Optimized utilization of groundwood lines with single layer grinding surfaces for pulp production and electrical grid stabilization

Tomas Björkqvist[a], Antti Hildén[b] Yrjö Majanne[c], Matti Vilkko[d], Pertti Pakonen[e], Olli Tuovinen[f]

[a] Tampere University, Automation Technology and Mechanical Engineering, P.O. BOX 589, FI-33014 Tampere University, Finland, tomas.bjorkqvist@tuni.fi

[b] Tampere University, Electrical Engineering, P.O. BOX 692, FI-33014 Tampere University, Finland, antti.t.hilden@tuni.fi

[c] Tampere University, Automation Technology and Mechanical Engineering, P.O. BOX 589, FI-33014 Tampere University, Finland, yrjo.majanne@tuni.fi

[d] Tampere University, Automation Technology and Mechanical Engineering, P.O. BOX 589, FI-33014 Tampere University, Finland, matti.vilkko@tuni.fi

[e] Tampere University, Electrical Engineering, P.O. BOX 692, FI-33014 Tampere University, Finland, pertti.pakonen@tuni.fi

[f] Valmet Technologies Inc., Yrittäjänkatu 21, 33710 Tampere, Finland, olli.tuovinen@valmet.com

ABSTRACT

The climate change is forcing the power production from controllable fossil-based combustion to intermittent renewable resources like wind and solar power. The power production and consumption must be equal at all moments to stabilize the power system. This has traditionally been achieved with controllable production but the new situation with intermittent production requires new solutions. One solution is demand response that means flexible consumption to achieve balance between production and consumption in the power system. This paper analyzes the techno-economical possibilities for groundwood lines with single layer grinding surfaces to both produce pulp and to participate in electrical grid stabilization. Thanks to the on/off nature of the batch processing and the fast-loading response in wood grinding the process is suitable also for more valuable reserve markets. Based on the measured loading response, reserve requirements and marketplace prices investments for participation in Frequency containment reserve for normal operation (FCR-N) and Fast frequency reserve (FFR) have a payback time shorter than 10 months that is attractive for forest industry. After payback the annual earnings are significant.

Keywords: *Single layer grinding surface, demand response, mechanical pulping, grinding, electricity market, reserve market, flexibility.*

INTRODUCTION

The climate change is accepted to be man-made and mainly a result of fossil fuel usage in power production. To stop the negative development the energy systems are increasingly penetrated by carbon free renewable energy sources, i.e., mainly solar and wind power. Already for some years, the main global investments in new power productions have been in renewable resources, whose nominal capacity has grown more than fossil fuel production capacity [International Energy Agency 2021]. Unfortunately, their power output is heavily intermittent and does not typically correspond to power consumption, so other means must be utilized to balance the grid. Traditionally, the power balance has been conducted with flexible power generation. However, the new price situation makes the flexible generation by traditional condensing power plants economically unprofitable. Still flexible generation by hydroelectric power is feasible but this resource is only given to a few countries like Norway and Sweden. One alternative solution to balance the grid is to shift some power consumption from one time instant to another. The trivial solution for that is to exploit electricity storages. Unfortunately, they are still too expensive in large scale. Another option is demand response, where the load is shifted from one time instant to another. From the viewpoint of power balance, load shifting is equivalent to momentary production at peak load i.e., considerable demand response can substitute investments in expensive new peak load capacity. An attractive source of demand response is power intensive industry [Lund et al. 2015], which is also reviewed by Shoreh et al. 2016 and estimated in Finland by Pihala et al. 2005. The prerequisites for utilizing substantial demand response are power consumption intensive sites, natural apparent electrical energy storages and even higher load capacity than needed at a mean. The last prerequisite is essential and may need investments in the order of costs of new peak load capacity if not already existing. This presentation analyzes the demand response possibilities enabled by new single layer grinding surfaces, called "Galileo technology", in groundwood mills.

The energy saving of the new grinding surface technology enables significant production increase of the grinders. The production increase is typically about 30 %. The efficient method was presented in [Lucander et al.2006] and discussed by Björkqvist 2011. The new grinding surface product and its background were reported by Tuovinen 2016. As the pulp lines already include pulp towers and the pulp can be stored 8 hours without quality decrease, the increased

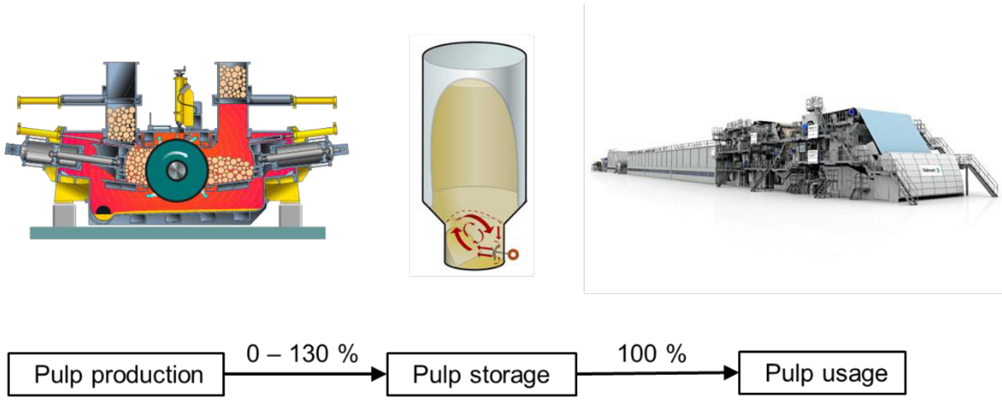


Figure 1. Demand response concept enabled by usage of the single layer grinding surface [Björkqvist et al. 2018].

production capacity can be utilized as demand response without jeopardizing continuous paper or board production. Figure 1 shows the demand response concept enabled by usage of the single layer grinding surface.

The paper “Improving Mechanical Pulping Business Potential by Operating Single Layer Grinding Surfaces on Electricity Market” in IMPC 2018 analyzed the investment profitability potential for upgrading the pulping line to achieve the needed original pulp capacity and for upgrading the rest of the pulping line to achieve demand response capacity for the day-ahead market [Björkqvist et al. 2018]. This paper analyzes business potential in more valuable electricity markets enabled by new technology development in groundwood mills, which are seen as an attractive application of demand response [Paulus et al. 2011].

LOADING RESPONSE OF GRINDER LINE WITH SINGLE LAYER GRINDING SURFACES

We analyze the active power usage during normal operation to determine the power response during wood batch operation. The analysis uses data acquired with power quality analyzer measurements for both current and voltage values of the 10.5 kV medium voltage three-phase feeder of the synchronous motor for a tandem grinder line.

The data acquisition was done in a pulp mill of a Finnish paper mill on one grinder line consisting of one synchronous motor driving two grinders. The nominal effect of the line is 12 MW and both grinders are equipped with single layer grinding surfaces. The line produces groundwood pulp for printing paper. The reason for special data acquisition is that the conventional power measurement by the automation system filters the power signals and acquires data at too low frequency to reveal fast load changes. The measured data consists of six approximately 15 minutes measurements during normal operation.

Data acquisition for power measurement of a tandem grinder line

Two Dranetz PowerXplorer PX5 power quality analyzers were used for the active power usage measurement of the grinder line synchronous motor feeder. The power quality analyzers were installed in parallel, and they monitored the three line-to-line voltages of the feeder and the currents of the phase conductors L1, L2 and L3. The voltages were measured from the secondary of an instrument transformer of the feeder and currents were sensed with LEM Flex RR3030 current probes that were installed temporarily around the conductors of the feeder. The measurement setup is illustrated in the diagram of Figure 2. Photographs of the power quality analyzers and the current probes are presented in Figure 3.

The power quality analyzers sampled voltages and currents at rate of 12.8 kHz. One of the power quality analyzers was used for a continuous measurement recording of voltage and current at one-second interval and the other one was triggered to record 20-millisecond rms values and waveforms of the voltages and currents over batch operation periods. The waveform data were utilized in the analysis of this paper to post-process 20-millisecond three-phase total active power values that are calculated every 10 milliseconds. The post-processing was done in Dran-View 7 software.

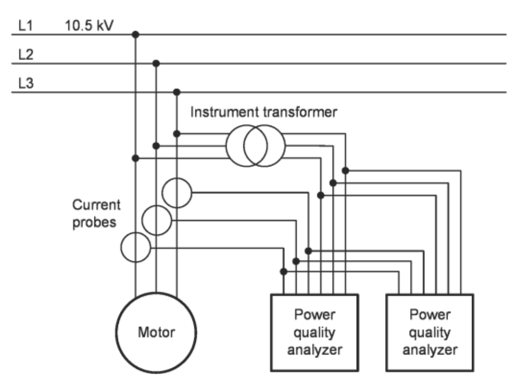


Figure 2. Diagram of the measurement setup of the grinder line synchronous motor.

Figure 3. Measurement setup with power quality analyzers and current probes around the feeder conductors of the grinder line synchronous motor.

Data acquired from a Finnish pulp mill

Figure 4 shows an example of power usage calculated from current and voltage measurements from one of the measurements. All six measurements are though similar in nature. The data shows the cumulative power usage of four loaded pockets of the two grinders, each pocket with a nominal power of 3 MW. The fast power drops reflect ending of a batch and the somewhat slower power increases shows starting of a new batch. The figure mainly shows load levels representing grinding situations where two, three or four wood batches are in operation. As batch operations work partly dependently there is seldom the situation when only one batch or zero batches are in operation. The duration of one grinding batch is 2 to 3 minutes and batch reloading takes at maximum 30 seconds.

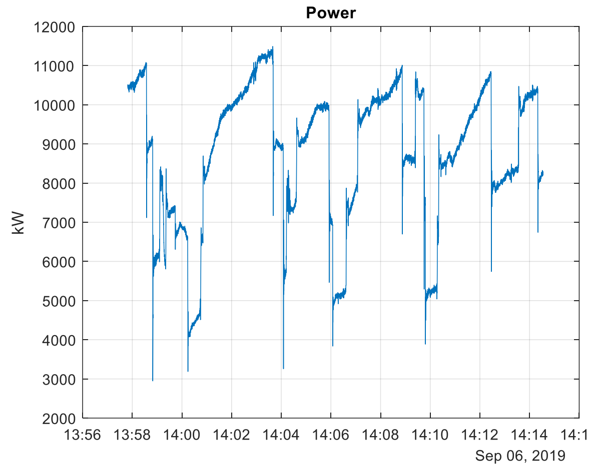
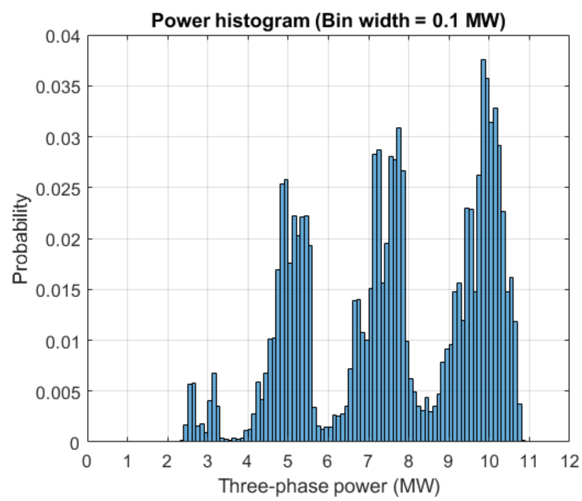


Figure 4. Power usage of the tandem grinder line during normal batch operation.

The complete frequency and power usage data of the six measurement periods are illustrated in histograms in Figure 5. The histograms show how the magnitudes of the measured values are distributed. In case of power usage, four groups of magnitudes are evident. The groups represent grinding of one, two, three and four batches simultaneously. No occasions of zero batches were measured and only small amount of one batch operation. Two to four batches were grinded most of the time, the four-batch operation being the most common. The highest bar of the frequency histogram is slightly below 50 Hz. Mean of the frequency values is 49.98 Hz. The frequency values distribution has a lower gradient in the higher frequency side. The frequency measurements also include some values that are outside the normal frequency range (49.9–50.1 Hz) meaning that there are needs to contain and restore the frequency during these moments.



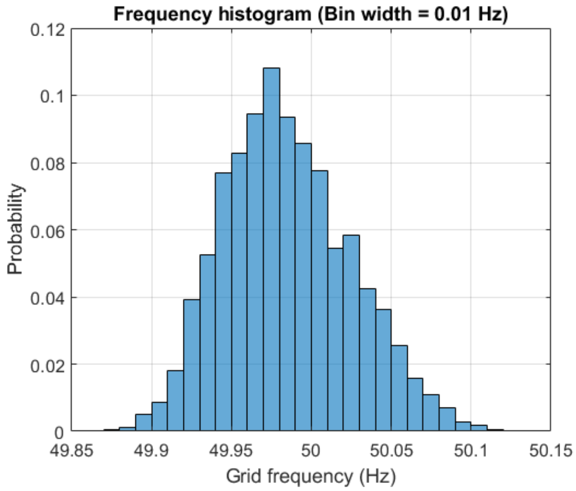


Figure 5. Histograms of power and frequency for the complete data of six measurement periods.

Based on the data, we analyzed the power step response of starting and ending batches. Figure 6 shows power decreasing steps gathered from Figure 4. To concretize, these drops occur when a wood batch is ending, and the hydraulic press foot is withdrawn to prepare for the loading of the next batch in normal operation. The initial drop occurs in 250 ms and stable new power level is achieved in approximately 1500 ms. The relatively high power amplitude swaying is due to dynamics of the tandem grinder line i.e., release of potential energy stored as rotational strain in axes between motor and grinder stones and kinetic energy stored in rotor of motor and in grinding stones. An additional reason for power swaying after fast power drop is activation of dynamics in the power feed that alters local line-to-line voltages and frequency. The change in power level for ending a batch is approximately 2.5 MW.

Figure 7 shows power increases when new grinding batches are starting. Due to initial rearrangement of the roundwood and compacting of the wood batches the power rise is more irregular than the power decrease in ending the batches. When compacting is achieved the power rise is as fast as in the dropping case and similar power swaying is measured. The change in power level is approximately 1.5 MW as the power level further increases during the batch as can be seen in Figure 4.

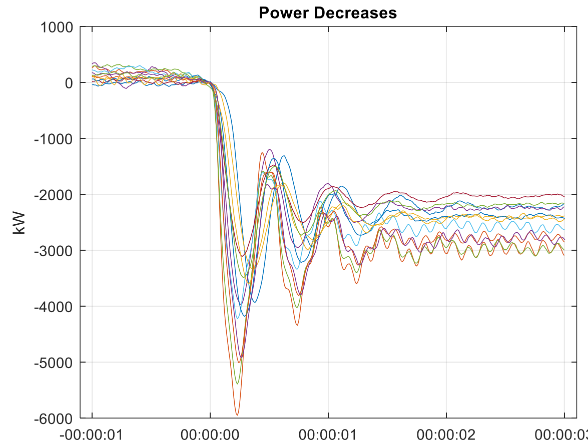


Figure 6. Power step response of ending batches.

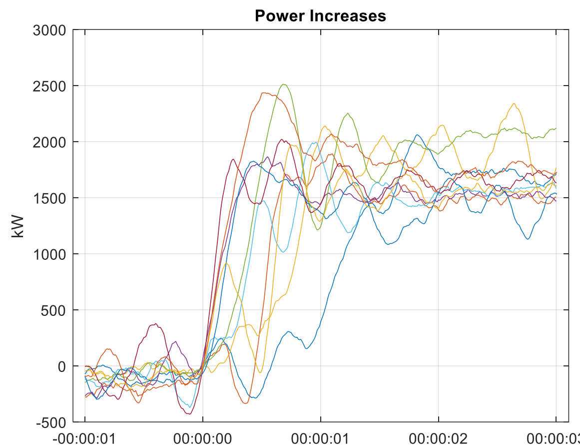


Figure 7. Power step response of starting batches.

DEMAND RESPONSE MARKETS

In this part, we present reserve products and electrical system stabilizing reserve marketplaces. We also compare the achievable power step response against requirements of reserve products. Both very fast response on a new inertia market and response in a few minute levels on a frequency containment reserve market are interesting. Here we refer to the reserves and balancing power instruments maintained by the Finnish transmission system operator Fingrid in the Finnish electricity market [Fingrid 2022a]. Equal markets exist in the other Nordic countries and very similar markets are maintained by the transmission system operators in the European Union and elsewhere in the world. Demand response can take part in the reserves and balancing power market as a decrease in consumption equals an increase in power generation from the viewpoint of balancing the electricity system. Correspondingly a rise in consumption equals a decrease in generation.

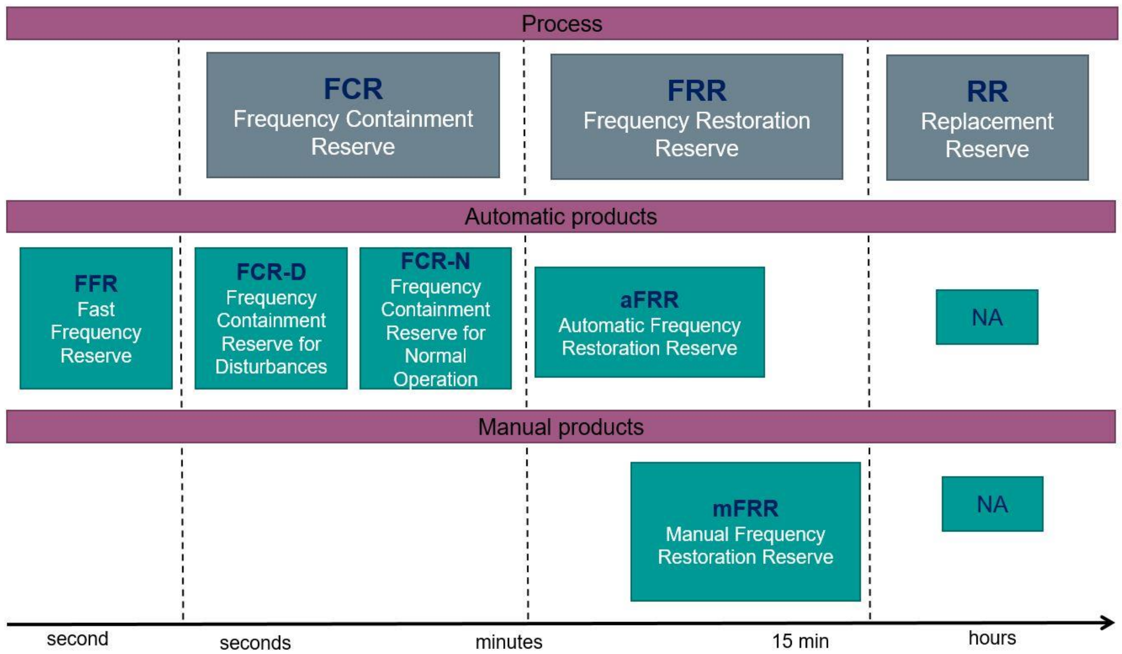


Figure 8. Reserve market products pictured on demanded activation time scale [Fingrid 2022a].

Reserves and balancing power

Electricity production must be always equal to electricity consumption. The balance between production and consumption is indicated by the frequency of the electricity grid which has a nominal value of 50.0 Hz in Finland. The market operators plan and balance their consumption and production in advance, but in practice there are deviations during each hour. To balance these deviations, Fingrid procures different kinds of reserves from reserve markets. Reserves are power plants, consumption resources and energy storages which adjust their electric power according to the need of the power system. [Fingrid 2022a]

Reserves are divided into three groups based on their purpose:

1. Frequency Containment Reserves (FCR) are used for constant control of frequency.
2. The purpose of Frequency Restoration Reserves (FRR) is to return the frequency to its normal range (49.9–50.1 Hz) and to release activated Frequency Containment Reserves back into normal use.
3. Replacement Reserves (RR) release activated Frequency Restoration Reserves back to a state of readiness in case of new disturbances. (Not used in the Nordic power system).

In addition, Fast Frequency Reserve is used in the Nordics since May 2020. It contributes to frequency containment in low inertia situations. The reserves are pictured in Figure 8 on a time scale that shows roughly the demanded activation time. Next, we introduce two reserve products that are interesting for groundwood pulp mills and comment on the activation and deactivation time requirements. [Fingrid 2022a]

Frequency containment reserve for normal operation (FCR-N)

In the case of the loading response of grinders the frequency containment reserve market for normal operation (FCR-N) is interesting as the compensation for participating is highest among the conventional instruments. FCR-N is an active power reserve that is automatically controlled based on frequency deviation. Its purpose is to contain the frequency during normal operation within the standard frequency range of 49.9 Hz to 50.1 Hz in Europe. FCR-N is a symmetrical product that must be capable of both up- and down-regulation. Up-regulation means increasing power production or decreasing consumption. Down-regulation means decreasing power production or increasing consumption. 100 % of the participating reserve capacity shall be activated as upward balancing, when the frequency is 49.9 Hz or less. Correspondingly, when the frequency is 50.1 Hz or more, 100 % of the reserve capacity shall be activated as downward balancing. In the frequency range of 49.9 to 50.1 Hz, the volume of the activated capacity shall be proportional to the magnitude of the frequency deviation. As a result of a stepwise frequency change of 0.10 Hz, the control shall be activated in full in three minutes. According to Figures 4, 6 and 7 the required activation time can be directly achieved. [Fingrid 2022a]

Fast frequency reserve (FFR)

The newest instrument, fast frequency reserve (FFR), is very interesting as only up-regulation by increasing the delivery of power to the grid or by reducing the consumption of power is required. Additionally, the whole participation power is activated at once that is normal for the on/off nature of batch grinding. The required response time is low but very fast power decreases at batch endings are shown in Figure 6.

The purpose of the FFR is to ensure that the loss of an individual electricity production unit or HVDC link will not cause the frequency to fall below 49.0 Hz. The FFR is needed for managing low-inertia situations in the power system and it is procured at times when the amount of inertia so requires. [Fingrid 2022a]

The FFR is activated as up-regulation by increasing the delivery of power to the grid or by reducing the consumption of power. When the frequency reaches the threshold, the reserve capacity shall be activated in full within the required activation time. The FFR has three alternative combinations of activation frequency and activation time, of which the balancing service provider selects one. The options are presented in Table 1.

Table 1. Activation frequency and activation time of the FFR [Fingrid 2022a]

Activation frequency (Hz)	*Activation time (s).*
≤ 49.70	≤ 1.30
≤ 49.60	≤ 1.00
≤ 49.50	≤ 0.70

The activation of the reserve can be for example a step or a ramp. By comparing the requirement with the power decrease of ending batches in Figure 6 all options can come into question when the power swaying is used for determination of the amount of activated power. The measurements in Figure 6 are acquired during normal batch endings but a short withdrawal of the hydraulic press foot during grinding should be possible. This could not be verified during the measurements of this paper as no function for this was integrated in the automation system of the grinder room.

There are two options for the minimum support duration (duration of the full activation) of the FFR, depending on the speed of the deactivation of the reserve unit. Deactivation means restoring the power of the reserve unit back to a state where the reserve capacity is not activated. The options are described in Table 2. The reserve must remain activated for the minimum duration regardless of the frequency. After the minimum duration, deactivation is permissible regardless of the frequency. [Fingrid 2022a]

Table 2. Minimum support duration of the FFR [Fingrid 2022a]

Minimum support duration (s)	*Maximum speed of deactivation*
30 sec	not limited
5 sec	up to 20% of the reserve capacity per second

If the grinding batch is restarted in five seconds or slower, then the activation time is only five seconds. If grinding is restarted faster than in five seconds, then the activation time must last for at least 30 seconds. Both are possible for the grinding batch with proper control. The power change of the reserve unit resulting from the activation may exceed the capacity approved for FFR by no more than 20%. The reserve unit must be able to reactivate after 15 minutes have passed since the last activation. The last two requirements are also plausible for the grinding batch.

ANALYSES

In this part, we analyze the suitability of the grinding lines to the requirements of chosen reserve products, introduce their marketplaces and estimate the business potential of participation.

Investment incentives for upgrading the pulping line to achieve demand response capacity for FCR-N market

As the load of a grinding batch is on/off to is nature the proportional requirement of activated capacity cannot be fulfilled by participating the FCR-N market with only one batch. A piecewise linear activation in five steps for the whole participating capacity is also allowed. This implies that at least five batches, preferable more, should be included in the capacity taking part in the market. E.g., two tandem grinder lines include eight pockets that would fulfil the piecewise linear activation directly. The participating capacity represents the excess capacity of 30 % achieved by upgrading the grinders with single layer grinding surfaces. This implies the need of a large grinder room based on eight tandem grinder lines where upgrading of six lines gives old nominal capacity and two lines are upgraded to fulfil the piecewise linear activation in discrete power steps of the size of batch loads. The linear activation requirement can be compared to the frequency measurements in Figure 5 that also include some values that are outside the linear range of FCR-N reserve market product (49.9–50.1 Hz) meaning that full capacity of reserves should bee activated for up- and down-regulation of the frequency during these moments. When comparing the required three minutes activating time to the loading response of a grinder the normal start-stop operation of batches can be used as the batch duration is less than three minutes. Furthermore, batches in a large grinding room approach ends and starts more frequently than the requirement which can be utilized with proper control.

A reserve provider may offer FCR-N capacity to the yearly and/or hourly market. In the yearly market the bidding competition is organized once a year and in the hourly market the reserve provider submits daily offers. The price in the yearly marked is based on the most expensive bid approved for the yearly market. The price on the hourly market is correspondingly set based on the most expensive bid approved separately for each hour. In year 2020 the price on yearly marked was 13.20 €/MW,h and the reserves were bought for 7000 hours yielding 92 400 € per participating megawatt.

The equivalent prices for years 2021 and 2022 were 12.50 €/MW,h and 12.24 €/MW,h correspondingly. As the reserve was bought for 8760 hours during 2021 each participating megawatt yielded 109 500 €. In year 2019 the volume-weighted mean price in the hourly market was 31.4 €/MW,h and the reserves were bought for 4000 hours yielding 125 600 € per participating megawatt. In year 2021 the corresponding price was 21.9 €/MW,h and bought hours 8628 yielding 188 953 euro for each participating megawatt. As an example the price on the hourly market fluctuates heavily being between 1 and 192 €/MW,h during the period 1.5. - 4.5.2022 having a mean price of 74 €/MW,h. [Fingrid 2022a, Fingrid 2022b]

By investing in the single layer grinding surfaces an excess capacity of 30% can be achieved and utilized in the FCR-N market. The investments cost for upgrading 77% of the production line and achieving the nominal production is 80 kEUR/MW [Björkqvist et al. 2018]. The payback time thanks to the lower energy use is one year and acceptable in the industry. By upgrading the rest 23% of the grinding line, also to the cost 80 kEUR/MW, excess capacity of 30% can be achieved. By using this excess capacity on the FCR-N yearly or hourly market annual yields between 92 400 and 188 953 euro per megawatt could have been achieved according to market prices from years 2019 to 2021. The payback time for the investment is between 4.2 and 10.4 month that is even lower than the payback time for the base investment and therefore attractive for the industry.

Investment incentives for upgrading the pulping line to achieve demand response capacity for FFR market

The need to procure FFR depends on the inertia of the electricity system, so it is procured for only some of the hours and the volume to be procured varies. The procurement need is highest in the spring, summer, and autumn months at times when the amount of inertia is at its lowest. The procurement of FFR from the market is once a day. The price of the reserve capacity is determined separately for each hour based on the most expensive accepted bid. The mean price during year 2020 was 81 €/MW,h and during 2021 45.4 €/MW,h. FFR was bought for 1414 hours during year 2021 meaning that each participating megawatt yielded 64 196 € during that year [Fingrid 2022b].

In contrast to FCR-N, FFR is a passive power reserve that is activated very seldom. In years 2015 to 2020 on an average only during 1 to 3 seconds per day frequency was lower than 49.8 Hz and never lower than 49.0 Hz [Fingrid 2022c]. When comparing these statistics to the alternative activating frequencies in Table 1 one can assume that activation happens only a few times during the year. In addition, the alternative support durations in Table 2 are 30 second or less at each activation. These facts mean that no production is lost in practice when participating in FFR. Furthermore, this means that participation can be enabled to only the cost of planning and implementing a control for starting and stopping batches even in the middle of a batch. In theory the whole grinding capacity can be offered to the FFR market with a very short payback time.

DISCUSSION

Investments in single layer grinding surfaces to gain excess capacity for participation in the FCR-N market have a payback time between 4 and 10 month that is attractive for the pulping industry. After the payback time the earnings are between 92 400 and 188 953 euro per invested excess megawatt annually. Due to the requirement of symmetric piecewise linear activation and on/off nature of grinding batches only relatively large groundwood mills can participate without special arrangements. These arrangements could include batch grinding at controlled alternating power that on the other hand affects negatively groundwood quality. Alternative arrangements to enable smaller groundwood mills to participate can include one other flexible power resources in the mill of the same power level as one grinding batch to fulfil the linear activation requirement by aggregation.

Participation in the FFR market do not need excess capacity as in the case of participation in FCR-N market. In the FFR only the normal on/off nature of grinding is utilized that makes participation very attractive.

In principle the invested excess capacity can participate in the FCR-N marked and yield better than in the FFR market. Simultaneously the free capacity or 40% can participate in the FFR market. In theory a large groundwood mill of 75 MW can participate with 22 MW in the FCR-N market and with 30 MW in the FFR market. By using 140 k€/MW as a mean value of annual earnings in the FCR-N market and 64 k€/MW as annual earnings in the FFR market the groundwood mill can earn 5 million euro annually by participating in the reserve market.

Introduction of large amount of demand response resources to the reserve markets can lower the bidding prices. On the other hand, more shifting in power production from controlled production to intermittent production increases the need for reserve amount that increases the bidding prices. Alternative markets for grinder demand response are frequency containment reserve for disturbances up (FCR-D up) where loads reduce consumption at frequency drops below 49.9 Hz. FCR-D up on the hourly market has economically been even more attractive than FFR but activates more often and has the linear participation requirement that makes participation more challenging. Activation is still so seldom that production amount is not much affected. Also, operation on the day-ahead-market as shown in Björkqvist et al. 2018 is assumed to be economically more attractive in the future as energy price fluctuation increases due to power production shift to renewable intermittent resources.

The control of both reserves is based on local frequency measurement. To participate in the market, accurate frequency and active power measurement must be installed and a proper and fast control system must be included in the grinding control system. The functionality of the system also must be verified before participation. Power measurements of short withdrawn of hydraulic press foot before normal batch end should be done to verify the assumption that it is possible.

CONCLUSIONS

Groundwood lines with single layer grinding surfaces can be utilized both for pulp production and electrical grid stabilization with no scarification of pulp quality and production. This operation mode optimizes the utilization of previous process resources and new investments for better economy in mechanical pulping. Processes with naturally varying power consumption can be used in demand response markets when the activated power can be confirmed in the control system.

Contribution of demand response is a way to utilize the non-continuous pulp production of grinders which is not advantageous in normal pulp production. Thanks to the normal on/off nature of batch grinding, utilization do not increase wear on grinders nor need for more maintenance. The fast-loading response and the natural start-stop operation of the grinder enable operation on valuable electricity markets that enhance the possibilities of introducing 260 MW of climate neutral and resource efficient demand response solely to the Finnish electrical energy system.

ACKNOWLEDGMENT

This work has been supported by the Strategic Research Council at the Academy of Finland, project Transition to a resource efficient and climate neutral electricity system (EL-TRAN) grant number 314319.

REFERENCES

Björkqvist, T. (2011) *On the specific energy consumption in mechanical pulping.* International Mechanical Pulping Conference 2011, June 26 - 29, 2011. pp. 492-495.

Björkqvist, T., Korpela, T., Majanne, Y., Vilkko, M. & Tuovinen, O. (2018) *Improving mechanical pulping business potential by operating single layer grinding surfaces on electricity market.* 31st International Mechanical Pulping Conference 2018, May 27-30, 5 p.

Fingrid. (2022a) *Reserves and balancing power*. https://www.fingrid.fi/en/electricity-market/reserves_and_balancing/, accessed 27.4.2022.

Fingrid. (2022b) *Reserve products and reserve market places.* https://www.fingrid.fi/globalassets/dokumentit/fi/sahkomarkkinat/reservit/reserve-products-and-reserve-market-places.pdf, accessed 5.5.2022.

Fingrid. (2022c) *Frequency quality analysis 2020.* https://www.fingrid.fi/globalassets/dokumentit/fi/kantaverkko/suomen-sahkojarjestelma/frequency_quality_analysis_2020.pdf, accessed 5.5.2022.

International Energy Agency. (2021) *World Energy Investment report 2021.* https://iea.blob.core.windows.net/assets/5e6b3821-bb8f-4df4-a88b-e891cd8251e3/WorldEnergyInvestment2021.pdf, accessed 6.5.2022.

Lucander, M., Bjorkqvist, T., Tuovinen, O. (2006) *Method and Apparatus for Mechanical Defibration of Wood.* U.S. Patent: US2006283990 (A1).

Lund, P.D., Lindgren, J., Mikkola, J., Salpakari, J. (2015) *Review of Energy System Flexibility Measures to Enable High Levels of Variable Renewable Electricity.* Renewable Sustainable Energy Rev, 45, 785-807. DOI: 10.1016/j.rser.2015.01.057.

Paulus, M., Borggrefe, F. (2011) *The Potential of Demand-Side Management in Energy-Intensive Industries for Electricity Markets in Germany.* Appl.Energy, 88(2), 432-441. DOI: 10.1016/j.apenergy.2010.03.017.

Pihala, H., Farin, J. and Kärkkäinen, S. (2005) *Sähkön kysyntäjouston potentiaalikartoitus teollisuudessa.* Report No. PRO3/P3017/05, VTT.

Shoreh, M.H., Siano, P., Shafie-khah, M., Loia, V., Catalão, J.P.S. (2016) *A Survey of Industrial Applications of Demand Response.* Electr.Power Syst.Res., 141, 31-49. DOI: 10.1016/j.epsr.2016.07.008.

Tuovinen, O. (2016) *End of stone age.* International Mechanical Pulping Conference 2016, IMPC 2016, September 26-28, 2016. pp. 234-241.