

Variable speed pumped storage hydropower for integration of wind energy in isolated grids

– case description and control strategies

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Abstract— this paper presents the use of variable speed pumped storage hydropower plants for balancing power fluctuations from wind power in an isolated grid. A topology based on a synchronous machine and a full scale back-to-back voltage source converter is suggested for obtaining variable speed operation of a pump-turbine unit. This topology has not been previously investigated for variable speed pumped storage power plants, but can now be considered relevant for small and medium sized pumped storage units because of the development of voltage source converter drives for higher voltage levels. A possible case for implementation of such a system is described based on the situation on the Faroe Islands, where controllable energy storage can help to allow for a higher share of renewable energy in the power system and by that to reduce the dependency on fossil fuels. Power control of the pumped storage unit by load following for direct compensation of the fluctuations in power output from a wind farm will limit the influence on the operation of the rest of the grid. By utilizing the pumped storage to take part in the primary frequency control of the power system, the frequency response to other changes in production or load will also be improved.

Index Terms— Isolated grid, pumped storage, power balancing, energy storage, synchronous machine, voltage source converter, wind power;

I. INTRODUCTION

Integration of fluctuating renewable energy sources into electric power systems requires adequate means of control to maintain stable and satisfactory operation of the grid and in many cases additional energy storage will be needed to reach a high share of annual electricity production from non-dispatchable sources [1]. With respect to large scale integration of renewable energy sources into the electric power system and reduction of dependency on fossil fuels

for energy supply, isolated and stand-alone power systems can serve as good examples and test-cases for development of necessary technologies and theoretical methodologies. Islands and isolated power systems will also be the first locations where it will be relevant and possible to achieve sustainable energy systems based entirely on environmental-friendly and renewable energy sources [2].

For increasing the share of renewable energy sources, like wind power and photovoltaic, in the power system of islands without connection to a larger electric power system, the use of pumped storage hydropower plants can be among the most relevant alternatives with respect to feasibility and cost [3]. Examples of such systems have also been planned and put into operation, while others are being considered for implementation [5]-[9]. Several studies regarding planning, design and operation of pumped storage power plants together with wind power installations in isolated power systems have also been published during the last years [10]-[15]. Still, operation of conventional pumped storage units with constant power in pumping mode will mainly help to improve the energy balance of the system without contributing to the frequency control and the instantaneous power balance. One way of introducing additional controllability will be to use several units of separate pumps, so that the load in pumping mode can be controlled in small steps that can be handled by controllable generators in the system. The most flexible and effective solution will be variable speed operation, such that the input power also in pumping mode can be controlled continuously within an allowable range of operation [3]. The controllability obtained by variable speed operation of a pumped storage power plant can be used to help balancing power fluctuations in the system, both in pumping and generating mode [16].

The development of variable speed pumped storage power plants have until now been mainly focused on large units intended for introducing controllability and energy storage into power systems with a large share of nuclear or coal-fired power plants running at almost constant production. Increased capability for fast control and energy storage have

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been beneficial for such power systems, to improve the system stability and help adapt the available power production to the load profile. Because of the high power ratings, the preferred topologies have mainly been based on doubly fed asynchronous machines, to reduce the cost and the rating of the power electronic converter required to obtain variable speed operation [17]-[20]. The possibility for variable speed operation can be even more important for a pumped storage unit in a small isolated grid than in a large power system, since introduction of a large share of fluctuating power production within a limited area can introduce additional challenges to the operation of the power system. At the same time, the lower power rating can allow for different choices of topologies for the pumped storage power station. This leads to the three main objectives of this paper that can be listed as:

1. To review existing pumped storage topologies, and on this background propose an alternative configuration for variable speed operation of a pumped storage hydropower plant in a small isolated grid.
2. To present a relevant case for investigation of the proposed configuration based on the isolated power system of the Faroe Islands as described by [16] and [21].
3. To present and discuss basic methods for control of the variable speed pumped storage that can allow for increased penetration of wind power in an isolated power system.

II. REVIEW OF EXISTING CONCEPTS FOR VARIABLE SPEED OPERATION OF PUMPED STORAGE HYDROPOWER

Pumped storage hydropower is the main type of energy storage that has been used extensively in power systems for a long time, and since reversible pump-turbines became available in the 1930's, the basic configuration of most large scale pumped storage system has been as sketched in Fig 1 [22]. Previously, pumped storage units of different ratings have been built with bulk energy storage as the main purpose, and have been based on traditional synchronous machines for operation with constant load in pumping mode. Since power systems with high share of nuclear and thermal power plants running at constant production have a need for increased controllability, there has been for long time an interest in variable speed operation of pumped storage units allowing for adjustable power also in pumping. Variable speed operation has also been of interest to improve the efficiency and the operating range of pumped storage power

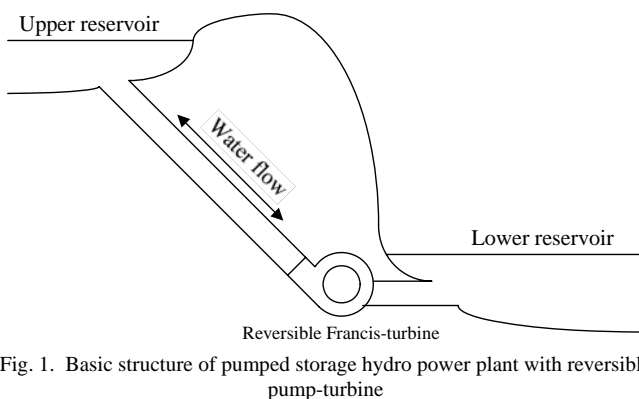


Fig. 1. Basic structure of pumped storage hydro power plant with reversible pump-turbine

plants, especially in the case of large variations in pumping head [17], [23], [24]. The development of variable speed pumped storage systems has been made possible by the development of high power semiconductors and power electronic drives, and several such units have been developed and put in operation during the last two decades [25], [26]. The focus of such developments has mainly been on large scale units in the power range up to several hundreds of MW. Most of the experience with such units is from Japan, where there has been a need for controllable energy storage to improve the stability and the frequency control of the power system and to be able to match the load profile during a day with the capacity of power production in the system [19], [26], [27]. For many years, variable speed pumped storage systems have also been topic of research in Europe, and recently the power plant Goldisthal in Germany, with two 300 MW variable speed units, has been put into operation [20], [28]-[31].

The focus on large pumped storage units for operation in traditional interconnected power systems has influenced the generator technology and power electronic topologies that have been considered relevant for variable speed operation. To limit the rating and the corresponding losses of the power electronic converter, most of the existing variable speed pumped storage power plants have been built with doubly fed asynchronous machines (DFAM). Depending on the required speed range of the unit, the converter rating for this configuration will usually be in the range of 10-30 % of the total power rating of the machines. The rotor circuit converter has usually been a thyristor-based cycloconverter, but back-to-back voltage source converters have been used for some of the newer installations [26], [27]. Ohkawachi power station in Japan have the largest units of this type that have been built until now, with machines rated for 395 MVA, and with 72 MW cycloconverters for the rotor circuits. For the 300 MVA units at Goldisthal in Germany, the rating of the rotor converters is reaching 100 MVA. Even larger units, with up to 475 MVA in total machine rating, are now being planned [19], [27], [31]. Simple schematics of the usual configurations of doubly fed machines for pumped storage plants are shown in Fig. 2, where the voltage source converter in Fig. 2 b) is assumed to be a three-level neutral point clamped converter as described in [32].

There has been some interest in variable speed operation of pumped storage power plants by the use of a full scale, thyristor based, current source converters driving a

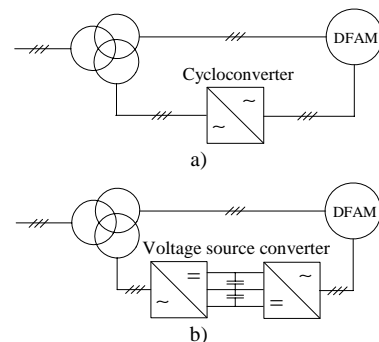


Fig. 2. Doubly fed asynchronous machine configurations where a) shows the connection with a cycloconverter while b) shows the connection with a voltage source converter

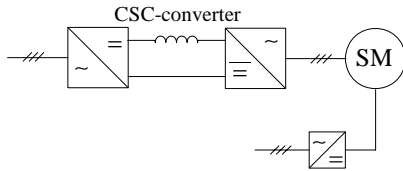


Fig. 3. Full scale, thyristor based, current source converter driving a wound field synchronous machine

traditional wound field synchronous machine (SM). This has also included configurations with direct connection of one or more pumped storage machines to a HVDC-line [23], [24], [33], [34]. The basic configuration is sketched in Fig. 3, and a few pumped storage units with variable speed provided by this type of configuration have been built in the power range up to around 100 MVA [26].

During the last years attention has been put to the utilization of pumped storage units for integration of wind power in power systems, and especially to allow for increased utilization of renewable energy sources in small isolated systems [3]-[16]. Even if several such projects are under consideration or construction, most of the published investigations until now have been mainly focused on the energy balance and the sizing of system components. The choice of machine and converter topologies, and investigations of the instantaneous power of the system, has attracted less attention. Many of the reported projects have also been designed with separate pump and turbine units, with the pumping based on several smaller pumps [3], [7], [8], [35]. In such cases the pumping units can be made completely independent from the turbine unit, and they can also be in operation at the same time. For systems with several pumps and some power control capability in the grid, stepwise connection and disconnection can be used to control the pumping power, or standard industrial drives can be applied to control the power from an external command. Variable speed operation of at least one unit in such a system has been shown to be the most beneficial solution [3], [10]. Even if this paper is proposing a topology for obtaining variable speed operation of a pump-turbine, the approach that will be discussed for power control can equally well be used for dedicated generators and pumping stations in an isolated grid.

III. INVESTIGATED SYSTEM

A. Proposed Topology

For small and medium sized pumped storage units, a reversible pump-turbine with a traditional synchronous machine and a full-scale back-to-back voltage source converter feeding the stator windings could be a possible solution. With the increased rating of self-commutated semiconductor switches and available high-power motor drives based on the voltage source converter topology, such a configuration could be an attractive solution, especially relevant for pumped storage units in isolated systems. The schematic layout of the suggested configuration is shown in Fig. 4, and the machine is considered to be a wound field synchronous machine with static excitation system. A suggested voltage level of 3.3 kV is indicated in the figure. Even if this suggested generator/motor drive systems is well known for other applications, and briefly mentioned as a possibility for variable speed operation in small hydropower

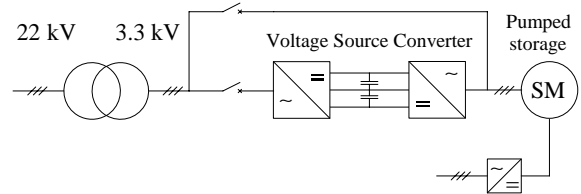


Fig. 4. Suggested topology for variable speed operation of pumped storage

plants in [39], there is not published any thorough description or analysis of such a system for variable speed operation of a pumped storage hydropower plant.

Since the suggested configuration is based on a normal synchronous machine with field windings, it will be possible to bypass the converter and operate the machine directly connected to the grid as indicated in Fig. 4. This can provide a kind of redundancy for the converter in case of operational problems, and can also be utilized to reduce the losses during normal generator operation. The topology of Fig. 4 is also of interest because of the possibility for operating the system as a conventional hydropower plant with traditional solutions available for the operators in case of operational problems. For a small power station in a remote area it can for instance be important to have the possibility to carry out a normal black-start of the power system with the pumped storage unit as a generator, even if the main converter is out of operation [36].

With the presented configuration, it will be possible to use a diode rectifier for the grid side converter and operate with variable speed only in pumping mode. This will reduce the losses during pumping, but will not allow for variable speed operation in generator mode. A configuration with an active-front-end converter for reversible power flow, will also allow for voltage control in the grid by use of reactive current. Variable speed operation in generator mode will also make it possible to run at optimal speed for a wide range of water head, or to increase the controllability and the speed of response for the system [16], [19]. A controllable grid side converter could also make stand-alone operation and frequency control of the grid possible, even without any other production units based on synchronous generators in operation. The control of the grid side converter in this case could be similar to what is described in [37] and [38] for the operation of an isolated system with battery energy storage.

B. Case Study and Simulation Model

A relevant example of an isolated power systems that could significantly benefit from a combination of wind power production and a variable speed pumped storage power plant, is the electricity supply on the Faroe Islands [16], [21]. The Faroe Islands have a population of about 48000 people, and an electric power system that is currently dominated by diesel generator units supplying around 60% of the annual electricity consumption. The minimum load of the system is in the range of 14 MW, while the maximum load can reach 70 MW. A few wind turbine units have been introduced to the system, but if the dependency on fossil fuels for the electricity generation is going to be reduced by utilizing the available wind resources, there will be a need for storage and more controllability to stabilize the system. There already exist hydropower plants with suitable reservoirs in the system. Therefore a variable speed pumped

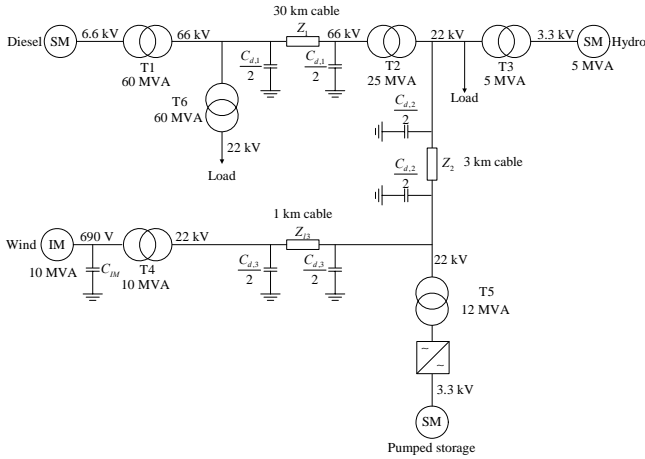


Fig. 5. Simplified grid model representing the main part of the power system on the Faroe Islands

storage power plant that can be used to balance the fluctuations in output power from a wind farm is an attractive possibility to allow for a higher share of fluctuating non-controlled power production in the system [16], [21].

A simplified model of the main part of the power system on the Faroe Islands is sketched in Fig. 5 with labels showing the most important ratings of the system. This structure is used as the starting point for a simulation model implemented in the PSCAD/EMTDC simulation software. A simple aggregated model is used for the diesel generators in the system, and standard parameters are used for the 5 MW hydropower plant. As a worst case, regarding power fluctuations from the wind farm, wind turbines with induction generators directly connected to the grid are assumed, and an aggregated model is used for the whole farm. The wind turbine model is based on a 2 MW unit, and passive stall control is assumed for simplicity. The generation of the wind speed input to the turbine is based on use of the Kaimal power spectra by use of a simulation model developed from [40], [41].

The most challenging situation for this grid will be operation at minimum load when there is high wind power production. Therefore, only results from this situation are considered, with the pumped storage operating in pumping mode. The pumped storage is simulated with a diode rectifier on the grid side of the converter, and the power control of the synchronous machine is implemented by flux oriented vector control as described in [16].

IV. POWER CONTROL STRATEGIES FOR THE VARIABLE SPEED PUMPED STORAGE SYSTEM

For power control of the pumped storage, an external power set-point as an input to the system is assumed. This set-point can be provided by the system operator based on scheduled operation and restrictions on operation due to limitation in reservoir capacity and the situation in the power system. The set-point value can have a relatively slow rate of update, and be in the time frame normally used for investigations concerned with optimization of the energy balance of the system. A local control system for the pumped storage unit can however act on the continuous power fluctuations from the wind farm, and use the pumped storage to balance the influence on the rest of the grid.

A. Balancing Power Fluctuations by Load Following

In the investigated system, the wind power production is in the end of a radial line and close to the pumped storage unit. This makes it possible and relevant to measure the power output from the wind farm and use the controllability of the pumped storage unit to balance these fluctuations directly, such that an almost constant and adjustable power flow is seen from the rest of the grid. This type of control can compensate the influence on the power system from the fluctuations in output power from the wind turbines. Assuming a forecasted power output $p_{w,set}$, and a measured power of p_{wind} from the wind farm, the additional power command Δp_w to the pumped storage unit can be calculated by (1).

$$\Delta p_w = p_{wind} - p_{w,set} \quad (1)$$

It can be noticed that the operation of the pumped storage in pumping mode will result in more production capacity on line during low-load conditions, and by that increase the control capability and the frequency response the system compared to the case without any pumped storage. Still, a power control structure for the pumped storage that is only including load following based on measured output of the wind farm will not fully utilize the controllability introduced by the variable speed pumped storage with respect to the operation of the power system [16].

B. Frequency Droop Control

Another way of controlling power, that can be highly relevant in an isolated grid, will be to make the pumped storage unit take directly part in the primary frequency control of the power system. Especially when the load in the system is small and the production from the wind farm is high, this will be a way of improving the response of the total power system to disturbances. By controlling the pumped storage power consumption in pumping mode based on a frequency droop, like in a normal hydropower station, the frequency response of the system during low load conditions will be increased. In this case, the frequency response will increase not only by the increased amount of production that will be on line to keep the pumped storage unit running, but also by the frequency response of the pumped storage unit as a frequency controlled load. This way, the introduction of the variable speed pumped storage will help improving the system performance to all kind of disturbances and changes of load or production. Basically, this will be a similar way of operation as for the large variable speed pumped storage units that have been installed in Japan and Germany to help balance production and load

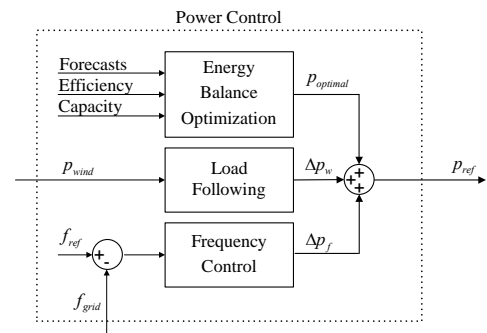


Fig. 6. Possible methods for power control of the pumped storage unit

in systems with large share of nuclear or coal-fired power plants running at almost constant production. With a simple droop, the additional power command Δp_f to the pumped storage control system will be given by (2) as the product of the droop constant K_{Droop} , and the difference between the reference frequency f_{ref} and the grid frequency f_{grid} .

$$\Delta p_f = -K_{Droop} (f_{ref} - f_{grid}) \quad (2)$$

C. Combination of Power Control Strategies

To utilize the controllability of the pumped storage to the benefit of the power system operation, several strategies for power control can be combined. This is illustrated by Fig. 6, where additional power commands from both a load following controller and from frequency control are summed. The possible control routines and algorithms for calculating the long term or stationary power control set-point to the system is also illustrated in the figure, although this is not within the scope of this paper.

The frequency control can be made more sophisticated than just the simple droop from (2). As an example, the controllability of the pumped storage unit can be further utilized by adding stabilizing signals to the power reference, to damp modes of oscillations in the power system as described in [42]. In the simulated system, a simple derivative term with time constant of T_d and a low pass filter with time constant T_{filt} can be added to the droop function, so that the power command from the frequency control will be given by (3). Other structures could be more relevant depending on the desired influence on the system.

$$\Delta p_f = - \left(K_{Droop} + \frac{sT_d}{(1+sT_d)(1+sT_{filt})} \right) (f_{ref} - f_{grid}) \quad (3)$$

An attempt to illustrate the influence of the pumped storage on the rest of the power system is made by Fig. 7. This figure shows the main parts of the pumped storage drive system, and how the operation of the pumped storage influences the power balance of the grid. Operation of the pumped storage at a fixed constant power or with load following as the only purpose can be considered an open loop influence on the power system, while frequency control will introduce a closed loop to the system as illustrated in the figure.

V. SIMULATION RESULTS

The isolated power system as described in section III B is simulated for a period of 80 s after reaching normal operation. The pumped storage is run in pumping mode with a power set-point of 8 MW. The pumped storage power is

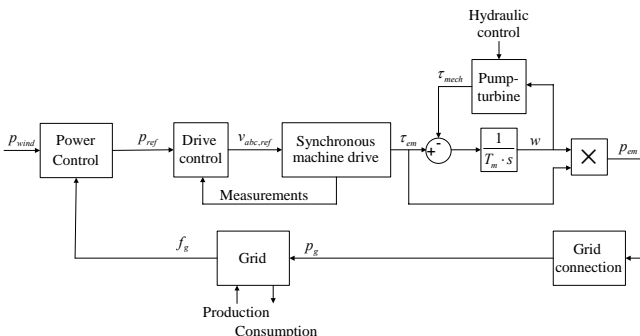


Fig. 7. Illustration of influence on the power balance and the grid frequency from operation of the variable speed pumped storage system

limited between 3 and 12 MW which could be considered realistic if for instance two 6 MW units are run in parallel. The traditional hydropower plant, carrying in average a load of about 4 MW, is disconnected after 40 s of the simulation time, to emulate the influence of a sudden loss of generation in the system.

Fig. 8 shows the power output from the wind farm during the simulated time. Simulation results are further displayed for 5 different cases that can be listed after the type of control for the pumped storage system:

1. Constant power as a reference case
2. Droop control with a frequency response of 25 pu or 5 MW/Hz
3. Droop control with added derivative term
4. Load following
5. Droop control with derivative term combined with load following

Figure 9 shows the power from the diesel generators for the cases with droop and droop with added derivative term, compared to operation with constant power for the pumped storage. It is clear from the figure that the droop is making the pumped storage to partly relieve the control of the diesel generators. By adding a derivative term to the frequency control, the pumped storage is also reacting to the speed of change of the grid frequency. By that some of the faster fluctuations in power output from the wind farm can be compensated by the pumped storage.

Figure 10 shows the power from the diesel generators in the case of load following, and in the case where a droop control with derivative term is combined with load following. It can be seen that with load following, most of the large influence from the variations in wind power output are compensated, but that some smaller oscillations remain. The remaining power fluctuations in this case are mainly because of delays and filtering effects in the power measurements and the pumped storage drive system.

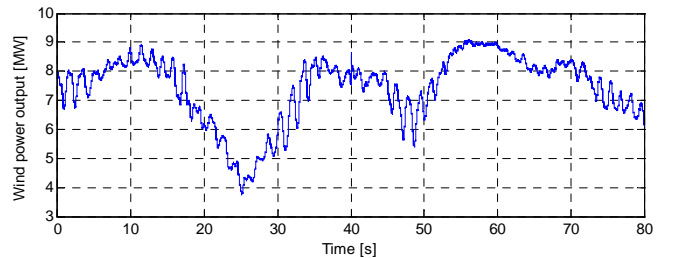


Fig. 8. Power output from the wind farm during the simulation run

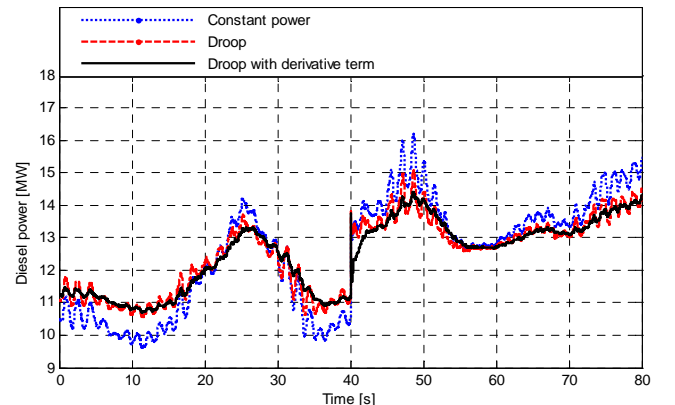


Fig. 9. Resulting power output from diesel generators with frequency control of the pumped storage, compared to operation with constant power

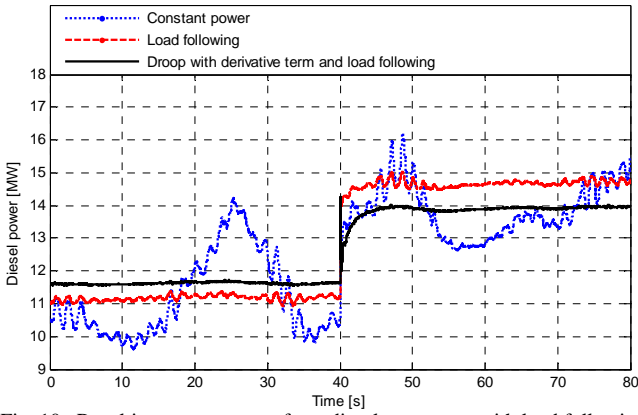


Fig. 10. Resulting power output from diesel generators with load following and combined control for the pumped storage, compared to operation with constant power

Introducing the droop and the derivative term to the system, the diesel generators are partly relieved from some of the response when the hydropower plant is disconnected, and at the same time the smaller fluctuations at higher frequencies are reduced. The result of using the pumped storage to relieve the system from the power fluctuations caused by the wind turbines is seen in Fig. 11. By comparing the pumped storage input power with the curves of Fig. 9 and 10, it can be seen how most of the fluctuations are moved from the diesel generators to the pumped storage unit when the power fluctuations are being balanced.

Figure 12 and 13 are showing the grid frequency in the same way as Fig. 9 and 10 are showing the response from the diesel generators. Since the diesel generators are controlled by a simple frequency droop, the grid frequency is corresponding closely to the power from the diesel generators in Fig. 9 and 10. It can clearly be seen how the droop control of the pumped storage is taking its proportional share of the frequency control, and how the derivative terms added to the frequency droop can contribute to smoothen some of the higher frequency power fluctuations. When the pumped storage is controlled only by load following, the long term wind power fluctuations are compensated while some smaller fluctuations with higher frequency remain. With only load following control, the pumped storage is not taking part in the frequency control of the system, as can be seen from the resulting change in frequency when the hydropower plant is disconnected. Combining all these methods, it can be seen that the

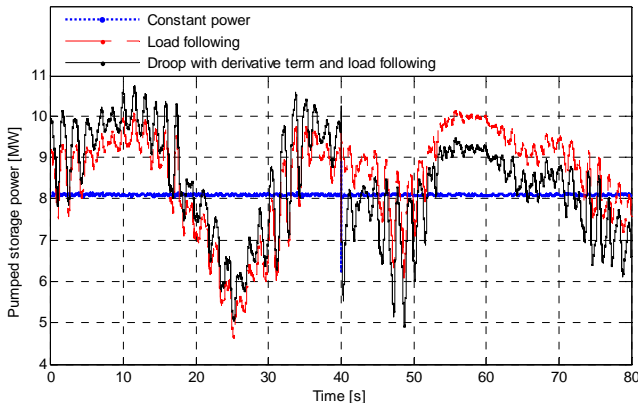


Fig. 11. Power input to the pumped storage for the cases of load following and frequency control combined with load following, compared to operation with constant power

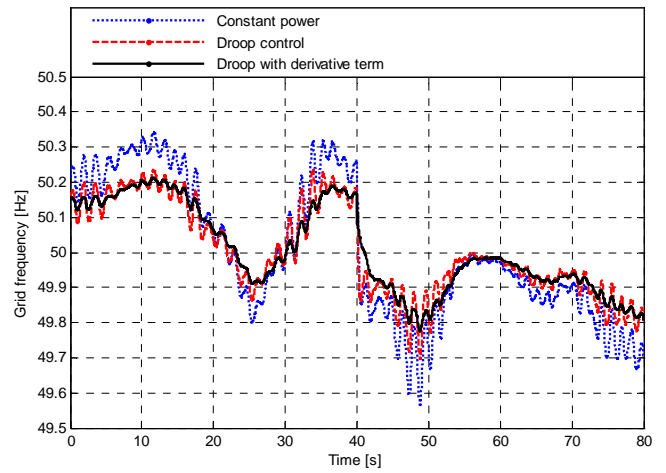


Fig. 12. Resulting grid frequency with frequency control compared to operation with constant power for the pumped storage

frequency is kept at an almost constant value as the power from the wind farm is fluctuating, although there is a stationary reaction to the loss of generation. The speed of the pump-turbine is not shown among the simulations results, but it should be noted that the short term power fluctuations will be smoothed by the inertia of the system. Therefore, mainly the larger variations in power input to the pumped storage unit are influencing the speed of the pump-turbine and the power into the water column. However, the limitations of the hydraulic system should be studied in more detail than for these simulations, to identify clearly the physical limits to the operation, and if there are critical modes in the system that should be avoided for the power control.

VI. CONCLUSION

A topology for variable speed operation of a pumped storage hydropower plant, based on a synchronous machine and a full-scale back-to-back voltage source converter is suggested as relevant for small and medium size units in isolated grids. This topology has become relevant for such applications due to the development of self-commutated semiconductor switches and power electronic drives, but detailed descriptions or investigations of such a system in an isolated power system have not been previously published. By using a synchronous machine, the pumped storage unit

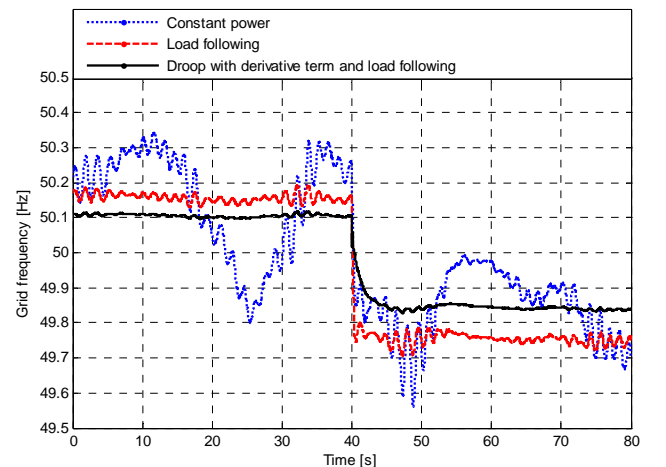


Fig. 13. Resulting grid frequency for control of pumped storage by load following and with combined control, compared to operation with constant power

can also be operated with the machine directly connected to the grid, like a conventional power plant running at constant speed. In this way the operability of the system will be less dependent on the reliability of the converter, and operation of the system as a traditional power plant will be easily available when bypassing the converter.

A possible case for study of the suggested topology in an isolated grid is also described, based on the situation on the Faroe Islands. The system is simulated with different power control strategies for the variable speed pumped storage unit and it has been shown how the pumped storage unit can influence the rest of the system.

The possibility of using the variable speed pumped storage unit for load following, to directly balance fluctuations in the power output from the wind farm, is shown to reduce the influence on the rest of the system from operation of the wind farm. This simple control method will not fully utilize the controllability of the pumped storage and the corresponding benefits that can be obtained for the rest of the power system. Control strategies where the pumped storage unit can take directly part in the primary frequency control, will increase the total frequency response and improve the operational characteristics and the control response of the system to other changes in load and production. Especially in cases with low load and high power output from fluctuating renewable energy sources, that are not normally taking part in the frequency control, the contribution from the pumped storage to the primary frequency control will be important. Further examples have been shown on how different strategies for power control can be combined to improve the operation of the system with respect to power fluctuations and changes in load or production. The presented simulation results illustrate how a variable speed pumped storage power plant can help to allow a higher share of electricity production from fluctuating renewable energy sources like wind power in isolated power systems.

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