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Reduction of energy costs and grid instability with energy flexible furnaces

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Abstract

Due to the fluctuations in energy generation from renewable sources, electricity prices on the stock exchange are often subject to strong variations and the control reserve market is becoming increasingly important. In this paper we simulate a flexible furnace that can reduce energy costs of electrical furnaces by varying the energy supply without interrupting the production output rate by using the molten metal bath as storage. The flexible furnace modeled can reduce its power supply and thus contribute to the stabilization of the energy grid.

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Keywords: energy flexibilty; process planing and scheduling; optimisation

1. Introduction and state of the art

In 2016, 32% of the German and 22.3% of the OECD members' electricity consumption was covered by renewable energy sources [1, 2]. Renewable energies satisfying energy consumption in Germany, for example electricity from photovoltaic and wind power plants, have seen a remarkable growth by 94% since 2010. However, the availability of these energy sources is not fully predictable and subject to fluctuations. To stabilize the grid fluctuations are compensated by both positive and negative control measures [3].

The stabilization of the grid and the security of supply can also be ensured by switching off regenerative plants (feed-in management). Providers of control reserve are compensated for call-offs or shutdowns. Furthermore, electricity prices for the German industry increased to 15.48ct/kWh, an increase of 1.47ct/kWh compared to 2016. [4]

This paper describes how energy flexible furnaces can participate on the control reserve market. The results of the simulation show, how flexible energy transfer within a production step can reduce energy costs by participating on the secondary and tertiary control market.

In 2015, 2.84TWh of secondary control reserve and minute reserve were called off and a total of €316 million was incurred to provide the balancing of power. In the same period, redispatch measures amounted to 16TWh or €412 million. Compared to the previous year, the costs for the provision of balancing power decreased by €121 million while redispatch costs rose by €227 million. [5]

With fluctuating energy sources on the rise, attention must be paid to the use of energy and, consequently, to its production as well. Therefore, not only the regulation of power generation but also load management on the consumer side is becoming increasingly important. However, these are only two out of four flexibility options [3]. In addition to the above-mentioned options "control of generation" and "control of consumption" there is also the option to "store energy" and the "regulation of transmission". The storage of energy, its conversion into a different medium (Power-to-X) or the flexible change of energy sources has often been discussed elsewhere [6, 7]. Renewable energies and combined heat and power plants (CHP) already participate on the control reserve market [8]. There are emergency generators, on-site generators and also micro turbines, which distribute their generation on the demand side market [9]. Some electric furnaces already participate in demand side management programs, but those are usually in households [10], electric arc furnaces [11], or have no production pressure. The main

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demand response potential for the die casting industry so far was to shift working hours to nights and weekends [12]. This paper shows a possible performance of die casting crucible furnaces on the control reserve markets - in terms of possible reduction of energy costs for manufacturers and technical performance indicators for operators of virtual power plants to increase their facility portfolio.

The following section (2-2.3) describes the general structure of the German control reserve market, defines how the market is organized and shows the regulations for participating in the control reserve market. The section after, describes the energy performance of a die casting furnace in different conditions during a working day. Before summarizing this paper in section 5, section 4 gives an overview, how the die casting furnace is modeled to participate on the control reserved market, which assumptions were made to participate and how high the financial impacts for providers might be.

2. Control reserve market

There are many ways to offer energy consumption or energy supply on the energy markets. There are three types of control reserve markets [13]:

- Primary control reserve
- Secondary control reserve
- Minute reserve (also tertiary control reserve)

Besides some varying regulations these three types mainly differ by the maximum time required for activation of control reserve.

The activation of primary control power runs completely automatic and must be ramped up or down within 30 seconds with the full power provided instantly. Beyond that, the amount of provided power is completely controlled by the transmission system operator. The primary control lasts for a maximum of 15 minutes in order to keep the main frequency in the electrical grid at 50Hz.

The next measure to keep the network stable is to activate secondary control. Due to the regulations the power of secondary control must be provided within five minutes. After 15 minutes it is replaced by tertiary control reserve [14, 15].

Next action to keep the grid running is to activate tertiary control reserve. This control power has to be fully available within 15 minutes after being called. The call duration can last "up to 4 quarter hours, or up to several hours in case of multiple disorders" [13].

2.1. Prequalification

Despite activation speed, the prequalification test for facilities to participate on the control reserve market is crucial. Among other tests of this qualification, like connectivity or security tests, the double peak test is the most important one. This test shows whether a facility can fulfill the requirements of minimum retrieval speed, or respectively reaction rate.

Figure 1 shows the development of a double peak curve that a facility has to follow when prequalified for tertiary or secondary control reserve. A possible call must be performed in two cycles within a double peak curve. The provider can decide, at which time of a day the machine should perform this double peak curve.

Two cycles are necessary to prove the ability of satisfying the requirements to the transmission grid operator. In figure 1 a combined double peak curve for providing secondary control reserve can be seen. Combined means, that both, regulations of negative and positive secondary control reserve is performed in one double peak curve. There are two peaks for ramping up and two ramps of shutting down.

Positive control reserve is required, when there is not enough energy in the grid. Negative control reserve is needed, when there is too much energy in the grid. The following table shows how positive and negative control reserve can be offered:

Table 1. Providing control reserve

States of facilities	Positive control reserve	Negative control reserve
Switching on energy source	X	-
Switching off energy source	-	X
Switching on energy consumer	-	X
Switching off energy consumer	X	-

When starting the cycle of a positive double peak curve, the energy consumer has 15 minutes when offering tertiary control and five minutes when offering secondary control reserve, to reduce the power which can be provided during this time. After 15 minutes (for tertiary control) or ten minutes (for secondary control) of holding this state, the power must be completely reduced within the same time.

This cycle has to be performed twice in sequence. In case of providing negative control reserve with energy consumers, this cycle has to be performed in the opposite way. First powering up and then reducing again in the same time periods. This is one of the requirements to be able to offer control power.

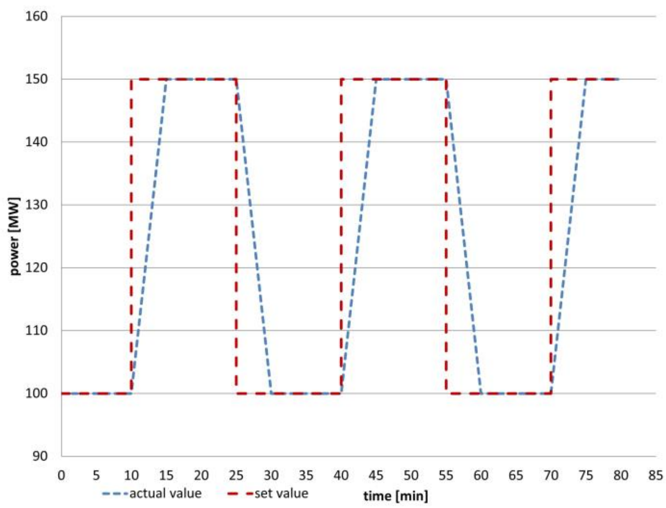

Fig. 1 Combined double peak curve for providing secondary control

For every facility that goes through a prequalification test the power gradient must be specified (Eq. 1). This equation shows how quickly a facility can power up, or reduce its power on average of the time period. Facilities that reach their full power beyond 300 seconds are not allowed to offer secondary control reserve. Those facilities could offer tertiary control reserve. The important indicator is the power that can be supplied within 300 seconds (for secondary control) or 900 seconds (for tertiary control).

$$Power\ gradient = Performance\ [kW]\ /\ time\ [\mathrm{sec}] \qquad (1)$$

Another regulation of the transmission grid operator is the minimum power necessary to be offered to participate on the control reserve market. For both, secondary and tertiary control, 5MW is the minimum power a facility has to offer. However, as a part of a virtual power plant, a facility can participate on the markets providing less than 5MW. [15]

2.2. Virtual power plants and Pooling

A virtual power plant is a network of several (decentralized) electricity generating and/or consuming facilities. These can be nearby or far away from each other. While generally, the facilities within the network of a virtual power plant can be arbitrarily located, in this context it is necessary that all of them are located in the same control area of a transmission grid (pooling).

Monitoring of a virtual power plant takes place in a central location. Virtual power plants are not allowed to offer primary control therefore primary control reserve is not further considered. Pooling is allowed for secondary and tertiary control reserve. [16, 17]

A virtual power plant can be implemented as part of an industrial smart grid. Within an industrial smart grid, it is possible to control and regulate centralized or decentralized facilities within predefined limits, restrictions and action strategies for a company. [18]

2.3. Revenues of control reserve

Payment for participants of control reserve by the transmission grid operator is divided in two different components. The first category is called “demand charge”. Providers of control reserve are paid for offering power regardless of effectively supplying energy. They only have to be accepted as a provider for the next delivery period via a merit-order auction.

The second component is called “energy price” and refers to the providers’ revenue when called to deliver control reserve. The amount of proceeds is again depending on the providers’ bid, chosen via merit-order.

Table 2 shows the possible average amount of combined revenues for 2017. [19]

Secondary control reserve has two periods of time for offering control reserve. The first time slot is called “peak time” and lasts from Monday to Friday between 8 AM and 8 PM. “Off-peak” time period contains the rest of the week.

Table 2. Combined revenues (CR) of control reserve of 0.1 MW

Control reserve typ	Positive control reserve	Negative control reserve
Secondary control reserve peak time (Mon-Fri 8am-8pm)	1,480€	337€
Secondary control reserve off peak time (not peak time)	2,924€	1,281€
tertiary control reserve	532€	1,345€

Tertiary control reserve also consists of several periods of time. It is divided into six periods with duration of four hours, with the first period beginning at midnight. Table 2 shows the monetary preferability to offer positive secondary control reserve in off-peak times for providers’ revenues.

3. Die casting furnaces

Supply of process heating can be subdivided into four segments: Fuel-based, electric-based, steam-based and other heating systems [20]. Currently, die casting crucible furnaces can be operated by burning natural gas, oil or by using electric induction coils or resistance heaters [21, 22]. However, in order to be able to participate in the control reserve markets the required heat must be generated via electricity. Hence, the following information and descriptions refer exclusively to electrically-heated crucible furnaces.

When an electrically-heated die casting furnace is called to offer negative control reserve there is no energy input during the call and the heat supply is interrupted. Consequently the temperature of the molten material sinks.

Depending on the molten material, melting capacity and size of the melt container the required connected load varies between 20kW and more than 0.5MW [23].

Figure 2 shows the electricity consumption of a small zinc die cast furnace with a connected electrical load of 28kW at a regular production day.

It can be seen that the temperature is held throughout the night at 395°C until 6 AM in the morning. The average power to keep the furnace at 395°C is about 3.75kW. At 6 AM the furnace starts automatically to rise its temperature to its operating temperature, which is between 417°C and 424°C. Lower or higher working temperatures could have a negative influence on product quality [24].

During heating time, the average power consumption rises to 28kW. This event recurs right after the lunch break, when the molten zinc has to be heated up to its working temperature again. After 17 minutes of heating, the heaters switch off, but the temperature of molten zinc continues to increase for another seven minutes.

During processing time, the average power consumption of the furnace is about 5.77kW. Before night mode starts again at 6 PM, the last stage of a production is the cooling-off period. This stage lasts about an hour until the die casting furnace has cooled down to 395°C and needs an average 0.08kW for its control system.

4. Modeling of furnaces for offering control reserve

Due to the relatively low power consumption of die casting furnaces, furnaces can only participate in the control reserve market as part of a pool or a virtual power plant as the individual minimum value of 5MW cannot be reached.

Before die casting furnaces can participate on the market as part of a pool, they have to perform the double peak test, proving their ability to change their power consumption within the specified time slot mentioned in 2.1. To simulate a double peak test, it is necessary to know the exact gradients of a die casting furnace. Therefore, the following gradients and critical values are determined out of the dates of figure 3:

- Power gradient (PG)
- Heating temperature gradient (HTG)
- Cooling temperature gradient (CTG)
- Maximum turn-off time
- Maximum power of control reserve

The power gradient can be calculated as described in equation 1. The heating temperature gradient is described in following equation (equation 2):

$$HTG = \Delta T_{heat}\ [K] / \ t\ [min] \tag{2}$$

Describing how quickly the furnace rises its temperature, it is important to know the heating temperature gradient of the processed material. To prevent quality defects, the molten metal should not overheat during working time. The heating temperature gradient of the analyzed furnace reaches a value of 1.26K/min.

To avoid quality defects caused by undercooled molten material, it is also necessary to calculate the cooling temperature gradient (Equation 3).

$$CTG = \Delta T_{cool}[K] / \ t\ [sec] \tag{3}$$

For the analyzed furnace, the cooling temperature gradient has the calculated value of -0.34K/min.

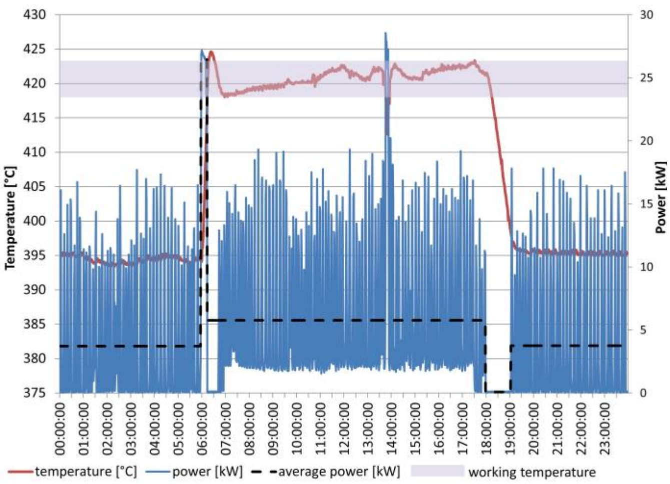

Fig. 2 Energy consumption of a die casting furnace

One method for offering positive control reserve is to turn off the facility's heaters. While the heaters are turned off, the temperature of the molten zinc decreases. Therefore, it is important to determine the maximum period of time without heating that does not interrupt the production (equation 4):

$$Turn - off\ time_{max} = \frac{T_{working\ max} - T_{working\ min}}{CTG} \tag{4}$$

The analyzed furnace allows for a maximum turn-off time of 20 minutes.

The maximum control reserve power which can be offered does not equal the maximum power of a furnace. It is the difference of the particular states, as shown exemplarily in equation 5.

$$P_{neg,night\ mode} = P_{heating} - P_{night\ mode} \tag{5}$$

Table 3 shows all calculated power values that can be offered as control reserve for the given use case.

Table 3. Maximum power (MP) to be offered as control reserve

Control reserve typ	Positive control reserve	Negative control reserve
Control reserve production time	5.69kW	22.23kW
Control reserve night mode	3.67kW	24.25kW

Figure 3 shows the simulated double peak curve of the die casting furnace. It is considered, that after switching off the heaters, the temperature of molten zinc still rises for another seven minutes. The control reserve provided has to be fully available after five minutes but after 30 seconds at the latest, the facility must start the control action. The heaters require two minutes to ramp up the complete power consumption. It can be seen, the temperature of molten zinc rises up to 445°C, which is about 20K above its working temperature. Higher temperatures of the melting bath do not cause any harm to the material quality or neither damages the furnace [25].

A second simulation, beginning with a temperature that is 15K below night mode temperature (380°C) shows a temperature increase of the molten material to 430°C. The experience of the operators and of aluminum melting crucible furnaces showed that lower starting temperatures also aren't problematic for the melting process later [22]. Only the

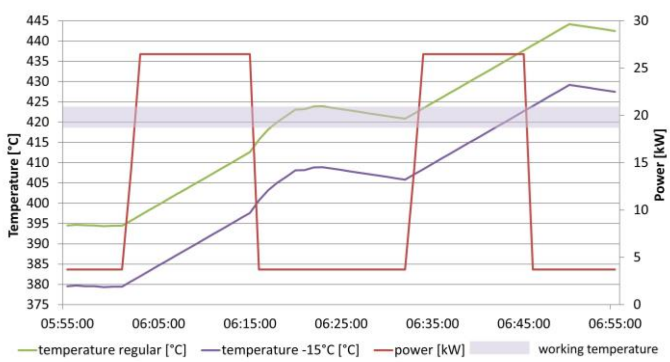

Fig. 3 Modeled double peak curve of a die casting furnace for secondary control reserve

furnaces have to be turned on earlier to archive the working temperature on time.

A double peak curve for offering tertiary control reserve is also feasible as the periods for notification are longer than for secondary control reserve. The process can thus be modeled with an even lower starting temperature.

4.1. Suitability of furnaces during off peak time

As shown, an offering of positive and negative secondary control reserve during off-peak time is possible. Since secondary control reserve only lasts for 15 minutes, the temperature increase of the molten zinc only accounts for up to 20K. This is the typical working temperature of a zinc die casting furnace and should not cause any problems in term of quality losses.

Currently the production of the analyzed company starts at 7AM and the furnace starts to preheat at 6AM. End of production is at 6PM. Off-peak period is between 8PM and 8AM during the week. To participate, shift time has to be adjusted for two hours.

Offerings at the tertiary control reserve market can last from an hour, up to several hours in the case of multiple disorders, leading to a temperature increase of at least 75K. A starting temperature of 395°C might cause difficulties in terms of the quality of the melt, leading to a reduction of night mode temperature to 350°C. It takes about an hour to preheat the molten mass.

Thus, participation on the tertiary control reserve market also results in a deferment of shift time of about three hours. Without any adjustments in working time it is possible to offer negative control reserve between 8 PM and 4 AM (2 of 6 periods).

4.2. Suitability of furnaces during peak time

During work shift, the temperature of molten zinc has to be kept between 424°C and 417°C at all times. Because a call for secondary control reserve lasts for maximum 15 minutes, offering of positive control reserve is possible (figure 3). The melt reaches the lower temperature limit during the call without violating the allowed boundary.

In contrast, offering negative control reserve is not feasible for a single furnace. Due to the narrow limits of the working temperature, the upper limit of the temperature is reached within six minutes. After six minutes, the heaters have to be turned off, otherwise quality problems can occur. However, a serial connection of at least three die casting furnaces with the same heat temperature gradient within a providers balance can facilitate an offering of negative control reserve. Alternatively a lower power value for each furnace can be offered without violating the 5MW restriction.

Offering tertiary control reserve with die casting furnaces during the working shift seems to be problematic as well, due to the same reasons as offering negative secondary control reserve. A positive tertiary control reserve call can last up to several hours. Switching off the heaters for an hour would decrease the furnaces temperature by about 21K. To offer positive control reserve, there must be three furnaces or a decreased value of power for each furnace.

To offer negative tertiary control reserve there have to be at least eleven die casting furnaces. The upper limit of the working temperature is again reached within six minutes. After six minutes the heaters of the die casting furnaces have to shut down to avoid quality problems. Due to the possibility that a tertiary reserve call can also last up to an hour, there have to be at least eleven die casting furnaces to provide the necessary energy during the call. One die casting furnace could also provide less tertiary control reserve. The temperature of the melt does not heat up so quickly. The provider would not need so many furnaces, but then the revenues of one die casting furnaces would decrease.

4.3. Financial Impact

The financial impact can be seen in table 4. Incomes are calculated with the requirements which have been outlined in 4.1 and 4.2. Therefore the combined revenues (CR), listed in table 2, and the calculated maximum power (MP), listed in table 3, are taken as basis. Also the production time had to be adjusted and starts at 8 AM and lasts until 8 PM for all scenarios. It is assumed that offering negative secondary control energy during peak times need four furnaces. All other scenarios for offering secondary control energy were calculated with one furnace. The temperature in night mode was not adjusted.

It's been calculated that offering positive tertiary control energy during peak time need three and offering negative control energy need eleven furnaces. In off peak times there is only one furnace necessary. For calculating the revenues for tertiary control energy off-peak time the night mode temperature has been reduced to 380°C, which is why the provider of furnaces can only participate in five of six slices. The sixth time slice is needed to heat up to working temperature. Equation 6 shows how the revenues have been calculated:

$$revenues = MP\ [kW] * CR\ [€/kW])/(furnaces) \qquad (6)$$

To calculate the revenues for example for negative secondary control energy the combined revenues of 3.37€ were multiplied with 22.23 kW and divided by the number of furnaces needed (here four furnaces). The revenues for a year are about €19.

As the simulations show, the incomes from negative secondary control, positive and negative tertiary control can only be realized, when several facilities work together. Therefore, the calculated incomes are divided by the number of the required facilities to offer the respected control reserve.

Being active on the control reserve market can reduce energy costs as shown in table 4. The highest income can be achieved by offering negative secondary control reserve during off-peak times and positive secondary control reserve in peak times. This combination leads to an overall income of €395 per year.

It can also be seen, that tertiary control reserve does not allow for high revenues due to the requirements. During peak time there are three or eleven furnaces required to offer control reserve. While offering tertiary control reserve during off-peak times also allows for comparable revenues.

Table 4. Income of control reserve with a 28kW die casting zinc furnaces

	Control reserve types	Pos. control reserve	Neg. control reserve
peak	Secondary control reserve	€84	€19
	Tertiary control reserve	€5	€14
off-peak	Secondary control reserve	€110	€311
	Tertiary control reserve	€10	€109

The incomes are relatively low due to the fact that the power consumption of the furnaces analysed is fairly low. However, there are furnaces with higher connected loads, which could participate in the market. It is assumed that furnaces with higher connected loads can perform the double peak curve with the same results.

Therefore the ratio of the connected load and the power which could be offered as control reserve has been calculated. This ratio can be transferred to other furnaces with higher connected loads (figure 4).

Figure 4 shows that higher connected loads also allow for higher revenues. With a 550kW furnace revenues of €6,100 for negative secondary control reserve (off-peak) and about €1,600 with positive secondary control (peak) can be realized. The combined revenue (maximum revenue) equals to €7,700 with one furnace. Figure 4 also shows that the energy costs also increase proportionally to the connected load of the die casting furnace. The energy costs include the preheating, production, and night mode energy consumption. By participating on the control reserve market, energy costs can be reduced by 6.6%.

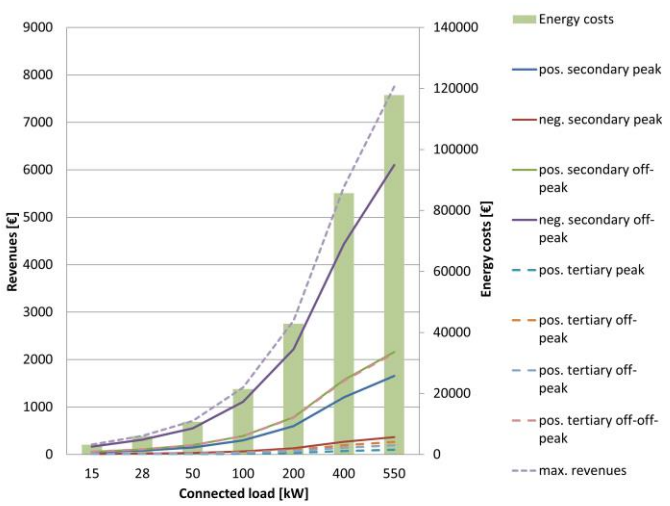

Fig. 4 Control reserve revenues and energy costs of furnaces depending on connected loads

5. Results

As part of a prequalification process double peak curve can be processed successfully with die casting furnaces. This was shown on the basis of a case study with a facility that can reduce and rise its power consumption within two minutes and can maintain its level of power consumption for ten or 15 minutes. Offering control reserve off-peak period is possible. Under certain conditions the analyzed facility can also offer control reserve without interruption of the ongoing production and can decrease energy costs of 6.6%.

6. Outlook

With the double peak curve modelled and simulated here, we showed that it is technically possible to participate on the control reserve market with die casting furnaces. The revenues, which reduce the energy and production costs, are highly dependent on the connected load of the die casting furnace. Continuative work has to analyse the interaction of several furnaces and the detailed costs of participating in a pool of facilities or a virtual power plant.

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