Implementation / Presentation of the 16 MW Hybrid Wind-Pumped Storage Plant Gaildorf in Germany

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Abstract
With the global aim of decarbonation the contribution of wind and solar and hence a volatile power production is increasing. It is beyond any doubt that this development is requiring a surplus of energy storage capabilities. Storage will be needed in different scales and hence will provide different services to the grid. Whereas Batteries can serve as a fast-acting short term power bank, a pump storage plant can act as a daily, weekly, or monthly storage facility. But not only the total capacity of the storage facility is a driving factor, also the CAPEX and the realisation time of such a project is essential. Battery storage has its clear advantage on project lead time and cost per kWh compared with pump storage plants but has its restrictions in lifetime and storage capacity.

Max Bögl is introducing an unconventional way of combining regenerative power production using wind mills and storage capabilities using a pump storage plant in the same location. By combining both not only benefits in application, space requirements, investment costs and lead time can be realized. Furthermore, the leading idea of such a combination is to utilize more typical wind location than typical pump storage plant locations. This means using medium terrain locations with a head of about 200m to 400m without typical formations like steep hills and existing terrain bowls for an upper reservoir. By giving up these classic requirements, a pump storage plant can nearly build at any location with a sound head. Whereas benefits in low space occupation and simplified application result in shorter project lead times, lower investment cost are essential for small pump storage plants as there is the direct competition with battery storage. To facilitate a limited footprint of such a combined plant, the upper reservoirs of the pump storage plant are located in the basement of the windmills interconnected by long pipes. But going an unconventional way this also comes along with certain challenges. Especially the transient behaviour of such an arrangement with distributed upper reservoirs, long interconnecting had race pipes and long penstock is requiring detailed transient studies to find the optimum arrangement and right technical parameters for a safe and reliable operation of the plant. Especial the different reservoirs and the resulting combination of long and short pipes and several connecting points in the water ways made the simulation model quite complex. This paper describes in detail the setup of the plant, the development of a model for hydraulic transients, the challenges during modelling and the outcomes of the same. It is demonstrated how the outcome of the simulation influences the final design of the plant.

1 Background
With the increasing need for storage capacities, the different technologies are taking their market shares. Implementing a new concept like Gaildorf it is essential to understand how it positions in this area of solutions. Comparing the different factors like costs, project lead time and space requirements is the key to predict a possible market share.

The world largest Batterie storage facility is operating in the USA, Moss Landing with 1600MWh storage capacity and a power output of 400MW [1]. Already ranking in its total output in the range of a comparable medium pump storage plant on the one hand and on the other hand it is not using a medium terrain location. That offers the interesting possibility to operate a storage plant in a location where it would not be possible in the future. Even there the requirements for head is not the same. The new concept of Gaildorf is utilizing a potential head of about 200m to 400m. Using this concept makes the development of a model quite complex. It is demonstrated how the outcome of the simulation influences the final design of the plant.
storage plants (PSP) but with a storage capacity clearly below. With specific costs of about 270 €/kWh and 1080€/kW it is already a strong competition to small and medium pump storages plants. Another clear benefit is the short realisation time of about the half of a conventional pump storage plant. The expected lifetime and capacity degeneration is depending on future utilisation and to be considered in the financial model.

Conventional PSP in large scale (500 MW to 1 GW) range within 60 €/kWh to 110 €/kWh respectively between 1000€/kW to 2000€/kW depending on the total installed power and volume of the upper reservoir. With energy storage capacities larger than 10 GWh its still ten times higher than the largest existing battery.

The small pilot project Gaildorf is ranging in a different power scale but nevertheless it shows promising numbers with specific costs already comparable to conventional PSPs. The storage capacity of 50MWh is far beyond the ones of its big brothers but is proving the brand name Waterbatterie.

The pressure on the specific cost is coming from the batteries and proofing that concept of low investment cost for a small PSP is the right approach. It is also giving the outlook on future projects, showing the necessity of a higher installed total capacity of such a PSP.

The following paragraphs describe in detail the cost optimized approach of the PSP Gaildorf and giving an outlook on future optimization.

2 Concept of Gaildorf

The pilot project Gaildorf is a combination of a windfarm and a pump storage plant. The plant is comprising of four windmills. In the basement of three the basins for the upper reservoir are placed. All reservoirs are interconnected via a PE pipe. The head race pipe is connected to a surge shaft containing the penstock guard valve. A buried penstock following the terrain surface is linking the powerhouse complex. Near to the powerhouse the penstock is completed by a surge vessel to damp the water hammer. The shaft type powerhouse is equipped with 3 variable speed reversible pump turbines of 6,1MW each. The power unit is completed by a squirrel cage motor generator fed by a full power converter. The total output is limited to 16MW. The lower reservoir is an artificial lake.

The windmills are GE 3.4 DFIG type with a power upgrade to 3.6 MW. With a rotor diameter of 137m and a turbine hub height over ground of 178m they have an average annual wind power generation of 40GWh.

Each upper reservoirs consists of two basins, the active and a passive reservoir. The passive reservoir has a diameter of 31,5m and a depth of 10,5m. The active reservoir is positioned inside the passive basin and has a diameter of 16m and a height of 42m. The windmill is positioned on the top of the active chamber and hence utilizing the additional height. The active chamber is providing an additional head for the plant and the passive chamber is giving the basis
for the storage capacity. The total storage capacity of all reservoirs is summing up to approximately 105,000 m³ and respectively to a storage capacity of 50 MWh.

Photo. 2. showing the upper reservoir, active and passive chamber [2]

The interconnecting head race PE pipes are of a diameter of 1.4 m with a total length of 800 between windmill 1 and 2 and a length of 580 m between 2 and 3. The penstock has a diameter of 1.76 m and a length of 2570 m. The pipes are installed in a trench with a top cover of 2 m. Hence the pipes and the penstock is following the terrain shape. The headrace surge shaft has a diameter of 12 m and a height of 50 m with a total volume of approximately 6000 m³. Ancient to the surge shaft the valve chamber is located housing the penstock guard valve and the aeration valves. The pressure vessel near the powerhouse is comprising of three vessels each one with a volume of 80 m³.

The reversible pump turbine with a nominal output of 6.1 MW at a rated head of 184 m has a runner diameter of 1.15 m and a rated discharge of 3.8 m³/s in turbine and 3.2 m³/s in pump mode. The speed range is between 871 rpm to 945 rpm in turbine and 898 rpm to 1060 rpm in pump mode.

The generator is a squirrel cage type with a nominal output of 6.1 MW respectively of 6.7 MVA at a rated voltage of 3.15 kV. The rated speed is 1000 rpm.

2.1 Concept for Cost optimization

Small hydro power plants have typically higher specific realisation cost compared to large plants. Hence an approach of cost reduction during planning and installation was used and finally leading to total new solution for a pump storage plant.

The concept of eased application was driven by the general approach of minimum environmental influence. Minimized space usage and tree felling was driving the design of plant and influencing mainly the concept of the upper reservoir. These combination of windmills and reservoirs results a space saving of approx. 4 ha. By dividing the upper reservoir into smaller basins they could be placed at the same location as the windmills. The size was mainly adapted to the space needed for the windmill and its construction. The interconnecting head race pipe is placed underneath existing roads. Such approach is limiting the visual impact to the existing scenery, is minimizing the total usage of land and finally avoiding additional tree felling. These arguments were enhancing the general acceptance of the plant and finally easing and accelerating the application. The construction permit was granted 11 months after application submission.

The approach of distributed reservoirs, shallow hill and hence long resulting length of the penstock is requiring a cost optimized solution for the pipes. Not only in relation to the material but also in the way of installation. For the head race pipes a PE pipe is used and for the penstock a glass fibre reinforced PE pipe will be used. For a cost-efficient installation, a special machine so called pipe crawler is utilized combining the welding and controlled lowering of the pipe. As this machine is crawling along the final track of the pipe no additional space aside the track for construction and traffic and hence no additional tree felling is required.
As the civil costs are a major part of the investment, it is essential to optimize these costs as far as possible. For that reason, precast parts were used for the upper reservoirs and the powerhouse itself. As the base plate of the upper reservoir is functioning as the foundation of the windmill and sealing of the basin it is casted at site. The wall segments of active and passive reservoir are made from precast parts and jointed together by using rubber seals and steel tensioning ropes.

The shaft powerhouse is built inside a circumferential bore pile shaft with a diameter of 19m and a depth of 26m. Inside the bore pile shaft a rectangular powerhouse is placed, made of precast segments.

Finally, to reduce the equipment cost standardized components were used. So the generator and the converter are series products from the wind industry.
3 Challenges for the pumped storage concept

This new concept of distributed reservoirs with short connecting pipes to a long head race tunnel and a long penstock makes the hydraulic transient behaviour of the plant challenging. In addition, a pipe alignment following the terrain surface entails even more challenges and makes a detailed simulation a must.

The unconventional pipe system with the different reservoirs led to a complex simulation model. In addition to that, the combination of long and short pipes led to the need for a short time step which made the computation time consuming. Furthermore, the generated data were of remarkable size which made the analysis of the simulation results even more time consuming.

In total 26 different load cases were simulated. The findings were used to optimize the setup and the system parameters. This ends up in a recursive optimisation process and a large number of simulations.

With the simulations the following key issues were identified.

A minimum pressure near to vacuum pressure was observed in the head race tunnel and in the upper section of the penstock. The minimum pressure in the head race tunnel was observed after an emergency shutdown (ESD) of all three units running in turbine mode at full load and min head. In the upper section of the penstock the minimum pressure was identified after arESD of all three units running in pump mode at full load and min head. By adjustments in the head race surge shaft this minimum pressure could be reduced to an acceptable value.

Maximum pressure in spiral case and trifurcation was simulated after a delayed emergency shutdown of three units in turbine mode at full load with maximum head. For this load case, modifications of the pressure vessel design led to acceptable value of the pressure rise.

Water level inside the head race surge shaft was also controlled during the simulations. Whereas the max level was simulated after a ESD of three units in turbine mode at full load and maximum head in combination with the penstock guard valve closing. The minimum pressure could be observed after a ESD of three units in pump mode at full load and minimum head.

The minimum pressure in the draft tube was simulated after a delayed ESD of three units in turbine mode at full load and maximum head. By adjustment of the tail race surge shaft and system parameters, the pressure drop could be adapted to acceptable values.

After several rounds the hydraulic system could be adapted in a way to ensure a future safe operation of the plant.
4 Conclusion

In general, the layout of pumped storage plant with reversible Francis-turbines is demanding due to its complex hydraulic behaviour (S-Characteristic) and requires detailed investigation of unique load cases. The approach of construction-driven design as done in Gaildorf with a preference to a wind location with sallow hills and distributed reservoirs at best wind location are in conflict with a usual hydraulic layout of the waterways. This uncommon layout of the Gaildorf plant necessitated further in-depth investigations not only to guaranty a safe operation and reasonable transient behaviour in all load cases but also to optimize the overall layout of the plant. Finally, the challenges were solved by sizing of components with the support of transient calculations and the safe operation is facilitated in a wide operational range.

The required level of detail for calculations lead to a complex simulation model and hence to increased computational effort and result evaluation.

A none-of-the-shelf plant layout in regards of construction and design needs a recursive and detailed simulation and design process.

The savings resulting from such a design on shallow hills must be carefully balanced with the necessary investments for head race surge shaft and pressure vessel to utilize a total benefit of this design. Gaildorf is proofing that its valuable to overthink established concepts and that is can be beneficial to go new ways. Nevertheless, as Gaildorf is a pilot project, room for further optimisation is already identified. This process will go on until the plant is fully commissioned.

One basic learning from the simulations is that the hydraulic design of the waterways cannot be neglected and totally sacrificed to the optimal windmills position. The position of the windmills and hence of the upper reservoirs and the routing and dimensioning of the head race pipes must be balanced to find the optimal setup. In the best case a head race surge shaft and a pressure vessel can be avoided in future projects, which will bring an additional benefit to the financial model.

References

2. Max Bögl Wind AG

The Authors

K. Lochschmidt graduated in electrotechnical engineering to a degree of “Diplom-Ingenieur” (comparable to M.Sc. Eng.) at the University of Ulm, Germany. He worked 19 years with Voith Hydro, where he could gain a wide range of experience in his function as a commissioning engineer, especially for pumped storage plants. In his subsequent work as a plant engineer in technical sales for hydropower plants, he was able to apply his expertise to technical optimization of entire plants, for which interactions between plant components, installation concepts, and also costs were fine-tuned. Thanks to his experience with pumped storage hydropower plants and converters, he supervised specifically variable-speed pumped storage plants throughout the Voith Group. In April 2021 he joined Fichtner GmbH & Co. KG as a senior project manager and serving as such for the pump storage plant Gaildorf since 2022. Further on he is involved in the development of pump storage plants worldwide.

Dr.-Ing. V. Brost is an expert for transients and control of hydro power plants. He graduated with a diploma degree in Mechanical Engineering at the University of Stuttgart, Germany, then continued at the Institute for Fluid Mechanics and Hydraulic Machinery (IHS) and obtained his doctoral degree in transient simulation of grid restoration scenarios with several hydro power plant in joint operation. Volker Brost has been active in the field of hydro power for more than 20 years. From 2000 to 2012, during his tenure as research associate, he gained experience in CFD-modelling of hydro power components, control of hydro turbines and simulation of the transient behaviour in combination with in-situ measurements of the control behaviour of hydro power plants. In 2012 he joined Schluchseewerk AG, Germany’s largest operator of pumped storage plants, and was responsible for the rehabilitation of hydro assets as technical project manager. Since 2014 he is a senior consultant in the renewable department of Fichtner GmbH & Co. KG, Stuttgart, Germany.

J. Zinner graduated in civil engineering to a degree of “Diplom-Ingenieur” (comparable to M.Sc. Eng.) at the University of applied Sciences Nürnberg, Germany. He worked 15 years as CEO for the development of Windfarm in Germany and France. In April 2019 he joined Max Bögl Wind AG as head of Naturstromspeicher in order to develop systems for Energy storage as such for the pump storage plant Gaildorf and Power to heat systems or Energy management systems.