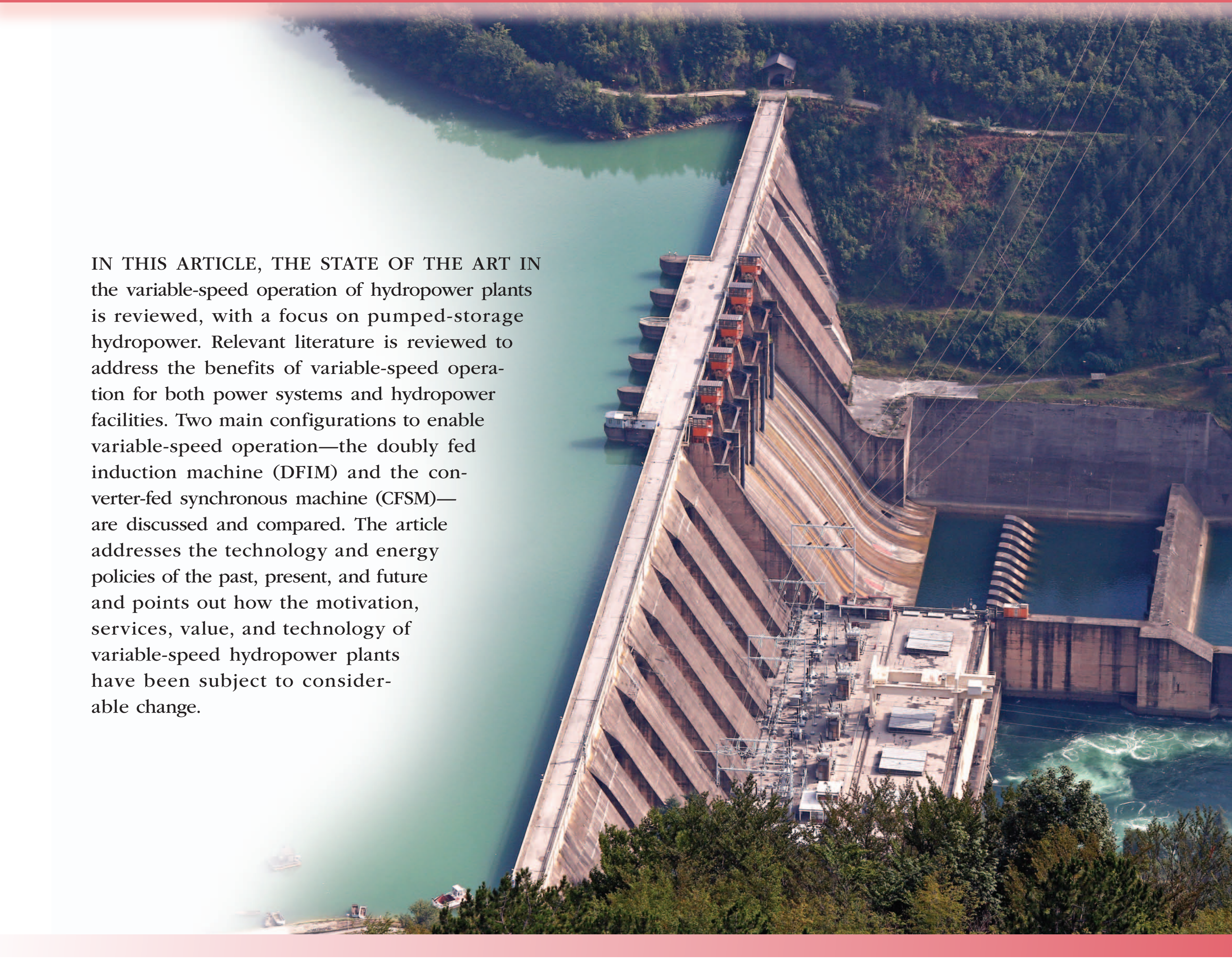
By Mostafa Valavi and Arne Nysveen



IN THIS ARTICLE, THE STATE OF THE ART IN the variable-speed operation of hydropower plants is reviewed, with a focus on pumped-storage hydropower. Relevant literature is reviewed to address the benefits of variable-speed operation for both power systems and hydropower facilities. Two main configurations to enable variable-speed operation—the doubly fed induction machine (DFIM) and the converter-fed synchronous machine (CFSM)—are discussed and compared. The article addresses the technology and energy policies of the past, present, and future and points out how the motivation, services, value, and technology of variable-speed hydropower plants have been subject to considerable change.

©ISTOCKPHOTO.COM/GOCE

Variable-Speed Operation of Hydropower Plants

A LOOK AT THE PAST, PRESENT, AND FUTURE

Digital Object Identifier 10.1109/MIAS.2017.2740467
Date of publication: 18 June 2018

1077-2618/18©2018IEEE

Pumped-Storage Plants

Variable-speed hydropower generators (motor–generators in pumped-storage facilities) do not need to operate at a constant rotational speed because they are no longer directly connected to the grid. In conventional hydropower plants, to produce the grid frequency, the rotational speed of the generator and turbine must be constant. In the case of pumped-storage plants, operation at a constant speed means that the pumping power cannot be properly adjusted. But variable-speed operation can offer many advantages. This article aims to address the opportunities and challenges of variable-speed hydropower facilities. The most relevant application is pumped-storage hydropower, which is the focus of this work. In addition, variable-speed operation in small hydropower and high-voltage dc (HVdc)-connected plants is discussed.

> Pumped-storage hydropower facilities are the most efficient and practical large-scale energy storage systems, with typical overall efficiency in the range of 70–85%.

Pumped-storage hydropower facilities are the most efficient and practical large-scale energy storage systems, with typical overall efficiency in the range of 70–85% [1]–[3]. In production mode, the plant operates as a conventional hydroelectric plant. In pumping mode, electrical energy from the grid is consumed to pump the water from the lower reservoir to the upper one. In a pumped-storage facility, a motor–generator is used to work either as a generator in the production mode or as a motor in the pumping mode.

For the hydraulic system, the following two configurations can be employed: 1) a reversible pump–turbine (usually of the Francis type) and 2) a separate pump and turbine (i.e., a ternary system). It is most common to use reversible pump–turbines in pumped-storage hydropower plants (such as the one shown in Figure 1). In this configuration, the direction of rotation must be reversed when the pumping mode is switched to the production mode and vice versa. As will be discussed later, in the design of reversible pump–turbines, priority is normally given to the pumping operation. The emphasis of this article is the variable-speed operation of reversible pump–turbines.

A way to bring additional flexibility to hydropower plants is to use ternary systems, in which a separate pump and turbine can work simultaneously. In this configuration, a pump and turbine are connected to the motor–generator so that there is no need to reverse the direction of rotation when the mode of operation changes. Hence, they can offer a quicker transition time between modes and a faster response. In addition, both the pump and turbine can be optimized, leading to a higher hydraulic efficiency.

The operation of ternary systems in hydraulic short circuit also makes it possible to regulate the pumping power. In contrast to reversible pump–turbines, the drawbacks include high investment costs, larger space requirements, mechanical complexity, and high operating and maintenance costs. As indicated in [3], both variable-speed and ternary systems are considered to be advanced pumped-storage hydropower technologies. In pumped-storage plants with relatively low heads, a mechanically complex pump–turbine solution (i.e., the Deriaz turbine [5]) with adjustable blades can extend the operational range and enable the regulation of the pumping power; its use, however, has been limited.

As a mature technology, conventional pumped-storage facilities have been used mainly for balancing the power production and load demand in the grid. Typical operation includes working in the pumping mode during off-peak hours (normally at night) and in the production mode during peak hours. The flexibility of pumped-storage plants allows large thermal and nuclear power plants to operate most efficiently at their peak production. In many countries, this was the main motivation for the development of pumped-storage technology in the 1970s [3], [6].

Today, such plants in the grid can play much a greater role than that. As intermittent renewable energy sources such as wind and solar become more important, advanced pumped-storage hydropower may be the enabling technology that allows for the higher penetration of renewable energies into the grid. Because the generation of these variable renewables is difficult to predict, flexible energy storage capacity is needed to improve

FIGURE 1. The runner of a 240-MW reversible Francis pump–turbine in the Limberg II pumped-storage plant, Austria. (Used with permission from [4].)

their grid integration. Conventional pumped-storage facilities with constant rotational speed are not capable of providing the high degree of flexibility that a power system needs in this case. The variable-speed operation of pumped-storage hydropower plants can bring additional flexibility to the power system while offering a variety of valuable ancillary services. In addition to the power system, the hydropower facility itself could benefit substantially from variable-speed operation, through, e.g., improved efficiency and an extended operating range.

This article reviews the state of the art in the variable-speed operation of hydropower plants and is an extended version of [7]. The status of the technology is reported, and future trends are discussed.

Benefits of Variable-Speed Operation

The development of variable-speed pumped-storage plants dates back to the early 1990s in Japan, where pioneering achievements took place and the world's first such facilities were successfully commissioned. The main reason for their development was to reduce the number of large thermal plants operating as reserves during the night and take advantage of the great flexibility offered by variable-speed pumped-storage facilities for frequency regulation [8].

The main advantage of variable-speed operation for pumped-storage plants is the ability to control power in the pumping mode. Hence, such plants can contribute to frequency control in the pumping mode as well as in the production mode. As will be addressed in this section, variable-speed pumped-storage facilities can also offer ancillary services to support the reliable and stable operation of the grid.

The application of variable-speed hydropower technology is, however, not limited to pumped-storage plants. In the case of HVdc-connected hydropower facilities [9], because the frequency of the generator is not tied to the grid, the operation of the plant can be optimized by adjusting the rotational speed. In such plants, it can be advantageous to employ variable-speed technology. Another application that could benefit from variable-speed operation is in small hydropower systems [10], where head and flow variations can be considerable. With variable-speed technology, it is possible to replace rather mechanically complex turbines with simpler ones, while maintaining a sufficiently high efficiency.

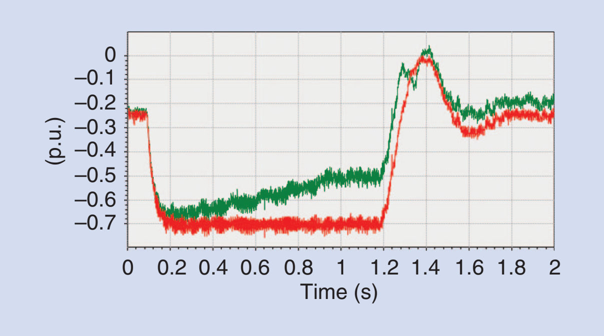


FIGURE 2. The measurement of instantaneous power injection (the flywheel effect) in a 3.3-kVA prototype DFIM. The per unit (p.u.) active power of the machine stator terminals is in red, and the network is in green. (Used with permission from [18].)

Benefits for the Power System

The flexibility and stabilization of the power system can be greatly improved with the ancillary services that hydropower plants with variable speed can provide. Offering high dynamic control, they increase the controllability of the power system. One obvious advantage of pumped-storage facilities is their ability to adjust the pumping power and hence contribute to frequency regulation. In fixed-speed systems, the pumping power cannot be properly varied, so one way to increase flexibility is to use multiple pumps. The variable-speed solution, however, has distinct advantages over the multiple pumps solution; for example, the capability for load balancing is much better, and there is no need for frequent start/stop sequences.

Variable-speed pumped-storage plants are also able to compensate in the production of variable renewables and improve their integration into the grid [3], [11], [12]. Still, nondispatchable production of these renewables is not the only challenge for this integration. The variable renewable sources do not provide inertia in the same way that classical units do, and, as a result, grid stability problems can be a limiting factor for high penetration of renewables [13], [14]. The stability of the grid can be greatly improved by the ancillary services provided by variable-speed pumped-storage plants, and there are many papers and reports that discuss this [3], [8,] [14]–[19]. The variable-speed hydropower approach is claimed not to need any power system stabilizer (PSS) functionality [20]. A comparison between variable-speed hydroelectric systems and conventional systems with PSS in terms of dynamic behavior is presented in [19]. Isolated grids are, in general, more sensitive in responding to frequency deviations; hence, pumped-storage facilities could play a key role in ensuring the safe operation of the grid [12], [21]. In addition, flexible pumped-storage plants, particularly those equipped with variable-speed technology, can greatly reduce the amount of wind power curtailment [3], [22].

In variable-speed systems, the output power can be controlled by the converter; by contrast, in conventional hydropower facilities, the turbine governor has this responsibility [3], [8], [23]. The result can be very fast and high dynamic power control that can be used to improve power system stability. In this regard, an interesting feature offered by variable-speed operation is instantaneous power injection [16], [18], [24], [25], as shown in Figure 2. In this case, because the rotational speed does not need to be constant, a large amount of active power can be injected into the grid by reducing the rotational speed (the flywheel effect). This can be particularly advantageous during disturbances, allowing a reduction of the grid's spinning reserve [16].

An example illustrating the role of variable-speed pumped-storage plants in providing grid support during disturbances is the operation of the Okawachi hydropower facility in Japan during an earthquake disaster in 1995 [3], [8]. It was reported that the variable-speed unit absorbed power disturbances in random spikes and satisfactorily contributed to maintaining grid stability.

As mentioned previously, one motivation for introducing variable-speed operation in pumped-storage plants is to provide frequency control. This feature can reduce the number of thermal plants needed to operate at night as a reserve for frequency regulation. Flexible operation of pumped-storage facilities can create a steadier operation profile for thermal units and reduce their startups/shutdowns and ramping costs [3]. As reported in [8], for the case of Japan, the most attractive evaluation factor for the adjustable speed operation is a reduction of the thermal power units to be operated for automatic frequency control at night.

As an alternative to large-scale pumped-storage plants, relatively small variable-speed pumped-storage facilities are being developed as closely as possible to wind farms, thus providing a decentralized energy storage capacity. As claimed in [14], this can be a key storage technology for future smart grids.

Benefits for the Hydropower Plant

Variable-speed operation can offer distinct advantages for hydraulic machinery and overall power plant performance. An important benefit is improving hydraulic efficiency, especially for reversible pump–turbines. Hydraulic machines are optimized for a single operating point (the best-efficiency point), which is a function of the head, discharge, and rotational speed. At a fixed speed, deviations in the head and discharge can lead to reduced efficiency and increased vibration and cavitation problems. Thus, only limited variations of the head and discharge are allowed. This is why hydraulic efficiency can fall rather sharply at partial loads in a fixed-speed system. While the operating range of fixed-speed pump–turbines is limited to a ratio of about 1.25 between the maximum and minimum head [26], [27], this can be extended, using variable-speed technology, to as high as 1.45, as claimed in [27]. Variable-speed operation offers a new degree of freedom to improve efficiency at each point of operation [25], [28], [29].

If the rotational speed can be adjusted, it is possible to reach an acceptably high efficiency even in the case of large head and discharge variations. In addition, vibration and cavitation problems can be greatly reduced, and the operating range can be extended. The efficiency gain depends strongly on the plant's operational conditions and hydrology. Efficiency improvements are expected to be higher at sites with large head variations and partial-load operation. It is also natural to expect greater efficiency gains in plants with single units compared with those having multiple units. As noted in [30] and [31], a hydraulic efficiency improvement up to 10% can be achieved. In the case of the 400-MW Okawachi pumped-storage facility, an average efficiency gain of 3% is reported [8]. Figure 3 shows the typical range of efficiency improvement for hydropower plants when variable-speed technology is employed.

As mentioned previously, it is most common to use reversible Francis pump–turbines in pumped-storage plants. In this case, a single hydraulic machine operates as both the pump and turbine. Because the hydraulic parameters are different for these two modes of operation, the hydraulic machine cannot have the best efficiency characteristics for both modes. They are normally first designed and optimized as pumps and then work with a reduced efficiency in the turbine mode [6], [14], [15], [17], [30], [33] because optimal speed during pumping is normally higher than that during turbine operation [6], [14], [30]. This problem can be solved with variable-speed operation so that both the pump and turbine can operate at their optimal rotational speeds to reach their maximum efficiencies.

In small and run-of-a-river hydropower plants with low heads or no reservoirs, the discharge rate may vary significantly. Here, mechanically complex Kaplan turbines

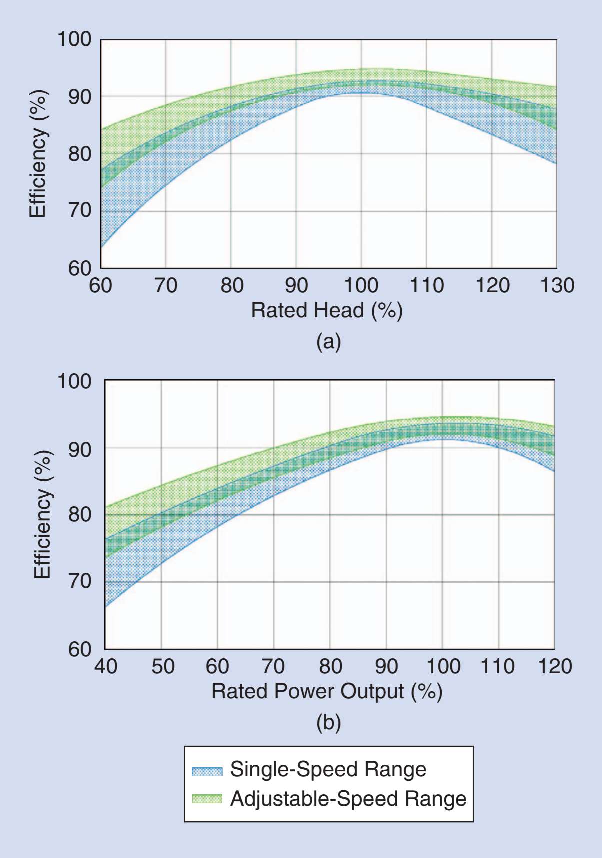


FIGURE 3. The turbine efficiency versus (a) the rated head and (b) the rated output power. (Used with permission from [32].)

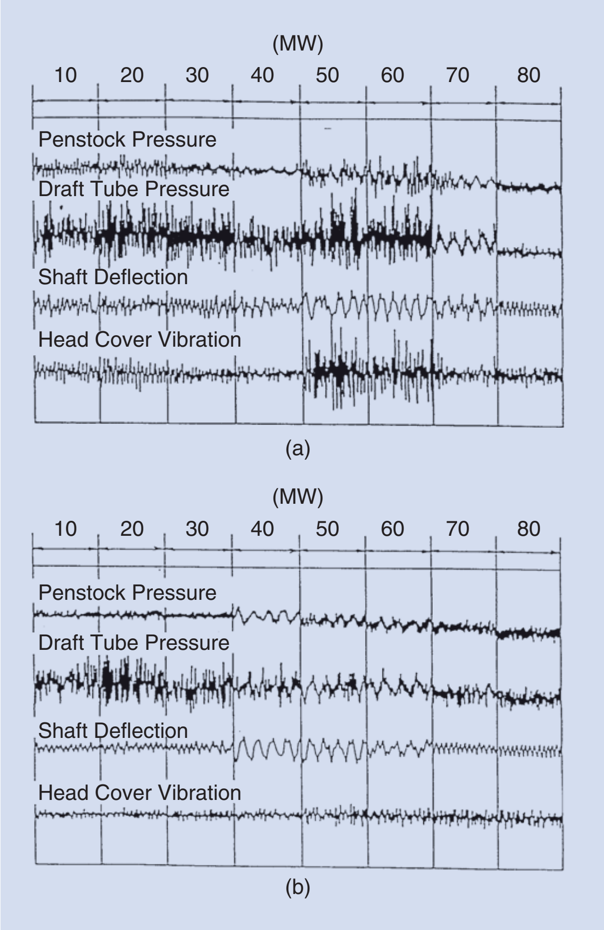


FIGURE 4. The pressure pulsation and vibration of a reversible pump–turbine with (a) fixed-speed and (b) variable-speed operations. (Used with permission from [37].)

can be used to maintain an acceptable efficiency amid the wide range of head and discharge rates. But an alternative solution is to use simpler and cheaper propeller turbines equipped with variable-speed technology [10], [34]–[36]. This technology could help in developing small hydropower projects where environmental impacts are less significant compared to large plants.

In addition to efficiency, flexibility in terms of choosing the optimal speed provides additional advantages for the hydraulic machinery. The speed can be adjusted to avoid hazardous operating zones and reduce cavitation and vibration problems. In fixed-speed systems, partial-load operation and specific gate openings (normally approximately 40–60%) can cause pressure pulsations and result in considerable vibration [3], [30]. This can be reduced in variable-speed operation. Figure 4 [37] presents a comparison between the vibration signals of a reversible Francis pump–turbine with fixed- and variable-speed operation in the Yagisawa pumped-storage plant. Reduced vibration and cavitation problems can potentially lead to less maintenance and an increased life span. In addition, because of improved cavitation behavior, less submergence may be necessary, which leads to a reduced civil engineering cost [14].

A further advantage of utilizing variable-speed technology in pumped-storage facilities is that there is no need to use additional equipment for the pumping startup. In conventional plants, frequency converters (previously pony motors) are needed for pumping startup and synchronization.

It should be noted that variable-speed technology does not normally allow a full range of variation (0–100%) in the rotational speed and hence the pumping power. The main limiting factors are the cavitation and stability considerations related to the hydraulic pump–turbine [3], [14]. Still, considerable improvement in the operating range is feasible, even with a limited allowed speed variation [3]. The typical power variation range in the pumping mode is approximately 30–40%.

Challenges

In general, the most important hurdle for pumped-storage facilities is profitability. New plants need a great deal of investment, take a relatively long time to construct, and could have a negative environmental impact; moreover, new project sites might be limited [1], [23], [38]. Regarding the initial investment, while pumped-storage plants were cost-effective in the past compared to flexible gas turbines, they are no longer economically competitive [3]. (In the case of Norwegian hydropower, however, it is claimed that, because of existing reservoirs, the investment costs for new plants can be greatly reduced [39].)

In addition, gaining revenue from energy arbitrage (i.e., pumping and producing when the electricity price is low and high, respectively) is no longer guaranteed for pumped-storage facilities [3], [40]. In Europe, for instance, the price difference between peak and off-peak electricity in the power markets has not been large enough to ensure plants' profitability [38], [41]. In addition, pumped-storage facilities today have to cope with a more dynamic operational routine, resulting in higher maintenance requirements [38].

Despite the investment issues, there have been changes, mainly in global energy policies, that favor flexible pumped-storage plants. For example, with the high penetration of variable renewable sources, there comes an increasing need for energy storage capacity in the grid. In addition, the ancillary services offered by variable-speed pumped-storage facilities are becoming more important in supporting the reliable operation of the grid. Within a well-defined market, pumped-storage plants can gain revenue from such services. However, most competitive markets currently do not pay for some of the advanced services offered by pumped-storage facilities [1], [3], [41].

While the added value of pumped-storage plants derived from their ancillary services is not well defined in the United States, some areas of Europe have stronger ancillary service markets [1], [3]. Establishing a market for these services makes variable-speed pumped-storage facilities more economically attractive. The value of such plants depends strongly on the level of renewable energy penetration in the grid. In [3], a detailed economic study is presented to assess the value of pumped-storage facilities in the United States. It is shown that their value increases with higher penetration of variable renewables in the grid. This indicates that pumped-storage plants will become increasingly valuable in future power systems.

Note that the previously mentioned challenges are related to the development of new pumped-storage plants in general. Including variable-speed technology will only slightly increase the total investment costs, while providing many advantages. As reported in [3], the incremental costs for incorporating variable-speed capability are in the range of 7–15%, mainly due to the increased costs for electrical equipment. Considering the challenges regarding the development of new pumped-storage facilities, upgrading existing plants to variable-speed technology is gaining attention [23], [42]–[44].

When adopting variable-speed technology in hydropower plants, several considerations must be carefully weighed.

- A more detailed analysis is needed in the design phase of a facility's hydraulic and electrical equipment, and the effects of speed variation should be thoroughly investigated.
- Because the speed can be varied, there is an increased risk of mechanical resonance in the system that should be considered.
- For variable-speed systems, more space is required to accommodate the power electronics converter and the associated cooling equipment.
- In electrical machines, converter-fed operation could bring more complexity and potentially greater losses, vibration, and insulation problems [9], [45], [46].
- Another challenge, as will be discussed in the "DFIMs" section, is the operation of a DFIM-equipped power plant in the event of grid failure.

Technology Evaluation

In conventional pumped-storage hydropower facilities, the electrical machine is directly connected to the grid. Hence, frequency and rotational speed are constant. A method to provide double-speed characteristics in the past was to use pole-changing synchronous machines [6], [33]. These machines are capable of changing the number of active poles and are equipped with two separate windings in the stator, corresponding to each pole number. They are heavier and more complex. Needless to say, this technology is not attractive today because its ability to provide adjustable speed is very limited.

To realize variable-speed operation, two solutions are available: DFIMs and CFSMs. Briefly stated, the CFSM provides superior performance, but the need for a full-rated converter is a main drawback. This makes the DFIM more attractive in high-power applications because the converter itself can be considerably smaller. This section discusses and compares these two solutions and also addresses technology status and future trends.

DFIMs

As shown in Figure 5, the DFIM stator is directly connected to the grid, while the rotor windings are connected via a power electronic converter, using slip rings. A detailed description of DFIM systems, including features related to pumped-storage hydroelectricity, can be found in [47]. Through frequency control of the rotor current, it is possible to have variable-speed operation while the stator frequency and voltage remain constant. In the DFIM, the stator frequency (f_s, in hertz) is a function of both the rotational speed (n, in revolutions per minute) and the frequency of the rotor current (f_r, in hertz):

$$f_s = \frac{n \times N_p}{120} \pm f_r, \tag{1}$$

where N_p is the number of poles. The ± before f_r depends on the rotational direction of the magnetic field produced by the rotor currents. According to (1), it is possible to vary the rotational speed in a certain range (above or below the synchronous speed) while having constant stator frequency (50 or 60 Hz). This variable-speed operation can be realized by controlling the frequency and voltage applied to the rotor windings. To have around ±10% of speed variation, the converter rating does not normally exceed 30% of the rated power. This is the main advantage of a variable-speed system with a DFIM, which makes it the preferred configuration for high power ratings (higher than 100 MW). Therefore, the cost and losses of the converter can be greatly reduced compared to the CFSM solution with a full-power converter.

Until recently, the cycloconverter-driven DFIM was the most common technology in variable-speed plants. The thyristor-based cycloconverter produces a lower-frequency three-phase output from the grid. The state-of-the-art technology, however, is the voltage source converter (VSC) [18], [33], as shown in Figure 5. The VSC

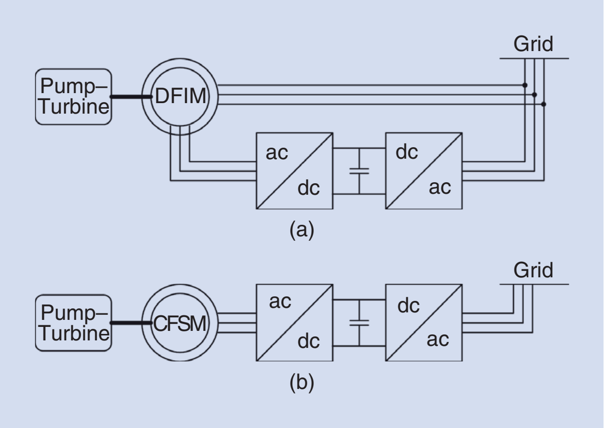


FIGURE 5. (a) A DFIM configuration and (b) a CFSM configuration. (Power transformers are not shown.)

offers many advantages compared to the classical cycloconverter solution, as noted in [1], [6], [16], [18], and [33]: a simpler structure, the ability to regulate reactive power (the cycloconverter absorbs reactive power, making compensation necessary), an improved ability to control the machine during faults, no need for an additional frequency converter during startup, and a much lower total harmonic distortion. In terms of power electronic devices, both transistor- and thyristor-based equipment can be used [6], [48]. The latter—e.g., integrated gate-commutated thyristors (IGCTs)—is claimed to be best suited for high-power applications [20], [23], [38], [49].

The concept of variable-speed operation in hydropower systems using the CFSM was introduced for HVdc application using current–source converters.

For providing variable-speed capability in pumped-storage plants, the focus has been on the DFIM configuration, both in industry and in academia. However, as will be addressed later, variable-speed hydropower systems with DFIMs have a considerable number of drawbacks compared with those utilizing CFSMs.

- The use of slip rings is a major drawback.
- The rotor is mechanically more complex and expensive than that of a synchronous machine.
- Because of the rotor complexity, the maximum DFIM speed is normally lower than that of a comparable synchronous machine.
- It has been claimed [49] that using DFIMs for sites with a maximal head higher than 600 m could prove challenging.
- The DFIM startup procedure can be difficult [33], [49], [50]; because of the limited starting torque, a time-consuming and costly dewatering procedure may be necessary.
- The performance of DFIMs during grid failure and in meeting grid code requirements, specifically low-voltage ride through (LVRT), can be challenging [24], [33], [49], [51], [52]. In this situation, the rotor voltage dynamically increases, and a special protection scheme must be designed to protect the converter [24], [52]. In the worst case (i.e., severe short circuit faults), a crowbar must be activated, short-circuiting the rotor windings, to protect the converter against the overvoltages before the circuit breakers switch off the drive. In this case, it is impossible to control the DFIM [33]. Improving the LVRT capability creates additional complexity and costs. Demanding new grid codes may require the power rating of the converter to be increased [38], [49].

For upgrading existing plants to variable-speed technology, the synchronous generator's rotor and exciter system must be replaced with the new DFIM rotor. In some cases, it might be possible to keep the stator. It should be noted, though, that if fractional-slot windings are used in the stator, operation as a DFIM could be problematic because of the subharmonics and reduced air gap length. In this case, one probable consequence would be a considerable increase in the vibration level, as reported in [53].

CFSMs

In this configuration, a synchronous machine is connected to the grid via a full-rated converter. As shown in Figure 5, a back-to-back VSC is used to connect two ac sides using a dc link. Hence, the frequency of the motor–generator does not need to be equal to the grid. Since the machine is decoupled from the grid, a wide range of speed and frequency variations is possible. Obviously, the drawback is the full-rated converter, which could be very expensive and not practical for the high power ratings. Converter losses could also be an issue. While the efficiency of the synchronous machine is higher than that of the similar induction machine, mainly due to lower rotor losses, higher converter losses make the CFSM less efficient than the DFIM system [54].

These problems limit the application of CFSMs to hydropower plants with power ratings below approximately 100 MW. This limit is expected to be pushed to higher power ratings in the future with advances in semiconductor devices (e.g., wide-bandgap semiconductors, such as silicon carbide) and converter topologies. It has recently become possible to build a frequency converter with a rated power in excess of 100 MVA [44], [49]. As claimed in [49], using modular multilevel converter technology with IGCT devices, it is possible to design converters for very high power ratings (up to 500 MVA). In the future, progress in power electronics may provide the opportunity for the CFSM to become the preferred configuration, even in high power ratings, because of its superior performance over the DFIM.

The concept of variable-speed operation in hydropower systems using the CFSM was introduced for HVdc application using current–source converters [9], [30], [46]. Because of the remote location of some hydropower plants, an HVdc transmission solution might be preferred. An HVdc link makes the hydropower generator independent of the ac grid, and the requirement for having constant speed and frequency is lifted. This can result in the relaxation of some restrictions imposed by the stability requirement, such as minimum inertia [30]. It should be noted, though, that the main motivation for the HVdc connection of hydropower facilities is transmission benefits; variable-speed operation is a further advantage, leading to improved efficiency and extended operating range. A detailed report regarding variable-speed operation of HVdc-connected plants is presented in [9]. More recently, HVdc-connected hydropower plants utilizing the CFSM configuration with a VSC are discussed in [55].

In small hydropower facilities, the CFSM configuration is normally preferred over the DFIM because of the relatively low power ratings. In the proposed concept of decentralized pumped-storage plants [14] with power ratings up to 50 MW, CFSMs are employed.

A pioneering project to use the CFSM system in pumped-storage facilities is reported in [56], where a 60-MW current source converter is provided between the existing generator and the grid to enable variable-speed operation in a hydropower plant with large head variation. Recently, a 100-MW CFSM system equipped with a VSC started operation at the Grimsel 2 pumped-storage plant in Switzerland [44], [57].

Compared to the DFIM, the CFSM offers superior performance and significant advantages. The startup is easier and faster and can be performed in water, thanks to the possibility of producing substantial torque at zero speed [49], [57]. In addition, speed and power variations can be larger [38], [49]. The CFSM system does not have the limitations on maximum speed that the DFIM has, and it can be used for sites with high heads and large head variations [49]. Compared with the DFIM, a variable-speed system with a CFSM offers good LVRT capability and better compliance with grid codes [38], [49], [51], [58]. The converter could be used (while not connected to the machine) as a reactive current static compensator, supplying considerable reactive power to the grid [49]. In addition, a CFSM configuration is more suitable for use in upgrading existing plants. With respect to the design of the synchronous machine, lifting the rotational speed and frequency requirements could initiate a new generator design strategy to achieve optimized operation [59].

In the CFSM configuration (and in contrast to the DFIM topology), a switch can be provided to bypass the converter, if needed [12], [44], [49]. The most relevant case is when the hydraulic efficiency gain due to variable-speed operation does not compensate for the converter losses. For this reason, the converter is bypassed in the production mode at Grimsel 2, as reported in [44].

Current Status and Future Trends

According to [1], out of 270 pumped-storage plants in the world (either operating or under construction), 36 are variable-speed systems, 17 of which are currently in operation. In Europe, 38% of the total pumped-storage capacity planned to be installed by 2020 is for variable-speed hydropower facilities [60]. Most of the operating variable-speed pumped-storage plants are in Japan, with Europe coming in second. Currently, there is no variable-speed pumped-storage plant operating in the United States, but, as reported in [3], many of the approximately 50 proposed projects (in various stages of planning and licensing) are considering variable-speed technology.

Since the early 1990s, when the development of variable-speed pumped-storage facilities started in Japan, the DFIM configuration has been the preferred technology for high power ratings. This is also the case for most of the plants under construction. The main reason, as mentioned previously, is the reduced size of the converter compared to CFSM technology. A list of the existing and planned large pumped-storage facilities with DFIMs can be found in [3]. Figure 6 shows the rotor of a 250-MW DFIM in the Linthal, Switzerland, pumped-storage plant (commissioned in December 2015).

Advances in DFIM systems have been related mainly to the frequency converter. The development of variable-speed pumped-storage hydropower facilities began with thyristor-based cycloconverters. Today, the preferred topology is the VSC. With the use of modern semiconductor devices—e.g., IGCTs, insulated-gate bipolar transistors, and injection-enhanced gate transistors—significant improvements have been achieved in the design and operation of power electronic converters. Regarding electrical machines, DFIMs can now be used in sites with higher rotational speed requirements. As reported in [23], the DFIM with the world's highest rated speed of 576–624 r/min was installed in a 340-MW pumped-storage plant in Japan in 2007. The pump head is more than 700 m, while the rotor weight exceeds 400 t.

In contrast to the established and mature DFIM technology, the CFSM configuration is still in its early development stage for use in hydropower plants with high power ratings. The experiences from the operation of a 100-MW CFSM system in Grimsel 2 have been promising [44]. Figure 7 shows the full-rated converter of the installed CFSM system in this power plant. Even though

FIGURE 6. A motor–generator rotor of a 250-MW DFIM in the Linthal pumped-storage plant, Switzerland. (Used with permission from [61].)

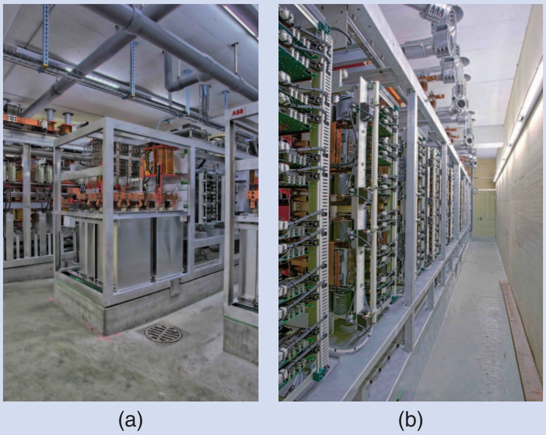


FIGURE 7. A full-rated converter of an installed CFSM in the Grimsel 2 plant: (a) the dc-link filter and (b) the converter block. (Used with permission from [62].)

it is not yet economically beneficial to use full-rated converters for high power ratings, the situation is expected to change over the coming years. Advances in power electronics (including the development of silicon carbide devices) make it possible to design converters with higher power ratings [62]. In [49], it is claimed that extremely high power ratings (up to 500 MVA) are achievable using modular multilevel converters and IGCTs. For future variable-speed hydropower systems, the CFSM configuration is expected to be the preferred technology even for high power ratings.

Conclusions

This article discussed the challenges and opportunities for variable-speed operation of hydropower facilities and addressed relevant applications of variable-speed technology in hydropower systems, with the most important being the pumped-storage plant. The significant benefits offered by variable-speed operation to both power systems and hydropower facilities were listed.

The DFIM and CFSM configurations to enable variable-speed operation were compared. The CFSM offers superior performance compared to the DFIM, but the need for a full-rated converter is a main drawback for this configuration. Because of advances in the field of power electronics, the CFSM configuration is expected to be the preferred technology in the future, even for plants with high power ratings.

Acknowledgment

This work was supported by the Norwegian Hydropower Centre (NVKS) and Norwegian Research Centre for Hydropower Technology (HydroCen).

Author Information

Mostafa Valavi (mostafa.valavi@ntnu.no) and ***Arne Nysveen*** are with the Norwegian University of Science and Technology, Trondheim, Norway. Valavi is a Member of the IEEE. Nysveen is a Senior Member of the IEEE. This article first appeared as "Variable-Speed Operation of Hydropower Plants: Past, Present, and Future" at the 2016 22nd International Conference on Electrical Machines. This article was reviewed by the IAS Electric Machines Committee.

References

[1] Pumped Storage Development Council, "Challenges and opportunities for new pumped storage development," National Hydropower Association, Washington, D.C., White Paper, 2012.

[2] J. Liang and R. G. Harley, "Pumped storage hydro-plant models for system transient and long-term dynamic studies," in *Proc. IEEE Power & Energy Society General Meeting*, 2010, pp. 1–8.

[3] "Modeling and analysis of value of advanced pumped storage hydropower in the United States," Argonne National Laboratory, Lemont, IL, Tech. Rep. ANL/DIS-14/7 105786, 2014.

[4] Voith GmbH. (2017). Pumped storage machines, reversible pump turbines, ternary sets, and motor-generators. [Online]. Available: http://www.voith.com/ca-en/11_06_Broschuere-Pumped-storage_einzeln.pdf

[5] A. Skotak and P. Stegner. (2014, Jan. 1). Choosing turbines for low-head pump-storage plants. [Online]. Available: https://www.hydroworld.com/articles/print/volume-22/issue-1/articles/choosing-turbines-for-low-head-pumped-storage-plants.html

[6] D. Fayolle and S. Lafon, "Variable speed applied to hydroelectric schemes: History of a technology and today's state of art," in *Proc. Hydro*, 2008.

[7] M. Valavi and A. Nysveen, "Variable-speed operation of hydropower plants: Past, present and future," in *Proc. Int. Conf. Electrical Machines*, 2016, pp. 640–646.

[8] T. Kuwabara, A. Shibuya, H. Furuta, E. Kita, and K. Mitsuhashi, "Design and dynamic response characteristics of 400 MW adjustable speed pumped storage unit for Ohkawachi power station," *IEEE Trans. Energy Convers.*, vol. 11, no. 2, pp. 376–384, June 1996.

[9] "Guide for preliminary design and specification of hydro stations with HVDC unit connected generators," International Council on Large Electric Systems, Paris, France, Tech. Rep. JWG 11/14.09, Aug. 1997.

[10] KWI Architects Engineers Consultants, "Status report on variable speed operation in small hydropower," European Commission, Directorate-General for Energy and Transport, Energie, New Solutions in Energy, St. Pölten, Austria, 2000.

[11] C. Nicolet, A. Beguin, B. Kawkabani, Y. Pannatier, A. Schwery, and F. Avellan, "Variable speed and ternary units to mitigate wind and solar intermittent production," in *Proc. Hydrovision Conf.*, Nashville, TN, July 2014.

[12] J. A. Suul, K. Uhlen, and T. Undeland, "Variable speed pumped storage hydropower for integration of wind energy in isolated grids: Case description and control strategies," in *Proc. Nordic Workshop on Power and Industrial Electronics,* Espoo, Finland, 2008.

[13] A. Ulbig, T. S. Borsche, and G. Andersson. (2014, Aug.). Impact of low rotational inertia on power system stability and operation. *Proc. IFAC World Congress*. [Online]. pp. 7290–7297. Available: https://www.sciencedirect.com/science/article/pii/S1474667016427618

[14] J. Krenn, H. Keck, and M. Sallaberger, "Small and mid-size pump-turbines with variable speed," *Energy Power Eng.*, vol. 5, no. 2A, pp. 48–54, 2013.

[15] J. O. Gjerde, T. Gjengedal, R. Flølo, and A. Elstrøm, "Enhancement of power system stability in a deregulated environment: ASD-machines a promising alternative," in *Proc. Power System Technology Conf.*, 1998, pp. 1393–1397.

[16] D. Schafer and J. J. Simond, "Adjustable speed asynchronous machine in hydro power plants and its advantages for electric grid stability," CIGRE, Paris, France, 1998.

[17] R. Sporild, J. O. Gjerde, and T. Gjengedal, "Economic and technological aspects of adjustable speed hydro machines applied for improved stability in power networks," in *Proc. IEEE Power & Energy Society Summer Meeting*, 2000, pp. 2469–2474.

[18] A. Hodder, J. J. Simond, and A. Schwery, "Double trouble," *IEEE Ind. Appl. Mag.*, vol. 14, no. 2, pp. 32–39, 2008.

[19] A. C. Padoan, B. Kawkabani, A. Schwery, C. Ramirez, C. Nicolet, J. J. Simond, and F. Avellan, "Dynamical behavior comparison between variable speed and synchronous machines with PSS," *IEEE Trans. Power Syst.*, vol. 25, no. 3, pp. 1555–1565, 2010.

[20] S. Auber, “Power on tap from variable speed pumped water storage scheme,” *Energize*, pp. 23–27, July 2012.

[21] C. C. Wu, W. J. Lee, C. L. Cheng, and H. W. Lan, “Role and value of pumped storage units in an ancillary services market for isolated power systems: Simulation in the Taiwan power system,” *IEEE Trans. Ind. Appl.*, vol. 44, no. 6, pp. 1924–1929, 2008.

[22] M. A. Hozouri, A. Abbaspour, M. Fotuhi-Firuzabad, and M. Moeini-Aghtaie, “On the use of pumped storage for wind energy maximization in transmission constrained power systems,” *IEEE Trans. Power Syst.*, vol. 30, no. 2, pp. 1017–1025, 2015.

[23] O. Nagura, M. Higuchi, K. Tani, and T. Oyake, “Hitachi’s adjustable speed pumped-storage system contribution to prevention of global warming,” *Hitachi Review*, vol. 59, no. 3, pp. 99–105, 2010.

[24] A. Bocquel and J. Janning, “Analysis of a 300 MW variable speed drive for pump-storage plant applications,” in *Proc. European Conf. Power Electronics and Applications*, 2005, pp. 1–10.

[25] Y. Pannatier, C. Nicolet, B. Kawkabani, J. J. Simond, and P. Allenbach, “Dynamic behavior of a 2 variable speed pump-turbine power plant,” in *Proc. Int. Conf. Electrical Machines*, 2008, pp. 1–6.

[26] Linthal 2015 case study: Variable speed pumped storage plant. Alstom. [Online]. Available: http://www.alstom.com/Global/OneAlstomPlus/Group/Documents/Press%20releases%20docs/Case-Study-Linthal-2015.pdf?epslanguage=en-GB

[27] K. Scherer, “Recent developments in pumped storage energy,” presented at the Int. Council on Large Electric Systems Panel Session, Aug. 2008.

[28] A. Borghetti, M. Di Silvestro, G. Naldi, M. Paolone, and M. Alberti, “Maximum efficiency point tracking for adjustable-speed small hydropower plant,” in *Proc. Power Systems Computation Conf.,* 2008.

[29] Y. Pannatier, B. Kawkabani, C. Nicolet, J. J. Simond, A. Schwery, and P. Allenbach, “Investigation of control strategies for variable-speed pump-turbine units by using a simplified model of the converters,” *IEEE Trans. Ind. Electron.*, vol. 57, no. 9, pp. 3039–3049, 2010.

[30] R. J. Kerkman, T. A. Lipo, W. G. Newman, and J. E. Thirkell, “An inquiry into adjustable speed operation of a pumped hydro plant. Part 1: Machine design and performance,” *IEEE Trans. Power App. Syst.*, vol. PAS-99, no. 5, pp. 1828–1837, 1980.

[31] Adjustable speed pumped storage features. Toshiba. [Online]. Available: https://www.toshiba.co.jp/tech/review/2015/high2015/high2015pdf/1503.pdf

[32] “Technical analysis of pumped storage and integration with wind power in the Pacific Northwest,” MWH Americas, Inc., Bellevue, WA, Tech. Rep. MWH-HDC-T12, 2009.

[33] J. Janning and A. Schwery, “Next generation variable speed pump-storage power stations,” in *Proc. European Conf. Power Electronics and Applications,* 2009, pp. 1–10.

[34] P. Lautier, C. O’Neil, C. Deschenes, H. J. N. Ndjana, R. Fraser, and M. Leclerc, “Variable speed operation of a new very low head hydro turbine with low environmental impact,” in *Proc. IEEE Canada Electrical Power Conf.*, 2007, pp. 85–90.

[35] D. Borkowski and T. Wegiel, “Small hydropower plant with integrated turbine-generators working at variable speed,” *IEEE Trans. Energy Convers.*, vol. 28, no. 2, pp. 452–459, 2013.

[36] P. Duflon and M. Mailloux, “Stanley-Adamson: The first industrial size variable speed compact hydro project worldwide,” in *Proc. IOP Conf. Series: Earth and Environmental Science*, 2014.

[37] P. Donalek. (1995). Application of adjustable-speed machines in conventional and pumped-storage hydro projects. Elect. Power Res. Inst. Palo Alto, CA. Tech. Rep. EPRI-TR-105542. [Online]. Available: https://www.osti.gov/biblio/206542-application-adjustable-speed-machines-conventional-pumped-storage-hydro-projects-final-report

[38] F. Senn and D. Wolf, *Pumped Storage Power in Austria: Experiences, New Projects, Economic Situation*. Tulsa, OK: PennWell Corp., 2013.

[39] M. Korpås, O. Wolfgang, and S. Aam, “Norwegian pumped hydro for providing peaking power in a low-carbon European power market,” in *Proc. European Energy Market Conf.*, 2015.

[40] G. Cavazzini and J. I. Perez-Diaz. (2014, May). Technological developments for pumped-hydro energy storage. European Educ. Res. Assoc. Berlin. [Online]. Available: https://www.eera-set.eu/wp-content/uploads/Technological-Developments-for-Pumped-Hydro-Energy-Storage_EERA-report-2014.pdf

[41] P. Fairley, “A pumped hydro energy storage renaissance,” *IEEE Spectr.*, vol. 52, no. 4, pp. 9–10, 2015.

[42] J. M. Henry, F. Maurer, J. Drommi, and T. Sautereau. (2013). Converting to variable speed at a pumped-storage plant. *HRW-Hydro Review*. [Online]. Available: https://www.hydroworld.com/articles/print/volume-21/issue-5/articles/pumped-storage/converting-to-variable-speed-at-a-pumped-storage-plant.html

[43] S. Antheaume, G. Darona, J. B. Houdeline, Y. Labrecque, and P. Laurier. (2015). Upgrading two pumped storage plants to variable speed. *HRW-Hydro Review*. [Online]. Available: https://www.hydroworld.com/articles/print/volume-23/issue-1/equipment-refurbishment/upgrading-two-pumped-storage-plants-to-variable-speed.html

[44] H. Schlunegger and A. Thöni, “100 MW full-size converter in the Grimsel 2 pumped-storage plant,” in *Proc. Hydro*, 2013.

[45] Europump and Hydraulic Institute, *Variable Speed Pumping: A Guide to Successful Applications*. Amsterdam, The Netherlands: Elsevier, 2004.

[46] R. J. Kerkman, T. A. Lipo, W. G. Newman, and J. E. Thirkell, “An inquiry into adjustable speed operation of a pumped hydro plant. Part 2: System analysis,” *IEEE Trans. Power App. Syst.*, vol. 99, no. 5, pp. 1838–1844, 1980.

[47] I. Boldea, *The Electric Generators Handbook Volume 2: Variable Speed Generators*. Boca Raton, FL: CRC, 2006.

[48] M. V. Pronin, O. B. Shonin, A. G. Vorontsov, and G. A. Gogolev, “Features of a drive system for pumped-storage plant applications based on the use of DFIM with a multistage-multilevel frequency converter,” in *Proc. 15th Int. Power Electronics and Motion Control Conf.*, 2012.

[49] P. K. Steimer, O. Senturk, S. Aubert, and S. Linder, “Converter-fed synchronous machines for pumped hydro storage plants,” in *Proc. IEEE Energy Conversion Congr. Exposition,* 2014, pp. 4561–4567.

[50] Y. Pannatier, B. Kawkabani, C. Nicolet, A. Schwery, and J. J. Simond, “Startup and synchronization of a variable speed pump-turbine unit in pumping mode,” in *Proc. Int. Conf. Electrical Machines*, 2010.

[51] E. Schmidt, J. Ertl, A. Preiss, R. Zensch, R. Schürhuber, and J. Hell, “Studies about the low voltage ride through capabilities of variable-speed motor-generators of pumped storage hydro power plants,” in *Proc. Australasian Universities Power Engineering Conf.*, 2011.

[52] M. A. Bidgoli, H. A. Mohammadpour, and S. M. T. Bathaee, “Advanced vector control design for DFIM-based hydropower storage for fault ride-through enhancement,” *IEEE Trans. Energy Convers.*, vol. 30, no. 4, pp. 1449–1459, 2015.

[53] J. M. Merino and A. Lopez. (1996, Mar.). ABB Varspeed generator boosts efficiency and operating flexibility of hydropower plant. *ABB Rev.* [Online]. pp. 33–38. Available: https://library.e.abb.com/public/5a122ee412d4a8c5c1256ddd00346d69/33-38m527.pdf

[54] L. Koedding. (2014). Modern design for variable speed motor generators. VOITH. [Online]. Available: http://www.shf-hydro.org/maj/phototheque/photos/pdf/2-enh-014-koedding_final.pdf

[55] X. Yang, C. Yang, C. Yue, D. Yao, and C. Yuan. (2014). Optimized operation of hydropower plant with VSC HVDC unit connection. CIGRE. Paris, France. [Online]. Available: https://library.e.abb.com/public/dae5b0ddbc83bd7bc1257d0400508f0d/Optimized%20Operation%20of%20Hydropower%20Plant%20with%20VSC%20HVDC%20Unit%20Connection.pdf

[56] G. Galasso, “Adjustable speed operation of pumped hydroplants,” in *Proc. AC and DC Power Transmission Conf.*, 1991, pp. 424–427.

[57] Grimsel 2: The world’s largest power converter for variable speed pumped hydropower. ABB Case Note. [Online]. Available: https://library.e.abb.com/public/0ee456abcf33cf89c1257d6900347076/Reference_Grimsel_RevA.pdf

[58] C. Xin, H. Minxiao, and Z. Chao, “Power control analysis for variable speed pumped storage with full-size converter,” in *Proc. Annu. Conf. IEEE Industrial Electronics Society*, 2015.

[59] E. L. Engevik, M. Valavi, and A. Nysveen, “Efficiency and loss calculations in design of converter-fed synchronous hydrogenerators,” in *Proc. Int. Conf. Electrical Machines*, 2016, pp. 1636–1642.

[60] E. Muljadi, M. Singh, V. Gevorgian, M. Mohanpurkar, R. Hovsapian, and V. Koritarov, “Dynamic modeling of adjustable-speed pumped storage hydropower plant,” in *Proc. IEEE Power & Energy Society General Meeting*, 2015.

[61] A. Schwery, “Variable speed pumped storage,” in *Proc. Int. Conf. Electrical Machines*, 2016.

[62] P. K. Steimer, “High power electronics innovation,” in *Proc. Int. Conf. Power Electronics and ECCE Asia*, 2015.