A REAL TIME CONTROL MODEL FOR MICRO COMBINED HEAT AND POWER SYSTEM OPERATION

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ABSTRACT

This paper presents and approach for optimizing the operation of a micro-Combined Heat and Power system (µCHP) in a real time price market scenario. The objective is to determine the optimal operation set-point for the µCHP for the following five minutes according to the real-time price signal sent by the System Operator (SO) so as to maximise the profits obtained from the operation of the device while thermal demand requirements are fulfilled. The control algorithm makes use of the relative price concept in the decision making process as well as price sensitivity information of the end-user. Results of the simulated case studies show the feasibility of the proposed model for controlling the operation of a µCHP in a real-time price based market scenario in terms of economical profitability compared with a conventional thermostat based operation mode.

INTRODUCTION

The increasing pressure from the European and international community and national governments to move towards a low carbon generating future is substantially increasing the contribution from renewable (e.g. wind and photovoltaic) and more efficient energy sources (e.g. combined heat and power systems). Unlike conventional generation, outputs of many of these renewable sources follow weather conditions or demand for heat, which at high levels of penetration pose a significant challenge associated with balancing of demand and supply [1].

On the other hand, extensive roll-out of communication systems and intelligent metering capabilities is expected for the segment of small end-users of electricity. This information technology has the potential of enabling demand to respond to market signals, interact with system operation and participate in the system balancing. [1].

In this work, a real-time market scenario that lets distributed energy resources and flexible electricity demand receive and respond to real-time price signals defined by System Operator (SO) every five minutes is considered. This price reflects the need for up or down regulation due to an imbalance in the power system. If no imbalance exists, the real-time price is equal to the day-ahead price [1], [2].

In this paper a tool for optimizing the operation of a micro-Combined Heat and Power system (µCHP) in the described real-time price based scenario is provided. The objective of this "local controller" is to determine the optimal operation set-point for the µCHP that maximises the profits obtained from the operation of the µCHP while thermal demand requirements of the building are fulfilled. The µCHP unit is linked to a heat storage tank that provides it with flexibility by decoupling thermal generation and demand. Both, units controlled with ON/OFF settings as well as those that can operate at part load regulated in power steps are supported by the model.

The control algorithm makes use of the relative price concept in the decision making process for determining whether the current price is high, low or intermediate in relation to historical data. According to it as well as the current status of the µCHP and the price sensitivity of the end-user, the control action to be taken in the following 5 minutes is decided. Constrains related to start-up time of the µCHP as well as minimum on-time are taken into account in this decision process. The main advantage of the proposed model lays on its simplicity and low computational effort required in comparison with other controllers based on optimization algorithms [3],[4].

To demonstrate the applicability of the model a case study is considered. This is aimed to demonstrate the feasibility of the proposed algorithm for controlling the operation of the µCHP in a real-time market scenario in terms of economical profitability for the end-user compared with a conventional thermostat based operation mode.

µCHP CONTROL MODEL

In the considered market scenario, a real-time price is sent to consumers every 5 minutes. End-users are equipped with local controllers connected to Distributed Energy Resources (DER) or controllable loads. These are in charge of receiving the current price and deciding control actions for these devices with the aim of increasing end-user's income or reducing his electricity cost respectively.

This chapter describes the algorithm to be implemented in a µCHP local controller. The objective of this algorithm is to determine the optimal operation set-point for the µCHP for the following five minutes according to the received real-time price signal in order to maximize economic revenues coming from the selling of the generated electricity. It is considered that the unit, which is heat driven operated, works in combination with a heat storage tank that provides it flexibility to decouple thermal generation and demand. The proposed control model takes into account constrains related to start-up time and minimum on-time of the µCHP. In addition, it is valid for both, units controlled with ON/OFF settings as well as for those that can operate at part load regulated in power steps.

Inputs to the model are listed below:

P_{z+1}	Real time price of electricity for the following 5 minutes (€/kWh)
P_z^{aver}	Average price, calculated from last 24 hours real time prices (€/kWh)
P_z^{dev}	Standard deviation of price, calculated from prices of last 24 hours (€/kWh)
K_p	Relative price at which the controller will fully charge the heat storage system
τ	Time constant defining how long a price change affects the relative price (h).
J	Number of power steps at which the µCHP can be operated. These define percentages of its maximum capacity. Examples: J=4 : 25%, 50%, 75% and 100%; J=1: 100% (ON/OFF).
$Z_{chp}^{start-up}$	Start-up time of the µCHP (min.)
$Z_{chp}^{\min On}$	Minimum on-time of the µCHP (min.)
$T_{stor}^{\max}$	Maximum temperature of the heat storage system (ºC).
$T_{stor}^{\min}$	Minimum temperature of the heat storage system (ºC).
Z_{chp}^{iniOn}	Time that the µCHP is ON at the current time-step z. If the value is 0 it means that it is OFF (min.).
T_z	Current temperature of the fluid in the heat storage system (ºC).

The developed control algorithm makes use of the relative price concept in the decision making process for determining whether the current price is high, low or intermediate in relation to historical data. This price is calculated with the following formula [5]:

$$P_{z+1}^{rel} = \frac{P_{z+1} - P_z^{aver}}{P_z^{dev}} \qquad (1)$$

Where P_z^{aver} and P_z^{dev} are updated for each 5-minute time step (Δz) with formulas (2)-(4). Relative price definition needs initialization of P_z^{aver} and P_z^{dev}.

$$P_{z+1}^{aver} = P_z^{aver} + \frac{\Delta z}{\Delta z + \tau} \cdot (P_{z+1} - P_z^{aver}) \qquad (2)$$

$$P_{z+1}^{\mathrm{var}} = P_z^{\mathrm{var}} + \frac{\Delta z}{\Delta z + \tau} \cdot ((P_{z+1} - P_{z+1}^{aver})^2 - P_z^{\mathrm{var}}) \qquad (3)$$

$$P_{z+1}^{dev} = \sqrt{P_{z+1}^{\mathrm{var}}} \qquad (4)$$

The decision process is based on the following decision diagram where A%, B%… represent the different power steps at which the µCHP can be operated [5]:

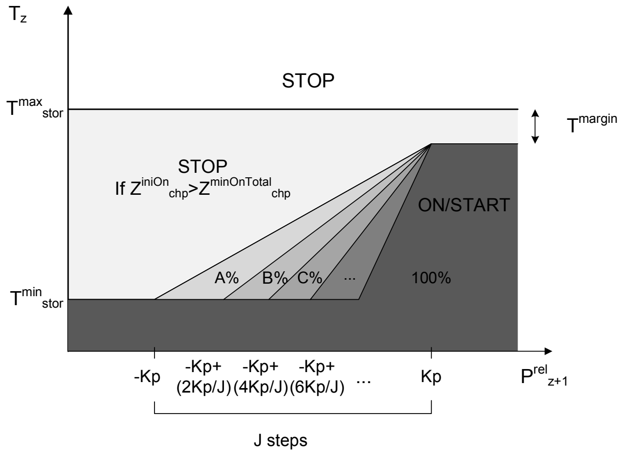


Figure 1- Decision diagram for the operation of a µCHP with J operating power steps

$Z_{chp}^{\min OnTotal}$ is the total time that the µCHP must be ON each time it is started. It is calculated by adding the start-up time and the minimum on-time.

The µCHP can only be started when there is a certain margin to the maximum heat storage temperature. For this purpose, the temperature safety margin T^{margin} is defined. It represents the temperature increment that it would be produced in the heat storage if the µCHP was operated at its maximum capacity during the minimum on-time total and the thermal demand was equal to zero.

According to the diagram, the set-point for the following 5 minutes is decided as a function of the relative price as well as the current temperature of the heat storage tank. The possible control actions are: start, stop or remain in the current status. For µCHPs with regulation capabilities it is also possible to increase/reduce its power output by changing their operation regime to other power step.

The parameter K_p affects the responsiveness to price changes and must be chosen carefully. It has to be taken into account that the storage temperature affects the opportunity to reach on future attractive prices. In this approach, it is assumed that the lower the relative price, the lower regime the µCHP is operated, and consequently, the lower the tmperature in the heat storage is kept. In this way the potential profit to be made when the price increases is maximised.

Finally, Figure 2 shows particularization of the previous decision diagram for a µCHP that is operated with ON/OFF control signals:

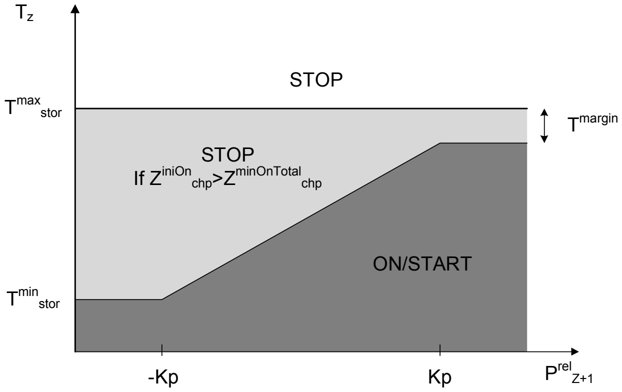


Figure 2 – Decision diagram for the oepration of a µCHP controlled with ON/OFF settings

CASE STUDY

In this section, simulations on a specific case study are conducted in order to assess the financial benefits obtained from the operation of the µCHP with the proposed control algorithm in a real-time price market scenario. For this purpose, comparison with a conventional thermostat mode operation is carried out.

Input data

A µCHP system of the following characteristics is considered:

Table 1 – Equipment data

Device	*Parameter*	*Value*
µCHP	Heating power	10.5 kW_t
	Electric power	5.5 kW_e
	Min-on time	15 min.
Heat storage	Temperature limits	50-80ºC
	Volume	750 l.

It is assumed that the thermal demand is constant during the whole day and equal to 5.25 kW_t. The µCHP is OFF at the beginning of the simulation being the initial temperature in the heat storage tank equal to 60ºC. User settings are K_p =1 and τ equal to 24 hours.

In the study, two different types of µCHPs are considered. The first one is controlled with ON/OFF control signals. The second one can be part-load operated in four power steps (25%, 50%, 75% or 100%). Simulations are performed on a weekly basis.

System simulator

To carry out the simulations it is necessary to define a system model that emulates the dynamics occurring in the heat storage tank as a function of the thermal production of the µCHP as well as the forecasted thermal demand. In this work, the following thermal balance is considered:

$$\Delta T = T_{z+1} - T_z = \frac{(P^{therm}_{chp_{z+1}} - D^{therm}_{z+1}) \cdot \Delta z}{C^{fluid}_{stor} \cdot v_{stor}} \qquad (5)$$

Where $P^{therm}_{chp_{z+1}}$ is the forecasted average thermal production of the µCHP during the following 5 minutes depending on the set-point decided by the µCHP-controller. v_{stor} is the volume of the heat storage tank (l.) and C^{fluid}_{stor} the specific heat capacity of the fluid in the heat storage system (kWh/(ºC·l)).

Results

Figure 3 shows the real time price time series considered for the case study [2]. It is composed of 2016 price values corresponding to a whole week of data:

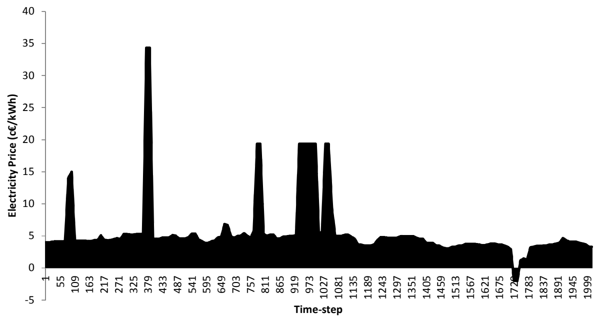
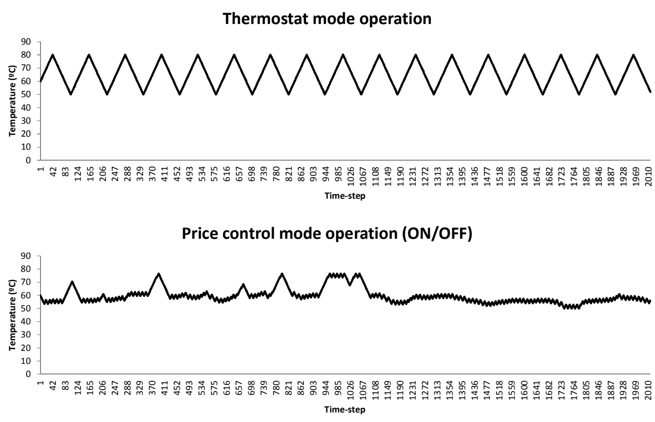


Figure 3 – Real time price time series (1-week test)

Results provided by the control algorithm are shown in Figure 4. Specifically, this figure provides the temperature variation in the heat storage tank for 1) thermostat mode operation (base case), 2) µCHP operated with ON/OFF control signals and 3) µCHP regulable.



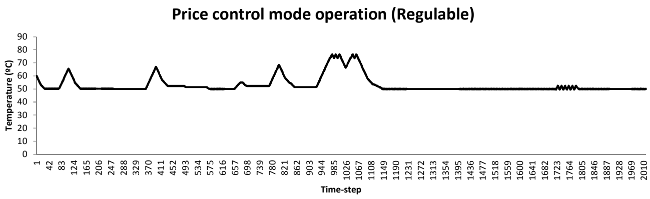


Figure 4 - Temperature in the heat storage tank for the different operation modes

It can be observed that in the thermostat mode operation, the µCHP is operated following ON/OFF cycles. Specifically, it is switched-on until the temperature in the storage tank reaches the maximum limit and afterwards it is switched off until the temperature reaches the lower limit. This pattern is repeated consecutively along the day independently of the electricity prices.

In contrast, in the price-control operation mode, the temperatures follow the price profile. In this case, the temperature in the tank is maintatined at low levels in order to have storage margin for maintating the µCHP in the ON status during the peak prices time period. With a regulable µCHP it is possible to carry out a more accurate operation of the µCHP and as a consequence, to adjust its operation better to the thermal demand. In this particular case, the thermal demand is half of the thermal capacity of the µCHP. Consequently, the µCHP is operated at 50% most of the time. However, the control algorithm decides to operate it at 100% during the during the peak prices period in order to maximise revenues.

Table 2 shows a comparison of the benefits and costs for the three different operation modes. The second column in the table includes the thermal costs of the µCHP due to the burned gas and the third column the revenues obtained from the selling of the generated electricity.

Table 2 – Results summary

Operation mode	*Algorithm solution*		*Total cost (€)*	*Savings*	
	Thermal cost (€)	*Electric income (€)*		*(€)*	*(%)*
Thermostat	61.08	-27.47	33.61	----	----
Price-control (ON/OFF)	61.08	-29.75	31.33	2.28	6.8%
Price-control (Power Regulation)	61.08	-30.95	30.13	3.48	10.3%

It can be concluded that the total operation costs of the CHP are reduced when using the control algorithm. The savings are higher for the µCHP with regulation capabilities because it is possible to perform a more accurate operation and therefore to fit better its production to the thermal demand. The obtained cost reductions are 6.8% and 10.3% for the ON/OFF and the regulable µCHP respectively. However, savings are influenced by many fators such as real-time price values of the electricity, initialization of the mean and deviation of the electricity prices, relative price limits set by the end-user, thermal demand profile, etc. So these results will depend on the considered scenario.

CONCLUSIONS AND FUTURE WORK

In this paper, a tool for optimizing the operation of a micro-µCHP in a real time price market scenario is described.

The main advantage of this model lays on its simplicity and low computational effort required in comparisson with a controller based on an optimization algorith. In this way it fulfils the requiremetns to be oeprated in a 5-minute time scale. Results of the simulated case studies have shown the feasibility of the proposed algorithm for controlling the oepration of a CHP in a real-time price based market scenarion in terms of economical profitability compared with a conventional thermostat based operation mode.

Future work will involve practical validation of the model in real test sites [2].

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