Utilization of District Heating Networks to Provide Flexibility in CHP Production

Citation

Year
2017

Version
Publisher's PDF (version of record)

Link to publication
TUTCRIS Portal (http://www.tut.fi/tutcris)

Published in
Energy Procedia

DOI
10.1016/j.egypro.2017.05.077

Copyright
This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 license. To view a copy of this license, visit http://creativecommons.org/licenses/by-nc-nd/4.0/

Take down policy
If you believe that this document breaches copyright, please contact tutcris@tut.fi, and we will remove access to the work immediately and investigate your claim.
The 15th International Symposium on District Heating and Cooling

Utilization of District Heating Networks to Provide Flexibility in CHP Production

Timo Korpela*a,*, Jyri Kaivosoja, Yrjö Majannea, Leo Laakkonenb, Maria Nurmoranta and Matti Vilkkoa

*aTampere University of Technology, Department of Automation Science and Engineering, Korkeakoulunkatu 3, 33720 Tampere, Finland
bValmet Automation Ltd., Lentokentänkatu 11, 33900 Tampere, Finland

Abstract

Increasing penetration of intermittent renewable energy production in power systems will remarkably increase the need of flexible and controllable power generation. As numerous existing thermal power generation units have been closed down, all the possible flexibility available in power systems should be harnessed to stabilize the power systems. Combined heat and power (CHP) generation is widely used in district heating (DH) systems. As total heat production into the DH network needs to be balanced with the total heat consumption, this sets significant limitations to the long-term power production. However, the heat load and electric production can be decoupled temporarily by using the heat storage capacity of DH networks and heat accumulators. This paper presents an analysis of dynamic operability of interconnected CHP plants and district heating networks. The flexibility of generation capacity was compared with the requirements set when attending the Automatic Frequency Restoration Reserve (FRR-A) market. For that, two case studies were presented that include FRR-A tests in two municipal CHP plants. The results indicate that both cases fulfil the requirements and that the DH network operation is affected only slightly. However, the rapid power level changes are disturbances to CHP boilers and DH networks that the process components and automation systems must adapt to. Therefore, these aspects must be considered carefully when applying such new operation practises in existing CHP plants.

© 2017 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the Scientific Committee of The 15th International Symposium on District Heating and Cooling.

Keywords: District heating; flexibility; CHP production; electricity; frequency control
1. Introduction

As a global trend, the capacity of intermittent renewable power production, i.e. wind and solar power, has increased rapidly and the drive to carbon neutrality ensures the upward trend in the future. As the life cycles of energy system components are traditionally very long, it is cost and resource efficient that the existing systems can be modified compatible to new operation environments with accelerated dynamics and flexibility. The special need is for the momentary change and especially the increase of the power production so that the other production and consumption units shall have time to adapt to a new state, e.g. additional boilers to start-up or running plants to increase their power output, or some consumers to reduce their consumption in a well-organized manner. A review of energy system flexibility measures that are applicable in existing technologies to enable variable renewable electricity is presented in [1].

District heating (DH) is a system for distributing heat that is generated in centralized units. DH has a high coverage especially in North, Central and Eastern Europe and it is primarily based on combined heat and power (CHP) production supported by heat only boilers. In CHP production, back-pressure turbo generators that produce electricity and heat at fixed ratio are very common. As total heat production into the DH network needs to be balanced with the total heat consumption, this sets significant limitations to the power production. This issue is important, as CHP production and DH are seen as a future prospect to lower CO2 emissions [2].

The momentary power increase in CHP production can be conducted in two ways, when the steam turbine is not yet running at its full capacity. The first option to increase the power production is to disconnect the fixed ratio of heat and power production in the unit, e.g. by controlling the bypassing reduction valves of turbines (by-pass), by reducing internal steam consumption (condensate stop) or other respective actions. The second option to momentarily increase the power production is to maintain the fixed ratio but increase the boiler power output, and to store or waste the excess heat that is produced along with electricity. The storing can be conducted by utilizing heat accumulators [3-7] and district heating networks as heat buffers [8-10]. In practise, the solution can be a combination of these both methods, depending on the required power change rate and capacity requirements. The second approach is studied in this article.

The most effective exploitation of the flexibility potential of CHP plants take place when the plant owners are able to take part in some market where the flexibility in electricity production can be tendered. One of such market is Automatic Frequency Restoration Reserve (FRR-A) in the Nord Pool power market in Nordic countries. The market structure defines the change rate and capacity requirements to enter the market. The attainment of the requirements depends on the CHP plant and DH network structures and their momentary operation regions. Therefore, it is useful to analyse the potential of different flexibility sources, to assess the possibility to take part in different markets and to analyse how the plant operates during momentary change of power level driven by external control signal. However, the flexibility markets are still developing, and as a part of the process the FRR-A is not currently active in Nordic countries. However, it provides indication of possible requirements and prospects in the future market structures.

In FRR-A type of operation, an external signal activates the power set point change without a prior notice, which can be considered as an external disturbance that will affect the operation of the boiler and the DH network and its nearby components such as heat accumulators and heat only boilers. When considering the effect of a sudden power level increase in a typical CHP boiler, the steam flow through the turbine increases. As the result, the steam pressure starts to drop, which the steam pressure controller starts to compensate by increasing the fuel power set point. The pressure control is typically assisted by feedforward connection from live steam flow to fuel feed. The pressure drop is modest if the fuel feeding system components, especially the coal mills, are fast enough to compensate the fuel power drop. On the other hand, the power increase will contribute also to increased heat power to DH network with fixed heat to power ratio. If the DH network is in balance before the disturbance, the supply water temperature will increase, which will again affect the operation of nearby DH accumulators and heat only boilers. Therefore, the sudden power set point change will affect widely the operation of the whole system and can be considered as external disturbance that the processes and automation systems must tackle. However, this kind of operation principle with fast dynamics is unfamiliar to existing and especially to municipal CHP plants, as the components, automation systems including controller tunings are not designed for that kind of operations and disturbances. Therefore, in addition to analysing the capability of CHP plants to fulfil the requirements of FRR-A, the operation of
other system components and automation system should also be analysed carefully, to discover the possible operational bottlenecks that might actually limit the utilization of rapid power change rate and volume in practice.

This paper studies technical flexibility potential of CHP production in DH network by analysing measured data to estimate the transient capability of CHP production and DH in relation to FRR-A requirements. For that, analyses of two case studies are made from two municipal CHP plants and DH networks. Although FRR-A requirements are of special concern of this article, the principles are somewhat the same in different flexibility market mechanisms but with different change rate and volume requirements, and hence the study is applicable to other markets as well.

The structure of this article is such that first the general control principles in DH network are described. After the introduction of principles and requirements of the FRR-A market, two case studies are presented that include FRR-A tests in CHP plants that utilize a heat only boiler and a DH accumulator to balance the heat production variations that are caused by changes in power production. Finally, the results are discussed and concluded.

2. Dynamics and control of DH networks

Control of DH systems consists of pressure controls and temperature controls. Pressure controls regulate the pump stations to produce desired DH mass flow and pressure difference for the DH customers. Dynamics of pressure transients are relatively rapid enabling the utilization of standard control methods. Instead, dynamics of temperature behaviour in DH network is related with the flow rate of DH water typically resulting to delays of several hours that vary depending on load and production characteristics and the structure of the network. Due to varying time delay, the uncertainty in estimation of heat consumptions and definition of optimal supply temperatures at different times are issues that have contributed for the current situation of low level of automation in temperature controls. For those reasons, the supply temperature is usually adjusted manually by the system operators according to the time of the day and outdoor temperature, and empirical knowledge about the system characteristics. However, with functional supply temperature controls the heat losses and pumping costs can be balanced to provide minimum running costs of the system. As the pumping costs are significantly lower than the heat losses, it is desirable that the supply temperatures in DH networks are kept as low as possible still to meet the load requirements [11].

The option to increase momentarily the supply temperature and flow in DH network enables the utilization of DH network as an energy storage capacity. This can be utilized to avoid temporary start-ups of supporting heat stations with significantly higher running costs, and especially in the future to utilize the DH network to accumulate heat in case that CHP plants increase their power output according to power grid requirements. However, there is a limit for temperature gradients (ΔT), in order to keep the thermal stresses of network structures at permissible levels. For this reason some rule of thumbs are provided for ΔT_supply in literature: maximum of 1–2°C in 6 minutes that is generally applied in Finland. In practise, some of the DH operators have much more conservative change rates, which is understandable when the increase of ΔT is not really required, e.g. due to objective to minimise thermal stress. However, the opposite goals are also presented [12]. In addition to the change rate, there is a limit for supply water temperature from a CHP plant should not differ more than 10°C from that of other units on operation in the same DH network to avoid excess thermal stresses in boundaries where the supply waters mix [13]. As a conclusion, the ΔT_supply should be constrained when utilizing the DH network accumulation capacity in varying process conditions.

3. Electricity market in Nord Pool

Nord Pool is a power market that offers trading, clearing and settlement in day-ahead and intraday markets across nine European countries: day-ahead market in the Nordic, Baltic and UK and intraday market in the Nordic, Baltic, Germany and UK. Additionally, balancing power and reserve markets exist in the countries that contribute to joint transmission system grid operation. [www.fingrid.fi] Finland is a Nordic country, and the Finnish market is of special concern in this article, although the markets in other Nordic countries are similar.

The reserve market products available in Finland are divided in respect to activation timeframes (seconds to hours) and procedures (manual and automatic), which are illustrated in Figure 1. Frequency Containment Reserves (FCR) are used for the constant frequency control in second-minute time scale. Frequency Restoration Reserves (FRR) are used for returning the frequency to its normal range and to release activated FRC back into use up to fifteen minutes. Replacement Reserves (RR) release the activated FRR’s back to back-up, but this market is not currently active in Nordic power system. [www.fingrid.fi]
An applicable reserve market product for CHP plants is Automatic Frequency Restoration Reserve (FRR-A\(^1\)), which enables that the frequency backup (upward and downward) capacity can be tendered in hourly market but are only activated in special cases when the frequency in Nordic transmission grid is significantly deviated from the reference 50 Hz. If the bid is accepted in the market, the operator receives a separate energy compensation based on regulation carried out in addition to the capacity payment. In those cases, the FRR-A operation is activated based on external activation signal by the local transmission system operator (TSO), which is Fingrid in Finland. There are two types of activation signals depending on the plant performance to change the power level. For the slower processes, e.g. for CHP plants, the reaction time requirement to activation signal is presented in Figure 2, which illustrates that at least 90 % of the power change must be achieved in less than seven minutes. The step response requirement corresponds to transfer function \( f(t) = 1/(1+sT)^4 \), where ‘\(s\)’ is Laplace variable and the time constant \(T\) is 35 seconds. [14]

When joining the FRR-A market, a contract is signed between a resource owner and the local TSO, in order to provide at least 5 MW\(_{el}\) in the defined time frame. The reserve unit can consist of one or several production units.

\(^1\) Application of FRR-A was interrupted for the present in December 2015 due to delays in development of capacity and energy markets in Nordic countries [Nord Pool].
which enable company level contributions. Before joining the market, activation test that include step changes up and down in a predetermined matter must be approved. [14] An indication of the test runs are presented in next section.

4. FRR-A test: Case studies

For the study, step response tests were made in two municipal coal fired CHP plants. The plants are located in Finland and they produce electric power to the Finnish power grid and district heat to their local municipal DH networks. The CHP units in both cases consist of pulverized coal fired boilers connected to single-stage back-pressure turbines. The first CHP plant is roughly half of the capacity compared to the second one. In the first plant, there is a heat only boiler in parallel with the CHP unit. It is used as a base load capacity, which can be used to compensate heat production variations in the CHP plant. In the second plant, there is a DH accumulator in parallel with the CHP unit which is used as buffer and back-up capacity to stabilize the misbalance between DH consumption and production. Other balance methods, e.g. turbine by-pass, additional condensing LP-turbine, or condensate stop for feed water preheating, were not applied during the tests.

Next the test results are presented and discussed. In both cases, first the operation of the boilers is studied followed by the responses to the DH networks.

4.1. Case 1

In the first case study, the validation test of FRR-A was conducted with the fixed power to heat ratio. Before the test, the CHP plant was operated at ca. 80 % of its nominal load. The electric power production was manipulated based on FRR-A type of control signal, which is presented in scaled form along with the response in Figure 3a. It can be seen that the measured power production followed the set point excellently. After the set point changes, the power levels started to change within 15 seconds and the desired power levels were reached in less than 3 minutes, which satisfy the FRR-A requirement clearly. Next in Figure 3, the set point signal for fuel power from the live steam pressure controller (b) and relative steam pressure and its set point (c) are presented. The boiler automation system is able to control the fuel power accurately and fast enough that the variations in the steam pressure remain low.

Figure 3d presents the supply water temperature of the CHP unit (measurement and set point) in addition to the supply water temperature of total (CHP + heat only boiler) flow to the DH network. It can be seen that the manipulation of fuel and hence the heat power of the CHP unit to the DH network affects the supply water temperature to a minor extent. Figure 3e and f present the relative DH flows and powers from the CHP unit, heat only boiler and their total effects. It can be seen that the effects of power production variations are compensated by the heat only boiler, and hence the DH network is not affected.

As a conclusion for Case 1, the disturbance affected by the FRR-A test to the DH network is negligible. The boiler and its components were fast enough to compensate the effect of the disturbances smoothly without significant fluctuations. Therefore, the CHP plant is ready for FRR-A operation as such.

4.2. Case 2

In the second case, the similar validation test of FRR-A was conducted with the fixed power to heat ratio, but at this time the disturbed heat production was compensated by manipulating heat power output of the DH accumulator. In the current control structure, the district heating pumps control the DH supply temperature of the CHP plant, and the DH accumulator is used to control the pressure in the DH network. In the test the output temperature of the DH accumulator was constant 87 °C, and the return water temperature from the DH network was constant 41.8 °C.

During the test, the electric power production was altered based on FRR-A type of control signal, shown in scaled form along with the response in Figure 4a. As the capacity of the CHP plant is roughly the double compared with the plant presented in Case 1 and the magnitude of power level changes were also double, the relative power set point changes were roughly same in both CHP units. It can be seen in Figure 4a that the measured power production followed the set point fairly well, despite at time period ca. 800–1600 seconds. The reason for the
overshoot was a human error in operation when conducting the test. Additionally, the turbine inlet pressure controller limiting the load change rate conducted by turbine controller was undesirably active at period 0–5000 seconds. Despite that, the power levels started to respond within 30–40 seconds after the set point changes and the desired power levels were reached within 2–3.5 minutes, which satisfy the FRR-A requirement. Additionally, Figure 4b presents set point signal for fuel power from live steam pressure controller, and Figure 4c the relative live steam pressure and its set point. Despite the operation
Figure 3. a) Relative FRR-A control signal and generated power, b) set point signal for fuel power from live steam pressure controller, c) live steam pressure and its set point, d) Supply water temperature of the CHP plant (measurement and set point) and total (CHP + heat boiler) flow to the DH network, e) relative DH flows and, f) relative DH supply powers.
Figure 3. a) Relative FRR-A control signal and generated power, b) set point signal for fuel power from live steam pressure controller, c) live steam pressure and its set point, d) Supply water temperature of the CHP plant (measurement and set point) and total (CHP + heat boiler) flow to the DH network, e) relative DH flows, and f) relative DH supply powers.

Figure 4. a) Relative FRR-A control signal and generated power, b) set point signal for fuel power from live steam pressure controller, c) live steam pressure and its set point, d) Supply water temperatures from accumulator and from heat exchanger (CHP), e) relative district heating flows, and f) relative DH supply powers.
of the inlet pressure controller, there were significant fluctuations in live steam pressure that were caused by the rather slow dynamics of the coal boiler. The plausible explanation for the slow response is the sluggish response of coal mills, which might have time delays of several minutes without the excessive overloading of mill air feeds. Therefore, the fuel set point was not reached in fast transients and hence the steam pressure fluctuated. Despite that, the desired FRR-A requirements were fulfilled, and the results were adequate for the boiler that is not designed for such the fast transients.

Figure 4d presents the supply water temperature of the CHP plant (measurement and set point) and the total supply water temperature (CHP + heat accumulator) supplied to the DH network. Figure 4e indicates the relative district heating flows and Figure 4f the relative DH supply powers. It can be seen that the manipulation of fuel power of the CHP unit affects the supply water temperature to some extent in smaller power changes, but the largest power level changes start the DH supply water temperature and flow to oscillate due to over-compensation. The excessive DH flow compensation can be seen in supply water temperature variation and after a delay in the discharge of accumulator that compensates the power fluctuations. Therefore, it seems that the control loops interfere with each other in large transients, so retuning of control loops is likely to improve the performance significantly.

As a conclusion, the slow response of coal mills and hence the slow dynamics of the boiler load change limited the dynamic change rate of the CHP plant. Additionally, the heat power fluctuations caused fluctuations in the DH network which can to significant extent be compensated by improved controller tunings that also consider the cases of fast and sudden disturbances caused by momentary power level changes. Despite of these facts, the dynamic transient requirements of FRR-A were clearly fulfilled, which is a good result from a CHP system that was not originally designed for such operation.

5. Discussion

CHP production can contribute to balancing the power grid and increase power production flexibility in two ways that are either relatively small amounts of power that can be obtained fast or relatively significant amount of power that can be obtained slowly. The first category was considered in this article. In the presented case studies, the first CHP plant is able to satisfy the FRR-A requirement without causing any disturbances to boiler pressure stability or to DH network. The second CHP plant is also able to meet the FRR-A requirement, but the slow dynamic responses of coal mills cause more fluctuations to the steam pressure. Additionally, the DH network was affected. The significance and value of all these flexibility actions depend on the amount of uncontrollable renewable power production compared to controllable power production, in addition to development of power consumption, storage technologies and other flexibility measures. However, cost correlation should be maintained in the new energy system, and therefore the primary and secondary effects of the flexible operation in existing CHP systems should be considered carefully e.g. in maintenance costs and emission control. In the short term the increased amount of renewables contribute to changes in operation practices of existing CHP systems and in long term to changes in dimensioning of the plants and their components, e.g. in coal mills, boiler energy capacity, turbine, materials etc. In all these cases the bottle necks must be identified and carefully considered, in order to provide safe and sound operation of the plants also in the future.

As was discussed, the reserve unit taking part in FRR-A can consist of one or several production units, which enable company level contributions. Therefore, all the existing system components can contribute to flexibility if they do not pass the test individually or the secondary effects of rapid power level changes are not acceptable for some reason, which is very advantageous in order to exploit all the flexibility there reasonably exists.

6. Conclusions

In this paper, utilization of district heating network to provide flexibility in CHP production was studied. In special interest were the properties of the grid balancing market (FRR-A) that sets requirements for change rate and volume in power production. For that, two case studies were presented that include FRR-A tests in two municipal CHP plants that utilize a heat only boiler and a DH accumulator to balance the heat production variations. The sudden and rapid power level changes are disturbances to CHP units and the DH networks, which the automation
systems must take care of. Therefore, the operation of the whole system must be considered, not just the power change properties. Despite of some operational aspects, the dynamic transient requirements of FRR-A were clearly fulfilled with both CHP plants, which is a good result from CHP systems that are not designed for such operation.

In order to provide dynamic flexibility to power production and when considering the CHP production, the dynamic bottle neck can be in the dynamics of boiler or in the DH network. For relative small power variations, e.g. provided in FRR-A market, the DH network operation is not affected that much, but this depends on the properties of the CHP unit, the DH network and the prevailing conditions. In cases where the variations in power output of CHP unit to the DH network can be compensated by the operation of DH accumulator or heat only boiler, the dynamics of the boiler might be the limiting factor. An indication of this was observed in Case 2 where the limiting factor for fast power changes were the properties of the coal mills. However, the operation of control systems should be carefully studied when new operation principles are put into operation.

In the future, the effect of flexibility to boiler and component structures should be studied thoroughly in order to operate the existing systems safely in operation environments that they are not designed for. Also the other dynamic balancing methods, e.g. turbine by-pass, additional condensing low pressure turbine, or condensate stop for feed water preheating should be studied. Additionally, district cooling should be included in the flexibility studies, since the application of district cooling has started to increase rapidly and it provides possibilities to improved overall energy efficiency. The effect of power level to dynamic flexibility in CHP systems should also be studied in the future.

Acknowledgements

This work was carried out in Task 2.3 of research program Flexible Energy Systems (FLEXe, grant no. 2532/31/2014) and supported by Tekes - Finnish Funding Agency for Innovation. The aim of FLEXe was to create novel technological and business concepts enhancing the radical transition from the current energy systems towards sustainable systems. FLEXe consortium, coordinated by CLIC Innovation Ltd, consisted of 17 industrial partners and 10 research organisations. Additionally, the work was supported by Strategic Research Council at the Academy of Finland via project “Transition to a Resource Efficient and Climate Neutral Electricity System (EL-TRAN, grant no. 293437). The authors of the article gratefully acknowledge the financiers and project partners.

References


