Utilization the heat accumulator in large heating system

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ABSTRACT

Cogeneration is currently one of the cheapest ways to generate electricity. The European Union promotes systems for combined heat and power generation. In Europe in general – and Poland in particular – there are numerous large district heating systems powered by CHP plants. Most plants are equipped with back-pressure turbines. Energy conversion efficiency for this class of installations reaches approximately 80%. The main disadvantage of cogeneration is that electricity production is directly related to heat production (i.e. demand). The load curve of the heating system varies depending on the time of day, day of the week, and season. On the daily scale the largest heat demand is observed at night and smallest during the day.

In contrast, electricity demand is lowest at night and highest during the day, with two standard peaks in the morning and afternoon. Accordingly, electricity is at its most expensive at that time. Therefore it is beneficial to maximise electricity generation during the morning and afternoon peaks, and minimise it during the decreased night-time demand. Electricity and heat outputs at a CHP plant can be uncoupled by using a heat accumulator.

This study proposes a mathematical model to plan out a large CHP plant with a heat storage tank to be used for the purposes of operational optimization. Potential increases in profits from electricity sales enabled by the heat accumulator are also quantified.

Keywords: heat accumulator, cogeneration, optimization, heating system

1 THEORY

The subject of the study is a large CHP plant typical for Poland. There are very similar plants in many other countries where district heating systems are popular.

To optimise the operation of a system equipped with a heat accumulator [1], [2] an operating plan must be prepared for the tank [3]. It is impossible to optimise operation just for the present moment. To achieve optimisation, the system load and energy prices need to be known for the immediate future – i.e. at least one day in advance. The authors restrict the scope of study to heat storage tanks for balancing the load in timeframes of several hours.

To model the operation of a system a complete mathematical model must be constructed, i.e. a model of the tank and cooperating plant. Mathematical models for the system outside of the tank itself do not feature in this paper, as they are dealt with at length in the literature [4], [5]. Figure 1 shows diagram of the considered system.

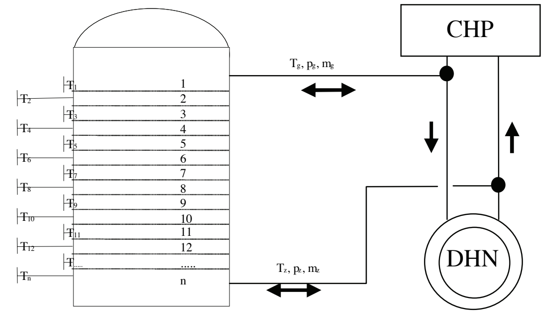

Figure 1. Model of a heat accumulator.

Objective function is needed to optimize. In this case it will by operational profit. Operational profit [6], [7], [8] during the subject period can be presented as:

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\begin{aligned}
Z_o = & \sum_i K^i_{EnEl} + \Delta K_{Zasobnika} - \sum_i K^i_{Emis} + \\
& - \sum_i K^i_{Pal} - \sum_j K^j_{Rozruch} + \\
& - \sum_k K^k_{Odstaw} - \sum_i K^i_{Kara}
\end{aligned}
\tag{7}
$$

where: i – computational step index, j – index of devices started up, k – index of devices shut down, K^i_{EnEl} – income from electricity sales in consecutive computational steps,

K^{i}_{Emis} – emission cost, K^{i}_{Pal} - fuel cost for individual computational steps, $K^{j}_{Rozruch}$ - start-up cost of individual devices, K^{k}_{Odstaw} - shutdown cost of individual devices, $\Delta K_{Zasobnika}$ - cost resulting from the difference between heat accumulated in the tank at the start and end of the subject time frame and its sales cost, K^{i}_{Kara} – fine (loss) resulting from failure to comply with the submitted electricity sales schedule.

The most fraught element of forecasting operations of a heat storage tank is device start-up and shutdown management. Nevertheless it is a necessary element of forecasting operations with a heat storage capability. The heat accumulator can affect the set of devices (units) operating at a given moment. It can allow the system to cover small excess loads. Therefore use of the heat storage tank can reduce start-up and shutdown costs.

The full computational process for operational optimisation of a heat storage tank must include determining loads for individual devices (sources) in the entire system (including those which do not directly cooperate with the tank, but have impact the load of those which do).

The process of optimising operating devices in most cases requires the calculation of all possible combinations. The number of possible configurations is usually greatly restricted by the parameters imposed. The configuration has to provide a range within the required minimum and maximum output and offer the ability to start up individual devices. Therefore it is possible to address all acceptable combinations of operating devices for a given load condition.

In case of calculations carried out to forecast the heat storage tank operation, the subject timeframe should be at least 24 hours. In many cases a longer period must be envisaged, for instance 7 days. The point is to address the specificity of different load curves for different days of the week, primarily during weekends. Operational optimisation of the tank requires that due consideration is given to all possible load conditions at the same time, because the charging level depends on the load in considered states.

A typical computational step for this type of calculation is one hour. In certain special cases shorter steps can also be considered, for instance 15 minutes. With the entire timeframe being between 1 and 7 days it is necessary to calculate from 24 to 672 load conditions at a time. For an average CHP plant the number of decisive variables (i.e. those subject to optimisation) for a single load condition is from c. 10 to 50 or even more. Under such conditions the number of such variables for the entire task (for all load conditions) is between 240 and 33,600. It is self-evident therefore that the magnitude of the computational task depends to a major extent on the assumptions. The time of calculations is also greatly dependent on the number of decisive variables taken into account in a single computational cycle. Determining optimal conditions for a situation involving a large number of variables and numerous time steps can be a laborious process.

If the optimisation task also includes full selection of the operating devices combination, the calculations need to be repeated for several such combinations. The devices can be started up in various time steps. Hence the task grows significantly.

In order to simplify and shorten the computational process an alternative solution was proposed for further discussion. The start-ups and shutdowns of devices in the model can be carried out according to an algorithm. Start-up of another device should be done as late as possible, i.e. when the output of the devices already in operation is no longer sufficient. Accordingly, shutdown should be done as early as possible, i.e. only when operation of the entire system is possible throughout the time step without one of the devices.

In a system with a heat storage tank, not every case of the system heat load exceeding total output requires the start-up of another source. A tunnel algorithm was developed to identify such situations. It determines manageable output in a system with tank.

Finding the tunnel of allowed accumulator conditions is an iterative process carried out for consecutive time frames. In each iteration the range of allowed states is determined by maximum $Q^{i}_{\max}$ and minimum $Q^{i}_{\min}$ charge in the tank at the moment i, and appropriate values for the next moment $Q^{i+1}_{\max}$ and $Q^{i+1}_{\min}$ are calculated. In order to find those values the following must be known:

- maximum and minimum possible heating output,
- maximum amount of heat which can be sent to/from the accumulator.

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Maximum $Q^{i}_{\max}$ and minimum $Q^{i}_{\min}$ amount of heat which can be generated can be calculated by solving a local case.

For the moments at which the electrical output is determined (by scheduling) the local cases impose additional restriction on electrical output except where the local cases are identical to the moments when the electricity output is not given.

The maximum rate at which it is possible to transfer heat into the tank is designated as $\dot{Q}^{i}_{\max\_in}$, while the maximum rate of heat transfer out of the accumulator is $\dot{Q}^{i}_{\max\_out}$.

If at a given moment the heat load (demand) $\dot{Q}^{i}_{o}$ fits in the range $\left(\dot{Q}^{i}_{\min\_p}, \dot{Q}^{i}_{\max\_p}\right)$ we can transfer the heat into, or collect the heat from the tank. So it is possible either to increase the $Q^{i}_{\max}$ or decrease the $Q^{i}_{\min}$.

$$Q^{i+1}_{\max} = Q^{i}_{\max} + \min\left(\dot{Q}^{i}_{\max\_in}, \dot{Q}^{i}_{\max\_p} - \dot{Q}^{i}_{o}\right) \cdot \Delta t \qquad (8)$$

$$Q^{i+1}_{\min} = Q^{i}_{\min} - \min\left(\dot{Q}^{i}_{\min\_in}, -\dot{Q}^{i}_{\min\_p} + \dot{Q}^{i}_{o}\right) \cdot \Delta t \qquad (9)$$

If $\dot{Q}^{i}_{o} > \dot{Q}^{i}_{\max\_p}$ then in order to keep the predicted heat supply it is necessary to discharge the accumulator. Nevertheless, there is still the question of the rate of discharge. The formula for $Q^{i+1}_{\max}$ changes to:

$$Q^{i+1}_{\max} = Q^{i}_{\max} - \left(Q^{i}_{o} - Q^{i}_{\max\_p}\right) \cdot \Delta t \qquad (10)$$

There is no $\dot{Q}^{i}_{\max\_speed}$ (max speed of loading accumulator) in the formula above, though it does not make this parameter totally insignificant – when $\dot{Q}^{i}_{o} - \dot{Q}^{i}_{\max\_p} > \dot{Q}^{i}_{\max\_speed}$ then the heat load cannot be covered by the discussed configuration.

If $\dot{Q}^{i}_{o} < \dot{Q}^{i}_{\min\_p}$ then even at the lowest heat output there is surplus heat, which has to be accumulated in the tank. Then the formula for $Q^{i+1}_{\min}$ changes to:

$$Q^{i+1}_{\min} = Q^{i}_{\min} + \left(\dot{Q}^{i}_{\min\_p} - \dot{Q}^{i}_{o}\right)\cdot \Delta t \qquad (11)$$

If $\dot{Q}^{i}_{\min\_p} - \dot{Q}^{i}_{o} > \dot{Q}^{i}_{\max\_speed}$ then there is no more heat accumulation capacity at the discussed configuration. The above equations do not have restrictions on the amount of heat accumulated in the tank. This however does not mean that any amount can be actually stored there. If a tank is full of water at maximum temperature, the temperature difference between the incoming and outgoing flows is 0, so the charging rate also falls to zero, and no more heat can be accumulated. Similarly, during discharge, a moment comes when the temperature of the topmost layer is equal to the DH system return water temperature and the discharge rate drops to zero.

The tunnel of allowed trajectories for the amount of heat in the tank generated according to this model also includes states which could be achieved without exceeding the limits at an early stage, but which would inevitably lead to the restrictions being exceeded later on regardless of the process control of the tank operation. It is possible to filter out such solutions. To do so, it is necessary to carry out the identical algorithm in reverse, starting from the latest moment. This way we get a tunnel of conditions which might be impossible to carry out, but which do not lead to breach of restrictions later on. The ultimate tunnel is a common part of both generated tunnels – calculated from the beginning and from the end.

If a tunnel narrows to a value of below zero or a common part of both tunnels is empty at some point of time, then it is impossible to keep within the limits at the given configuration. Depending on which restrictions are active at the moment the tunnel closes, it is possible to determine whether there is excess or insufficient heat in the tank and in which direction the configuration should be modified.

If the tunnel closes it means that it is impossible to meet demand, so additional devices need to be started up. The tunnel does not solve the issue of shutting down devices in cases where there are a number of sources running at minimum output. That is inefficient from the system's point of view and may be resolved by constructing the tunnel many times.

Through the multiple tunnel construction process it is possible to indicate necessary start-ups and shutdowns by modelling.

2 RESULTS

Currently there are no full calculation results available for presentation or measurements from a real plant. In order to estimate achievable potential, a simplified model of a CHP plant was built.

The CHP plant in question is equipped with three cogeneration units and a single water boiler, which is a peak load source. The cogeneration units are fitted with extraction-back pressure turbines coupled to electricity generators.

This system was supplemented with a heat storage tank. After connecting the accumulator to the process system of the plant the situation of the main units does not significantly change. The district heating water system is modified together with the process steam systems. There is also a new electrical system, accumulator control system and appropriate new auxiliaries. The connection between the heat storage tank, heat generating devices of the plant and the district heating grid allows heat production to be varied above/below current network demand through charging/discharging the accumulator.

The described model was used to simulate electricity production. The objective was to maximise electrical output at peaks and minimise it at electrical load valleys.

The results of the calculations for the summer season are presented in Figure 3 and Table 1. The chart depicts electricity production changes over individual hours. The table gives production output with and without the accumulator.

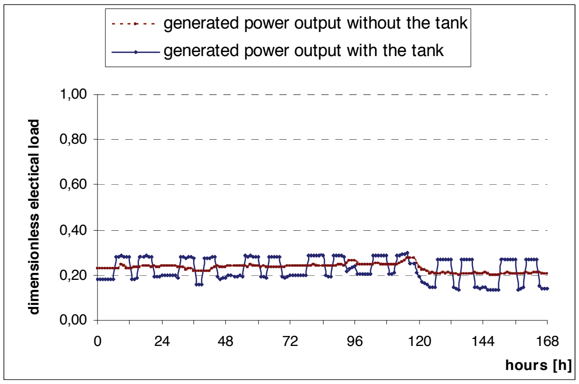

Figure 2. Change of generated power output with and without the tank for a selected 7-day summer period.

No	Item / operational mode	CHP without acc.	CHP with acc.	Change with-without
1	Morning peak	5.72%	6.98%	1.26%
2	Noon valley	2.82%	2.17%	-0.65%
3	Afternoon peak	4.79%	5.83%	1.04%
4	Night valley	9.81%	7.76%	-2.05%
5	Totally:	23.13%	22.73%	-0.40%

Table 1. Electricity generation for a selected 7 days of summer season – daily peaks and valleys are addressed.

Similar calculations were carried out for the winter season. The results are presented in Table 2 and Figure 4.

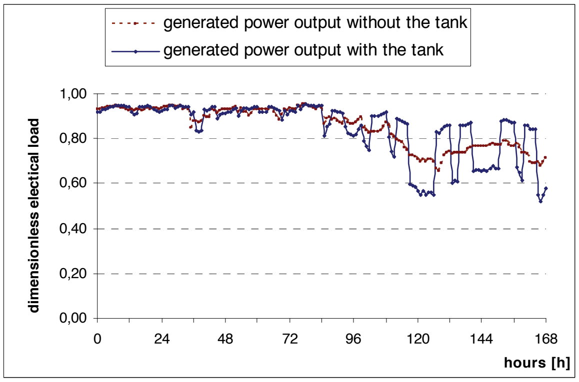

Figure 3. Change of generated heat output with and without the tank for a selected 7-day winter period

No	Item / operational mode	CHP without acc.	CHP with acc.	Change with-without
1	Morning peak	21.50%	22.92%	1.42%
2	Noon valley	7.94%	8.19%	0.24%
3	Afternoon peak	17.43%	19.10%	1.67%
4	Night valley	25.74%	25.65%	-0.09%
5	Totally:	72.62%	75.85%	3.24%

Table 2. Electricity generation for a selected 7 days of summer season – daily peaks and valleys are addressed

3 DISCUSSION

The presented results were only indented to verify the possibility of increasing electricity generation for a CHP plant resulting from installation of a heat storage tank. For this purpose two 7-day periods were selected to represent average conditions at several plants in Poland. In order to determine production, plant structure and output were defined. An appropriately dimensioned heat storage tank was proposed. All those assumptions impact the attainable production increase.

Additionally, one very significant simplification was made. It was assumed that the plant can vary output immediately. In reality, changing output takes time. Besides, there are many additional restrictions of a technical nature. Therefore, the results only show the potential which could be achieved.

The test calculations did not include operational optimisation for the plant. Only the output of operating sources and the tank were determined. Therefore, applying optimisation methods to the entire system could further increase the beneficial effect revealed by this simulation.

The calculations made indicate that for a proposed plant it is possible to increase electricity generation during load peaks by several per cent. The feasibility of the operating regime will be decided by the difference in electricity sales prices between night and noon valleys on the one hand, and morning and afternoon peaks on the other. The proposed financial optimisation criterion should automatically propose a regime which results in maximised electricity sales profits.

4 CONCLUSIONS

The issue of optimising operations of a heat storage tank cannot be considered separately from optimising operations of an entire CHP plant.

Currently, the authors are conducting further research into this issue. In the near future it will be possible to generate a full set of results for a real plant, which will illustrate operations of a large CHP plant fitted with a heat storage tank. It is planned to use the described algorithm for predicting the operations and optimising loads according to the description presented above, and to compare the results against real measurements. This paper is a presentation of initial stage results concerning cooperation between a heat storage tank and a large CHP plant based on a model of a CHP plant with an accumulator of that type.

ACKNOWLEDGMENTS

This scientific work was financially supported in the period of 2009 ÷ 2010 as a research project.

REFERENCES

[1] Bogdana Z., Kopjar D., “Improvement of the cogeneration plant economy by using a heat accumulator”, Energy 31, 2006.

[2] Badyda K.: “Heat storage in small and medium size systems”. (Magazynowanie ciepła w układach małej i średniej mocy). Opracowanie w ramach projektu CAMELIA, zadanie VI: Thermal Storage and Distribution, IPPT-PAN, Warsaw 2006.

[3] Dotzauer R. “Simple model for prediction of loads in district-heating systems”, Applied Energy 73, 2002.

[4] Stig-Inge Gustafssona, Karlsson B.G., “Linear programming optimization in CHP networks”, Heat Recovery Systems and CHP, Volume 11, 1991.

[5] Lund H., Münsterb E., “Modelling of energy systems with a high percentage of CHP and wind power” Renewable Energy, Volume 28, 2003.

[6] Bujalski W., Lewandowski J., Uzunow N., “On-line optimization of the load distribution in power generating installation”, Proceedings of the International Conference on Power Engineering-03 (ICOPE-03) November 9-13, 2003, Kobe, Japan

[7] Badyda K., Bujalski W.: “Analiza pracy elektrociepłowni z członem kondensacyjnym w warunkach uwolnionych cen” (CHP analysis in free market conditions). Zeszyty Naukowe Politechniki Warszawskiej s. Konferencje z. 24 (2005)

[8] Thorstensen B., “Combined heat-and-power plants and district heating in a deregulated electricity market”, Applied Energy Volume 78, pages 37-52, 2