Variable speed pumped storage hydropower plants for integration of wind power in isolated power systems

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1. Introduction

Energy storage is a key issue when integrating large amounts of intermittent and non-dispatchable renewable energy sources into electric power systems. To be able to maintain the instantaneous power balance and to compensate for the influence of power fluctuations that might result from renewable sources, flexible capability for power control is needed. Therefore, sufficient energy storage with suitable interface to the electricity grid is considered to be a necessity for development towards sustainable energy systems based on renewable energy sources (Dell & Rand 2001). Energy storage is also an important issue with respect to power system stability, load balancing and frequency control in power systems with large share of nuclear or thermal power plants that need to run at almost constant power (Shimada & Mukai, 2007; Faias et al., 2007).
Many types of energy storage have been proposed for power system applications, and the different technologies have large variety in storage capacity, power rating and cycling capability. There is continuous development going on to increase the performance, reduce the cost and improve the interface to the electric power system for different technologies like battery storage, hydrogen storage, capacitors, flywheels, superconducting magnetic energy storage (SMES), compressed air energy storage (CAES) and pumped storage hydropower. There also exist large scale test facilities, and a few commercial applications, with most types of relevant energy storage technologies, but until now only pumped storage hydropower is considered to be a mature technology with long history of large scale commercial application (Chen et al., 2009; Dell & Rand, 2001; Hammerschlag & Schaber, 2007; Ibrahim et al., 2008; Kondoh et al., 2000; Ribeiro et al., 2001).
Even if pumped storage hydropower systems have been used for more than hundred years, new improvements are still being introduced and development is going on with respect to rating, application areas and control. One of the most important advances during the last decades has been the development of variable speed systems to allow for controllable power in pumping mode (McClear & Meisel, 1984; Scherer, 2005; Terence & Schäfer, 1993). Such systems have been constructed on commercial basis in Japan since the beginning of the 1990s for load levelling in the power system, with more recent introduction also in Europe, and are usually based on a reversible Francis-turbine with a power electronically controlled

machine (Mori et al., 1995; Taguchi et al., 1991; Bocquel & Janning, 2003). With increased introduction of fluctuating renewable energy sources like wind power and photovoltaic in the large scale power systems, pumped storage systems are expected to gain even more importance (Sick & Schwab 2005)

Another important trend in research on pumped storage systems during the last decades has been the focus on application as energy storage in hybrid systems with wind power or other intermittent renewable energy sources as the main energy supply (Bueno & Carta 2006; Kaldellis et al., 2001; Katsaprakakis et al., 2008; Sommerville, 1989; Theodoropoulos et al., 2001). Such hybrid systems have mainly been considered for application in isolated power systems with limited ratings, as an important contribution towards a sustainable electricity supply without dependency on fossil fuels. The consideration of pumped storage schemes for hybrid power systems in isolated electricity grids have until now been mainly focused on simple and robust solutions where the main purpose has been to improve the energy balance of the systems when increasing the share of renewable energy. Although the controllability of variable speed units can be equally important in such hybrid systems as in larger systems using high-capacity pumped storage power plants for load-levelling, little attention has until now been focused on smaller scale variable speed units for isolated grids.

Starting from available scientific literature, this chapter will first briefly review the development history of hydroelectric pumped storage systems. The main focus will be on power electronic solutions for variable speed operation and on application of pumped storage systems to integrate renewable energy sources in weak or isolated power systems. After reviewing the historical development and the state of the art for pumped storage systems from the electrical perspective, the utilization of power electronic control and variable speed operation for grid integration of fluctuating renewable energy sources will be discussed. In specific, the use of a full-scale voltage source converter for control of the pumped storage will be suggested, since this might be a relevant solution in isolated systems with limited ratings. The characteristics of the proposed system will be discussed, and one possible control system for the power electronic converter will be described. This will be presented as a background for illustrating the short-term performance of the proposed system by time-domain simulations and discussing how the variable speed pumped storage system can be used to improve the power system operation and allow for larger shares or fluctuating renewable energy sources.

2. Brief review of pumped storage systems

Energy storage by water reservoirs is a conceptually simple type of energy storage that has been well known and utilized for a long time. The first hydroelectric pumped storage system was constructed in Switzerland already in 1909, and used separate pump and turbine units (EB, 2009). When the Rocky-River Pumped storage hydroelectric station was commissioned in 1929, as the first of its kind in USA, it was well recognized, although not utilized, that the installed pumps could be operated as turbines to generate electricity at reduced efficiency (ASME, 1980, Coleman et al., 1976). In the same time period, development and design improvements of reversible Francis-turbines was going on, and from the 1950s, this has become the standard solution used for almost all new, large scale, pumped storage systems (Coleman et al., 1976; Wikipedia, 2009).

This basic concept of pumped storage systems as sketched in Fig. 1 requires two water reservoirs and a reversible pump-turbine with a grid connected electrical machine. The machine must operate as a motor in pumping mode and as a generator by changing the direction of rotation when the system is operated in turbine mode. Such systems can be constructed in almost any power range with energy storage capacity only limited by the size of the reservoirs, and the round-trip efficiency is usually in the range of 75-85% (ESA, 2009). In this basic form, pumped storage is a mature technology that has been implemented in large scale on commercial basis with more than 90 GW of installed rating worldwide. An extensive, although not necessarily complete, list of the main pumped storage implementations in the world can easily be found from public sources like Wikipedia (Wikipedia, 2009).

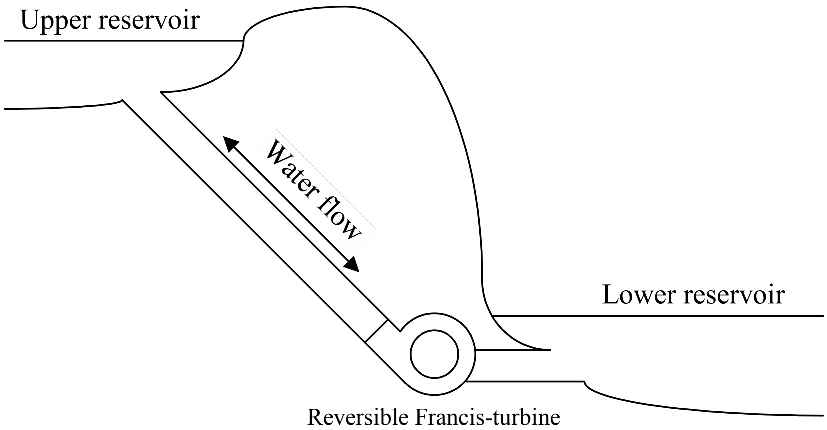

Fig. 1. Basic structure of pumped storage hydro power plant with reversible pump-turbine (Suul et al., 2008a)

2.1 Technological development and introduction of variable speed pumped storage

There has been a continuous development to increase the power rating and the maximum head of reversible pump-turbines, and systems exceeding 400 MW with more than 700 m of pumping head are now in operation (Ikeda, 2000). For the development towards increased heads and higher ratings of pump-turbines, the electrical equipment has not been the main limitation, and this issue will therefore not be further discussed here.

Regarding development of electrical solutions for pumped storage systems, the main issue during the last 3-4 decades has been the introduction of power electronic equipment, and the main achievement in this respect has been the development of power electronically controlled variable speed pumped storage systems. There are many factors that have motivated the drive for variable speed operation of pump-turbines, both regarding the operation of the pump-turbine itself and from the power system point of view.

2.1.1 Motivations for variable speed operation of pumped storage systems

One important motivation for variable speed operation has been the possibility to improve the efficiency of the pump-turbine, since the speed corresponding to maximum efficiency is different for pumping-mode and turbine operation, and is also changing with the water head (Galasso, 1991; Kerkman et al., 1980 a; Lanese et al., 1995; Merino & López, 1996;). Variable

speed operation can also be a necessity in pumped storage systems constructed for large variations in water head.
Even more important is the possibility for power control in pumping mode, since traditional pump-turbines with synchronous machines connected directly to the grid will operate at constant speed and by that constant power in pumping mode. Variable speed operation has therefore been strongly motivated by the possibility to obtain similar power controllability in pumping mode as when operated as a generator (Lung et al., 2007; Schafer & Simond, 1998; Taguchi et al., 1991, Kuwabara et al., 1996). Another benefit by variable speed operation is that the allowable operation range in generator mode can be extended, and that problems with water hammering and other secondary effects in the turbine can be more easily controlled (Kuwabara et al., 1996; Gjengedal, 2001).
From the power system point of view, the possibility for power control in pumping mode is also one of the most important benefits obtained by variable speed operation of pumped storage systems. The power electronic drive system can also be used to increase the response time for power control by utilizing the inertia of the pump-turbine and the electrical machine, both in generating mode and in pumping mode. The fast response can allow for compensation of power fluctuations and damping of power oscillations, and by that improve the stability of the power system (Bocquel & Janning, 2005; Erlich & Bachmann, 2002; Goto et al., 1995; Grotenburg et al., 2001; Schafer & Simond, 1998).

2.1.2 Power electronic solutions to obtain variable speed operation

The possibility for variable speed operation of pump-turbines by use of electrical drives has been considered since power electronic systems like thyristor-controlled HVDC-links were introduced in the power system on a commercial basis. Some of the first investigations of variable speed operation of pump-turbines were therefore considering full-scale thyristor converters based on the configuration indicated in Fig. 2 (Kerkman et al., 1980 a and b). The same configuration has also been considered for variable speed operation of hydropower stations connected directly to an HVDC-link (Naidu & Mathur 1989; Arrilaga et al., 1992). Although this configuration is simple and based on using a traditional synchronous machine, the use of a full-scale converter has been considered a main drawback with respect to cost and losses for pumped storage systems with high total ratings. Therefore only a few pumped storage systems with high demands on operating range have used this topology for continuous variable speed operation until now (Lanese et al., 1995). However, thyristor converters with reduced rating have become a common solution for starting of pumped storage systems running at constant speed (Chiang et al., 1997; Fostiak & Davis 1994). Converters with reduced ratings have also been proposed for improved transition between different operating conditions of pumped storage systems with constant speed (Magsaysay, 1995).

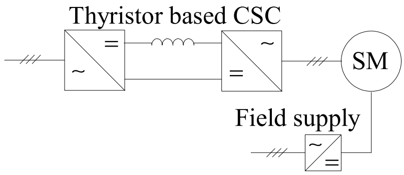

Fig. 2. Full-scale thyristor based Current Source Converter (CSC) driving a synchronous machine

For most applications of pumped storage systems, only a limited controllable speed range is needed during normal operation (Bendl et al., 1999; Boquel & Janning 2003; Mori et al., 1995; Schreirer et al., 2000). This allows for obtaining variable speed operation by utilizing the concept of a doubly fed asynchronous machine (DFAM) and a power electronic converter with reduced converter rating compared to the total machine rating. This topology was considered at an early stage of the investigations on variable speed pumped storage systems and has later been preferred in most large scale implementations to limit the converter ratings. With this concept, the industry has been able to build units with total ratings in the range of several hundreds of MVA (Gish et al., 1981; Hayashi et al., 1988; Lanese et al., 1995; Lung et al., 2007; Sugimoto et al., 1989; Taguschi et al., 1991). In addition to the reduced converter rating compared to the full scale current source converter, this configuration has as another advantage that the reactive power exchange with the grid can be controlled. This can be utilized for voltage control in the grid and contribute to improving the stability and the operating conditions in the rest of the power system (Boquel & Janning 2005; Schafer & Simond, 1998; Taguchi et al., 1991).
When the first commercial, large scale, implementations of variable speed pumped storage systems were investigated, the power electronic converters had to be based on thyristors to achieve sufficient ratings. Since the required frequency for the rotor circuit in the doubly fed machine is given by the deviation from synchronous speed, it is usually limited to a few Hz. Therefore configurations with cycloconverters as shown schematically in Fig. 3 a) has been considered suitable solutions that can be made with rugged designed for high capacity and low losses (Boquel & Jannig, 2005; Furuya et al., 1993; Kuwabara et al., 1996; Taguchi et al., 1991).
As the voltage and current ratings of gate-controlled switches like GTOs, GCTs, IGCTs and IGBTs have increased, topologies based on back-to-back voltage source converters have become relevant for feeding the rotor windings of the doubly fed machine. This configuration is shown in Fig. 3 b), and usually a two-level or three-level neutral-point-clamped voltage source converter is considered as the preferred converter topology. The voltage source converter topology is gaining even more relevance as the development of high power voltage source converters for other drive applications is continuing, and is being used in some of the most recent pumped-storage implementations (Furuya et al., 1995; Hodder et al., 2004; Hämmerli & Ødegård, 2008; Mitsubishi (2009); Sapin et al., 2000; Toshiba, 2008).

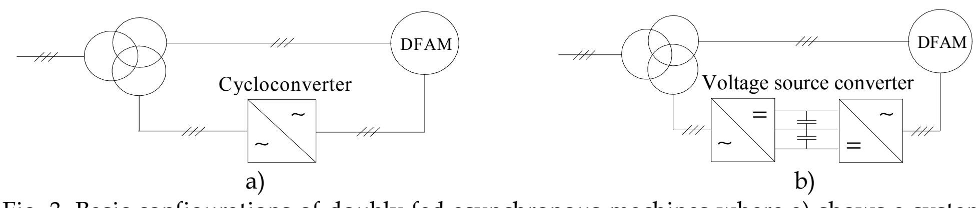

Fig. 3. Basic configurations of doubly fed asynchronous machines where a) shows a system with a cycloconverter feeding the rotor windings while b) shows a system with a back-to-back voltage source converter and capacitive DC-link

The configurations presented in Fig. 2 and Fig. 3 are the basic schemes that are currently used for variable speed pumped storage systems, and such systems can of course also be

considered for normal hydropower plants at sights were variable speed operation is considered to be beneficial (Ansel 2006; Arrilaga et al., 1992; Gjengedal 2001, Naidu & Mathur 1989; Sporild et al., 2000).
The alternative solution of using a full scale voltage source converter to drive the machine has not yet been used for commercial applications although it has been suggested as relevant for small scale hydropower stations (Abbey & Joos 2005; European Commission 2000; Fraile-Ardanuy et al., 2006). This topology can be applied both for cage induction machine and for synchronous machined, but except for the lowest power ratings, the synchronous machine might be the most relevant. Configurations with full-scale power electronic converters should however be further investigated for use in pumped storage systems and for applications in weak and isolated grids, and will therefore be the topic of discussion in section 3 (Suul 2006, Suul et al., 2008 a and b).

2.2 Trends in application of pumped storage systems

As explained, hydroelectric pumped storage systems have been constructed for more than 100 years, and until the last two decades the pump-turbine systems were operated at constant speed by synchronous machines directly connected to the power system. For such systems, bulk energy storage has been the main motivation since pumping occurs at constant power. Pumped storage systems can in this way be economically beneficial by utilizing cheap electricity for pumping water and regenerating the electricity at a higher price during peak hours (Allen, 1977; ESA, 2009; Wu et al., 2007). In generation mode, the power of the pumped storage will however be controlled like in a normal hydropower station and this will contribute to improve the controllability and maintain the power balance of the power system.
One of the main limiting factors for implementation of pumped storage systems is the dependency on available sites with possibility for suitable reservoirs. Therefore, several strategies for utilizing the principle of pumped storage systems have been proposed. One of the earliest suggestions has been the use of underground pumped storage systems utilizing suitable geological formations (Allen, 1977). This concept has recently been proposed for development into commercial applications (Riverbankpower, 2009). Also systems utilizing seawater and the sea as a lower reservoir for pumped storage systems have been developed and put in operation (Fujihara, 1998). Recently, pumped storage systems with the sea as upper reservoir, and artificial lakes below sea-level has been suggested as an alternative configuration (KEMA, 2009) Even systems utilizing natural depressions below sea-level as lower reservoirs have been proposed (Murakami 1995). Another possibility that has been proposed is to combine pumped storage systems with utilization of tidal streams (MacKay, 2007).

2.2.1 Large scale power system applications

As described in section 2.1, one important trend in development of pumped storage systems during the last two decades has been the introduction of variable speed systems. The first commercial systems with large doubly fed asynchronous machines were commissioned in Japan around 1990, and the first large scale implementation with a full-scale thyristor converter for operation with wide speed range and wide range of water head was constructed in China around the same time (Lanese et al., 1995; Taguchi et al., 1991;Terens & Schafer 1993). In Japan, the development of pumped storage systems was intended for both energy storage and to improve the controllability of the Japanese power system because the dominating energy source was nuclear power plants running with almost constant production. Therefore, pumped storage power plants with high degree of controllability both in generating mode and in pumping mode were needed to improve the daily balance between production and load and to improve the frequency control of the system. For utilizing the benefits with respect to power system operation, large units were needed, and several units with ratings up to the range of 400 MVA have been developed (Kuwabara et al., 1996; Mori et al., 1995; Mitsubishi, 2008). More projects are still under development and machines up to 475 MVA of total rating are being planned (Toshiba 2008).

In Europe, only smaller scale test facilities were constructed at the time when the first commercial units were commissioned in Japan (Merino & López, 1996; Terens & Schafer, 1993). Recently, one large scale variable speed pumped storage system with machines rated at 300 MVA and rotor circuit cycloconverters rated for 100 MVA has been implemented in Europe and two new units are now under constriction in Slovenia and Switzerland (Alstom, 2009; Bocquel & Janning, 2003; Mitsubishi, 2008). The pumped storage systems in Europe have had the same main motivation as the systems in Japan, and the operation of the pumped storage has been intended to improve the controllability of the power system in presence of a large share of nuclear or coal fired power plants (Erlich & Bachmann, 2002; Schafer & Simond, 1998; Simond et al., 1999). As attention towards utilization of renewable energy has increased, it has also become clear that pumped storage systems have additional value with respect to the ability to compensate for variations in both production and load in the system. Pumped storage systems as a suitable complement to wind power installations and other renewable energy sources have therefore received significant attention (Allen et al., 2006; Bose et al., 2004; Jaramillo et al., 2004; Lilly et al., 1991; Papathanassiou et al., 2003; Sick & Schwab, 2005).

2.2.2 Applications in small and isolated power systems

Hybrid systems, where energy storage is used to increase the utilization of renewable energy sources in isolated power grids has also received significant interest during the last years. Many of the presented projects and studies have been directed towards utilization of wind power in isolated systems and the use of pumped storage systems to increase the annual share of the energy supply that can be covered by the wind turbines (Bakos, 2002; Bueno & Carta, 2006; Bueno & Carta, 2005 a and b; Ceralis & Zervos, 2007; Chen et al., 2007; Kaldellis et al., 2001; Katsaprakakis et al., 2007; Katsaprakakis et al., 2008; Protopapas & Papathanassiou, 2006; Protopapas & Papathanassiou, 2004).

Most small and isolated power systems on islands and in remote areas have been based on diesel generator sets, and many of the proposed hybrid systems are intended for substituting the fossil fuels needed for the existing power supply by renewable energy sources (Bakos, 2002; Bueno & Carta, 2006; Jensen, 2000). Several studies considering pumped storage systems for energy storage and utilization of wind power have therefore been presented regarding small islands with different locations as for example Mediterranean islands, Shetland, and Hawaii (Bollmeier II et al., 1994; Kaldellis &Kavadias, 2001; Kaldellis, 2002; Katsaprakakis et al., 2006; Sommerville, 1989; Taylor, 1988; Theodoropoulos et al., 2001). Some of the presented projects, like the plans for the electricity supply on the Spanish island El Hierro, have even more ambitious goals of obtaining sustainable energy supplies bases entirely on renewable energy sources (INSULA, 2008; Piernavieja et al., 2003). With the goal of increasing the share of the annual electricity consumption provided by renewable energy sources, the energy balance over the year, sizing of the storage capacity and selection of ratings for the different units in the system has been the main focus of many of the presented studies (Anagnostopoulos & Papantonis, 2008; Brown et al., 2008; Bueno & Carta, 2006; Katsaprakakis et al., 2008). Therefore most of the available literature on hybrid power systems with a pumped storage power plant is discussing investigations based on economical considerations and stochastic methods applied for long time periods, to assess the operability and suitable sizing of the components with expected variations in weather conditions over the years.

When the energy balance has been in focus, and because small systems have been considered, simple and robust practical solutions for the pumped storage schemes have been assumed. Utilization of Pelton turbines for the hydropower station appears to be the preferred solution in most small systems, and by that configurations with separate pumps are necessary. The pumping stations is usually assumed to consist of a number of pumps with specific ratings that can be operated in parallel to control the total power in steps, although it has been shown that variable speed operation of at least one unit will be the most flexible solution (Anagnostopoulos & Papantonis, 2007, Bueno & Carta 2006, Bueno & Carta, 2005a).

From the available literature, it appears that dynamic control of the instantaneous power balance and operation of hybrid systems including wind power and pumped storage schemes has not been extensively investigated and documented in the available literature. When introducing controllable power electronic converters to the pumped storage systems, it is therefore relevant to investigate the dynamic control and operation of a hybrid wind and pumped storage system, as will be presented in the following sections.

3. Variable speed pumped storage topology for operation in weak and isolated grids

From the presented discussion, it is clear that pumped storage units with a full-scale voltage source converter controlling the stator windings of the machine can be a possible configuration. With the increased rating of self-commutated semiconductor switches and available high-power motor drives based on the voltage source converter topology, this configuration could be an attractive solution, especially relevant for pumped storage units in weak and isolated systems (Suul, 2006). The schematic layout of such a 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 although any other standard voltages for medium voltage drive systems could be chosen. The voltage source converters are considered to be standard industrial drives based on the three-level neutral-point clamped topology, although any other voltage source converter topology with ratings suitable for a specific implementation can be used.

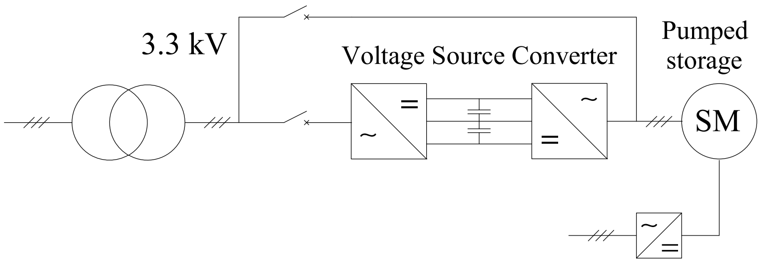

Fig. 4. Suggested topology for variable speed operation of pumped storage

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 allow for a kind of redundant operation of the system in case of problems with the converter, 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 (Holm, 2006).

With the presented configuration, it will be possible to use a diode rectifier for the grid side converter and have variable speed operation only in pumping mode (Suul et al., 2008a). This can reduce the losses during pumping, but will not allow for variable speed operation in generator mode. 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. 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. Since such a system is capable of operation with any power factor, the grid side converter can be used to control reactive power and grid voltage (Suul et al., 2008b). The grid side converter can be operated for control of grid voltage even in the case when the pump-turbine is not in operation, and will then function as a Static Synchronous Compensator (STATCOM). 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.

3.1 Control system overview for investigated configuration

The main structure of one possible control system for operating the suggested configuration in pumping mode is included in Fig. 5 (Suul et al., 2008 b). The figure shows how the grid side converter, connected to the main transformer through a LC-filter, can be controlled by a voltage oriented vector current control system in a synchronously rotating dq-reference frame. The estimate of the voltage phase angle used for the park transformation is obtained by a Phase Locked Loop (PLL) that is also tracking the grid frequency and the voltage components in the rotating reference frame (Chung, 2000, Suul, 2006). The d-axis of the rotating reference frame is aligned with the grid voltage vector, and the q-axis is leading the d-axis by 90°. The current controllers are PI-controllers in the rotating reference frame with feed-forward from measured grid voltage and decoupling terms depending on the filter inductance and the grid frequency (Blasko & Kaura, 1997). To avoid oscillations in the LC-filter, an active damping routine can be added to the function of the current controllers (Mo et al., 2003). The output from the current controllers is divided by the DC-link voltage to decouple the current controllers from the dynamics of the DC-link. After transformation into phase coordinates and adding third harmonic injection, the reference voltages are used for PWM modulation of the switches of the converter. Since the d-axis is aligned with the voltage vector, the input reference to the d-axis current controller is generated by an outer loop DC-link voltage controller that is maintaining the power balance of the system. The q-axis current reference can be generated by an outer loop controller for grid voltage or flow of reactive power.

The grid frequency from the PLL is also used for the power control of the pump turbine. Different structures for controlling the power flow of the pumped storage system in pumping mode, and for generating the power reference to the drive system of the synchronous machine will be discussed in the next section. The details of the drive system of the synchronous machine are not of main importance to the characteristics of the pumped storage system as seen from the grid if the response is fast and precise. In this paper a similar vector control structure as for the grid side converter is used, but since the machine has salient poles, a stator flux oriented ml-reference frame is used for the control of torque and flux while a rotor oriented dq-reference frame is used for the current controllers (Alaküla, 1993, Suul, 2006). Basically the same control structure can be used for controlling the synchronous machine drive in generating mode, but an additional speed controller and the hydraulic control system of the turbine will have to be included in the model.

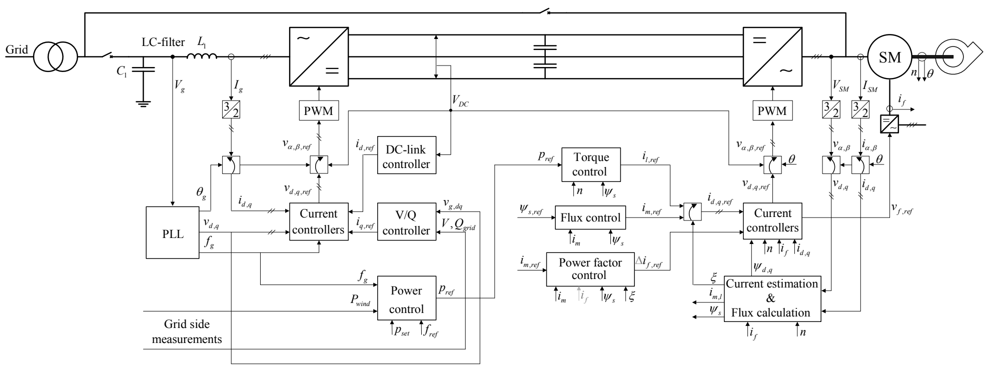

Fig. 5. Overview of possible control system for the investigated converter topology (Suul et al., 2008b)

3.2 Power control strategies for the pumped storage system

For power control of the pumped storage, an external power set-point, p_{set}, as shown in Fig. 5 is assumed as the main input to the control system. 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. The main interest in this context is however how the local control system can respond to power fluctuations from a wind farm and control the power of the pumped storage system to mitigate negative influences on the rest of the power system.

3.2.1 Balancing power fluctuations by Load Following

If a wind farm or another source of power fluctuations is assumed to be in the end of a radial line and close to the pumped storage unit, the power flow in the grid can be measured and the controllability of the pumped storage unit can be used to compensate these fluctuations directly. This way, an almost constant and adjustable power flow is seen from the rest of the grid as long as the pumped storage system is within its limits of operation (Suul et al., 2008a). Assuming a forecasted power output $p_{w,set}$, and a measured power of p_{wind} from a wind farm, the additional power command Δp_w to the pumped storage unit can be calculated by (1).

$$\Delta p_w = p_{wind} - p_{w,set} \tag{1}$$

It can be noticed that the operation of the pumped storage in pumping mode will result in more production capacity on line during high wind and low-load conditions, and by that increase the control capability and the frequency response of the power 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 wind farm will not fully utilize the capability for improvement of the power system operation that is available with the high degree of controllability introduced by the variable speed operation (Suul, 2006).

3.2.2 Frequency Droop Control

Controlling a variable speed pumped storage unit to take directly part in the primary frequency control of the power system, can be of significant importance also in a weak or isolated system. Especially when the load in the system is small and fluctuating power production from a wind farm is dominant, this can be an important 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 (Suul, 2006, Suul et al., 2008a). Basically, this will be a similar way of operation as described for the large variable speed pumped storage units that have been installed in Japan and Germany to help balance production and load 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}.

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

The introduction of frequency droop control for the pumped storage system can be considered as a contribution to the closed loop control of the grid frequency. Operation of the pumped storage with fixed or slowly varying power to operate the pump-turbine at the maximum efficiency, or operation with load following as the only purpose can be considered as an open loop of feed-forward way of control with respect to influence on the grid frequency. It is therefore clear that the introduction of frequency dependent control of the pumped storage system will give a conceptually different behaviour with more potential for utilization of the controllability to the benefit of the power system operation.

3.2.3 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 (Suul et al., 2008a). The possible control routines and algorithms for calculating the long term or stationary power control set-point to the system are also illustrated in the figure, although not of importance for this investigation.

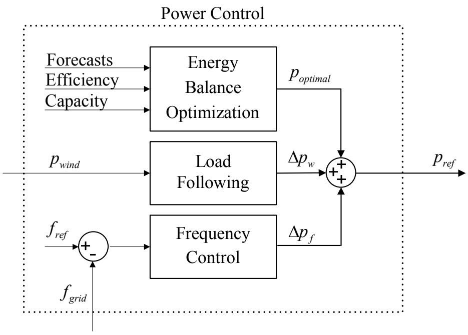

Fig. 6. Possible methods for power control of pumped storage system (Suul et al., 2008a)

The frequency control can also 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 (Goto et al., 1995, Suul 2006). For this investigation, a limited 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 additional damping structures could be more relevant depending on possible critical modes and the desired influence on the system.

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

4. Operation of proposed topology for compensation of wind power fluctuations

To illustrate the operation of the proposed topology and the described control system for a variable speed pumped storage system, time domain simulations of an isolated power system with a large wind farm will be presented. The power control strategies described in section 3.2 will be used as input to the drive system from section 3.1 to investigate how the operation of the pumped storage system can mitigate the influence of wind power fluctuations, and relieve the other generators in the isolated grid in case of changes in production or load. Since a full-scale back-to-back voltage source converter is used, it will also be shown how the voltage or the reactive power flow of the system can be controlled by the drive system of the pumped storage power plant.

4.1 Description of simulated case

A simplified model of an isolated power system described in (Suul, 2006) is used as a starting point for the presented simulations. This case is taken as an example of an isolated system that can significantly benefit from a combination of wind power production and a variable speed pumped storage power plant, but here the energy balance and the possibility for reduction of diesel consumption for electricity production are not further investigated. The minimum load of the system is specified in the range of 14 MW, while the maximum load can reach 70 MW. Introduction of a wind farm rated for 10 MW and a pumped storage power plant in the same power range is considered for the simulations. The most challenging situations for this system will be operation at minimum load when there is a high average power production from wind turbines, and this situation will be the starting point for the simulations.

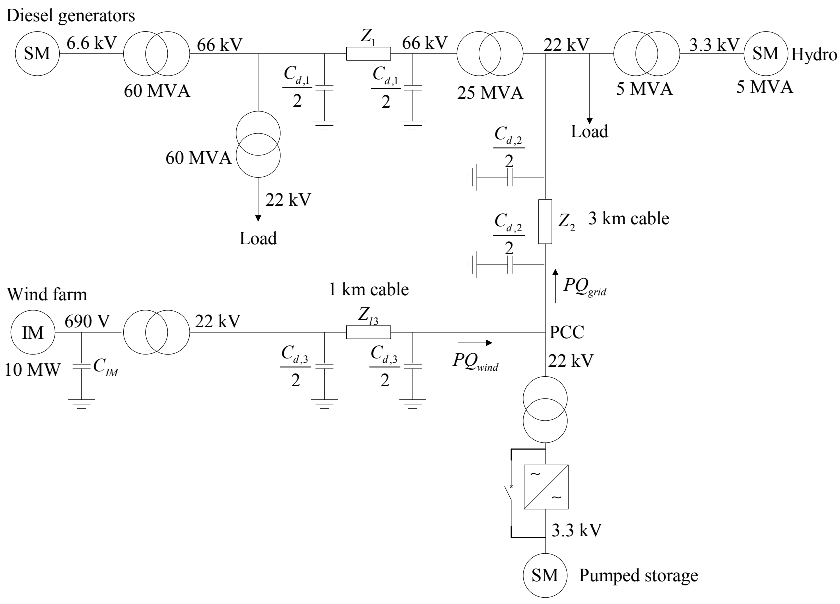

Fig. 7. Simplified grid model of the isolated system used for the presented simulations (Suul, 2006)

The system is simulated by use of a model of the power system including the proposed converter topology and the corresponding control system of the pumped storage unit, developed in PSCAD/EMTDC. All control loops for the drive system of the pumped storage is included in the model, but average models of the converters are used so the instantaneous PWM pattern is not simulated. The basic configuration of the isolated grid, including the ratings of the different units is shown in Fig. 7 while more detailed information about the system is given in Table 1. The system is simulated for 80 seconds and the wind speed input used for simulation of the wind farm is based on the Kaimal power spectra developed for PSCAD simulation from (Sørensen et al., 2002). The power output from the wind turbine model is almost independent of the operation of the pumped storage system, and can be considered equal to the power series given in Fig. 8 for all investigated situations. After 40 seconds of simulation, the hydropower plant is tripped without reconnecting it to the system.

Wind farm	- 10 MW aggregated model - Induction generators directly connected to the grid - Constant capacitors for reactive power compensation
Hydropower plant	- 5 MW synchronous machine with DC-machine exciter system - Power set-point 0,8 pu = 4MW - Static droop; 25 pu = 2.5 MW/Hz
Diesel generators	- 18 MW aggregated model - Power set-point 0.7 pu = 12,6 MW - Static droop; 25 pu = 9 MW/Hz
Pumped storage	- Power control range 4-12 MW - Static droop; 25 pu = 5 MW/Hz

Table 1. Parameters of simulated system (Suul et al., 2008b)

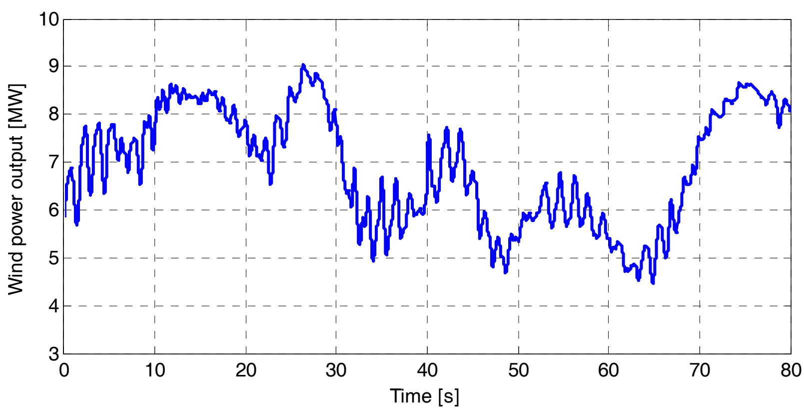

Fig. 8. Power output from wind farm during simulated time series (Suul et al., 2008b)

4.2 Power control

To investigate the power flow and the frequency control of the isolated system from Fig. 7, simulations with different power control strategies are presented. With reference to the power control strategies described in section 3.2, three different cases are compared (Suul et al., 2008 a and b):

1. Constant power input to the pumped storage system as a reference case
2. Load following for direct compensation of wind power fluctuations by the pumped storage power plant
3. Frequency droop with derivative term as given by (3), combined with load following.

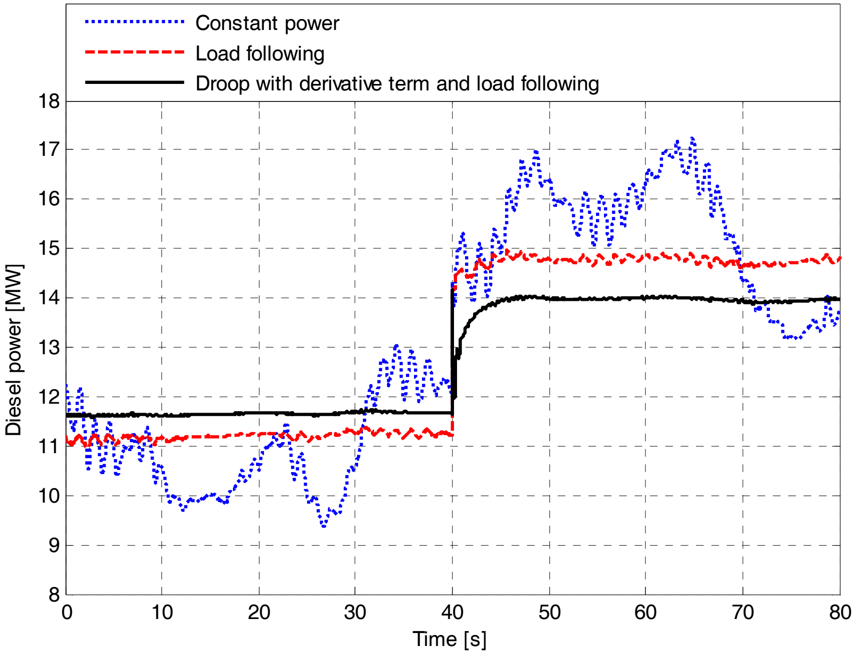

Fig. 9. Power output from diesel generators with different power control strategies for pumped storage power plant (Suul, 2008b)

The response of the diesel generators in the system to the wind power series from Fig. 8 is shown in Fig. 9. It can be seen that with constant power to the pumped storage, the diesel generators have to cover most of the power fluctuations from the wind farm. This result in both large variations in output power that will reduce the efficiency of the diesel generators, and in smaller short term fluctuations that might introduce extra tear and wear in the system. The diesel generators will in this case also have to cover almost all the loss of production when the small hydropower plant in the system is tripped. When controlling the pumped storage power plant to balance the power fluctuations from the wind turbine by load following, it can be seen that the diesel generators are relieved from covering most of the power fluctuation, but that they still have to cover all the loss of production when the hydropower plant is tripped. There are also some small remaining oscillations in the system, mainly because there is some delay in the measurement of the power flow that influences

the accuracy of the load following. Adding the frequency droop to the power control of the pumped storage system, the diesel generators are relieved also from some of the steady state frequency control, and the derivative term added to the frequency control is damping the remaining power oscillations in the system.
The response in speed of the pump-turbine in the pumped storage power station is shown in Fig. 10. This figure shows how the short term power fluctuations from the wind farm are filtered by the large inertia of the electrical machine and the pump-turbine, so that mainly the slower power variations are reflected in the speed of the system. It is also seen how the frequency droop control is reducing the power input to the pumped storage system, as seen by a reduction in speed of the pump-turbine, when the hydropower station is tripped.
The grid frequency curves plotted in Fig. 11 show how the rest of the system is relieved from the influence of the variable power output from the wind turbines when the fluctuations are compensated by the pumped storage system. It can also be seen how the frequency response of the power system is improved when the pumped storage is used for frequency control. The results in Fig. 9, Fig. 10 and Fig. 11 indicate how the control of the pumped storage can limit the necessary operating range of the diesel generators, and by that also limit the fluctuations in grid frequency. This can allow for having less diesel generator capacity on line, and since the remaining units in operation can be operated at a higher average load, the efficiency of the diesel generators can be increased, contributing to further reduction in the fuel consumption of the electricity supply system.

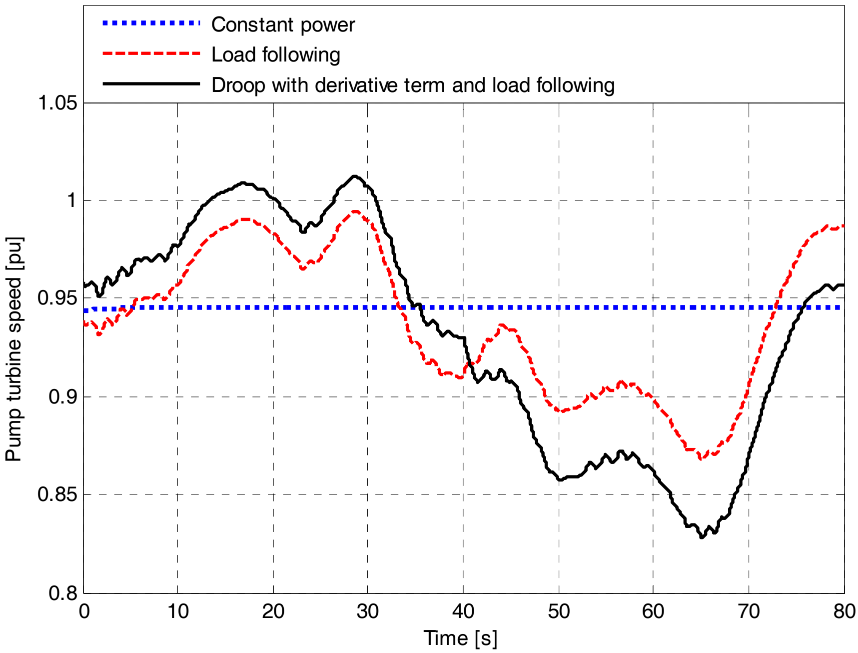

Fig. 10. Speed of pump-turbine with different power control strategies (Suul, 2008b)

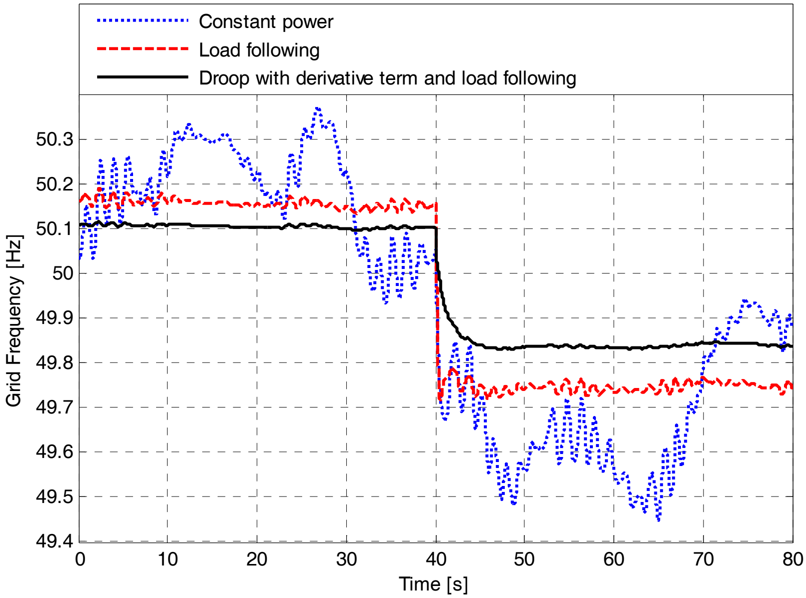

Fig. 11. Grid frequency with different power control strategies for the pumped storage unit (Suul, 2008b)

4.3 Voltage and reactive power control

With the back-to-back voltage source converter, the reactive current on the grid side can be controlled independently of the active power flow. As long as the total current rating is not exceeded, the grid side converter can therefore be used for controlling reactive power flow in the grid or for taking part in the voltage control. In contrast to frequency, that can be considered a global variable in steady state, the grid voltage is a local variable and the design of the control loops for voltage or reactive power will therefore be dependent on the configuration of the local grid. The control objective can also be different depending on what kind of grid the system is located in and what are the most critical challenges of the specific location. The presented topology has the flexibility to easily implement different control structures for voltage or reactive power control.

In the investigated model, the grid is mainly consisting of high voltage cables, and is therefore quite strong with respect to voltage variations and possibilities for voltage collapse. Still voltage flicker can be a problem with large amount of wind power in the system, and control for mitigation of voltage fluctuations is thus relevant.

The influence of different voltage control strategies on the grid voltage, and the flow of reactive power, is illustrated with the simulations shown in Fig. 12 and Fig. 13 (Suul et al., 2008b). The simulations are carried out with the 3rd power control strategy from section 4.2, and results obtained with the following four different control strategies for voltage or reactive power are shown in the figures:

1. Zero reactive current in the converter
2. Grid voltage controlled to 1.0 pu by PI-controller.