow direction in pipes can change from one to another timestep what is an discontinuous process. Therefore, some models do not fulfil this criterion. The problem is solved by approximation of the discontinuous models by continuous functions. The next diagram shows for example the approximation of the absolute function:
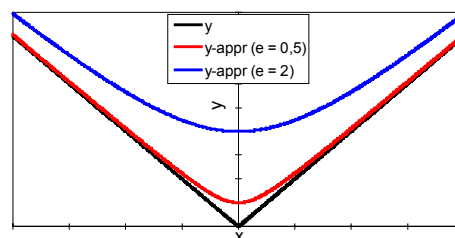
$$y \approx \sqrt{x + e}$$

Fig. 2-2: Approximation of continuously not differentiable functions

The solution of the complete optimisation model can be controlled by the approximation parameter e; A better approximation usually leads to a problem which is more difficult to solve.

2.2 *Objective function*

Solving economic questions the attainable profit often represents the quality of a decision. However, the incomes of the energy supply company cannot be influenced by the operation mode and therefore they represent a constant in the context of operational planning. That is why instead of the profit the operating costs are used for the evaluation of the quality of an operation mode.

The costs of the energy purchase as well as of the fuel supply for the production systems are the only costs influenced by the operation mode of the power supply system. Therefore, the total costs K for the energy purchase and the fuel supply are formulated as objective function of the optimisation problem.

$$\sum_{e \in GHWK} K_e + \sum_{e \in GTHWK} K_e + \sum_{e \in SB} K_e + \sum_{e \in HW} K_e + \sum_{e \in WB} K_e = 0$$

With

GHWK:	Set of production units with backpressure turbines
GTHWK:	Set of production units with gasturbines
HW:	Set of production units with heat only boilers (HOB)
SB:	Set of electricity purchase contracts
WB:	Set of heat purchase contracts

Target of the operational planning is the determination of the operation mode with the minimum operating costs. All the other equations represent constraints of the optimisation problem, which have to be kept.

3 Optimisation results

After several tests with virtual and small real DH-systems the software prototype for the nonlinear optimisation was tested for the Vienna CHP-system. The actual CHP-system of the Austrian DH-company "Fernwärme Wien GmbH" is designed for a total heat production and transport of 2790 MW, the maximum load of the year 1999 was 1605 MW. In the same year 4540 GWh heat was supplied to their customers. The heat supply takes place in 11 power units. The basic load by waste incineration plants (21% of total heat production), in the mean load by combined heat and power production (73%) as well as from gas/oil heat only boilers (6%). The actual transport and distribution network covers a total length of 974 km with a total volume of 76,000 m³ in the main transport network. There are 5030 substations attached. By which 202,000 housing customers and 4,400 big customers are supplied. The DH-network is designed on 25 bar/160 °C and/or. 6 bar/90 °C. The detailed network topology is represented in fig. 3.1 (left).

To carry out the nonlinear dynamic optimisation process a highly simplified DH-network of the Vienna supply system had to be designed by the simplification strategy of DH-systems described above. Fig. 3-1 (right) shows the simplified model of the DH-system in Vienna. The number of substations and pipes has decreased by almost 99 %. The average errors in terms of pressure and temperature differences etc. are less than 5 %. The simplification level is suitable to carry out the optimisation process and the accuracy is sufficient to guarantee meaningful results.

In order to test the optimisation procedure a time horizon of 24 hours has been regarded. For the 16.11.1999 heat and power demand profiles were given in 2 hour increments. This day can be characterised as a high load demand day with heat load peaks of up to 1300 MW and a total heat production of approx. 26 GWh. The target was to receive an optimised control regime for the heat and power units for that day. Mainly the heat and power input and the supply temperatures of all active input plants were of interest.
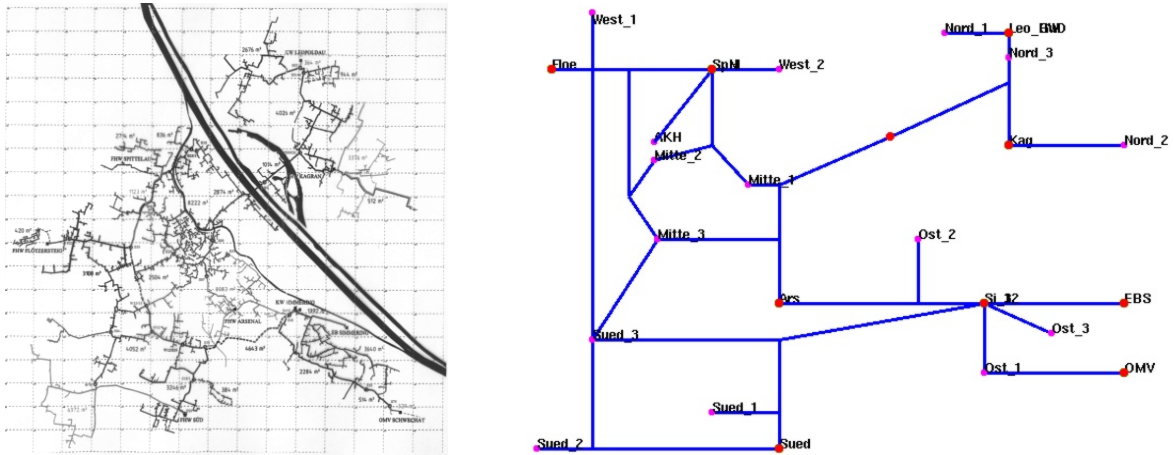

Fig. 3-1: Detailed (left) and simplified model (right) of the Vienna DH-System

The optimisation process took 9 hours using the solver CONOPT on a SUN-sparc2-station with 400 MHz. It is obvious that this time should be decreased highly by using more modern software and hardware. It was possible to reach a local optimum for the 24 hours optimisation horizon. The following figures show some results of the optimisation. On the left side of fig. 3-2 the total heat balance for the DH-system is illustrated. It can be seen that the two heat load peaks at 6 am and at 4 pm are shaved by taking heat from the DH-network. While the heat load is lower the DH-network is loaded, so the DH-network is used as a big heat storage. The heat load peaks are decreased by 150 MW and 40 MW, underlining the big potential of this control regime. Especially for companies with rigid heat and power production and power purchase contracts with power costs dependent on the peak load this offers a great cost saving potential. But also companies operating cost effective CHP-plants and cost intensive peak power plants can benefit by replacing the latter in peak times using the DH-network as a heat storage having been loaded by the former.
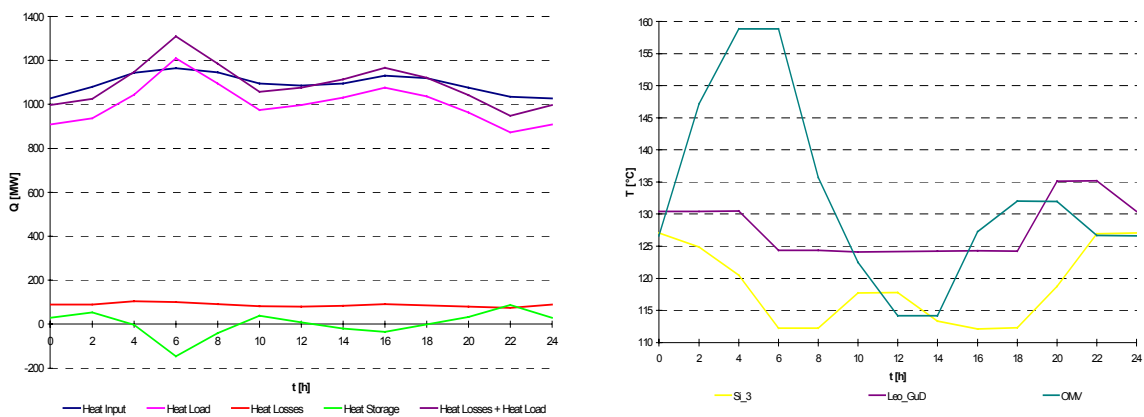

Fig. 3-2: Optimized overall heat balance (left) and supply temperatures of some power units (right)

The right side of fig. 3-2 shows exemplary the supply temperatures of 3 power units. The production costs of the units Leo_GuD and Si_1 are dependent from the supply temperature the units are operating. That is why the supply temperatures of this units are kept at a low level. The costs of the power unit OMV are independent from the supply temperature. Therefore this power unit is used to initiate the loading process of the DH-network by increasing it's supply temperature.

The results of the optimisation tests carried out in a cooperation between Fernwärme Wien GmbH and Fraunhofer UMSICHT show that there might be some potential for cost savings by an improved control regime using the DH-network as a heat storage. As a next step it is planed to verify weather the optimised control regime also in real world operation leads to lower operating costs.

4   Literature

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