Control Strategies for Variable Speed Operation of Pumped Storage Plants with Full-size Converter Fed Synchronous Machines

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***Abstract*—The full-size converter fed synchronous machine (CFSM) for variable speed operation of a pumped storage power plant exhibits multiple advantages over the state-of-the-art Doubly Fed Induction Machine (DFIM) technology. The CFSM technology is emerging as the most preferred system for pumped storage plants for efficient operation in wide range of water flow which is not the case in existing power plants. This paper presents the steady state control strategies to execute the variable speed operation of the pumped storage power plants in both turbine and pump mode using full-size back-to-back converter. Also, how the power plant can be started in pump and turbine mode from standstill have been proposed. In addition, the seamless transition of operating modes from turbine to pump mode and vice versa are presented, which is not the case in today's pumped storage power plants. The proposed control strategies are experimentally verified with a 100 kVA machine and converter setup with emulated reversible pump turbine (RPT).**

***Index Terms*—Pumped storage plant, Variable speed drives, Converter fed Synchronous Machine, Reversible pump turbine.**

I. Introduction

Pumped storage hydropower plants (PSHPs) are better known for its bulk energy storage capability compared to other energy storing technologies available in the world. The operation of such plants can be made optimal by varying the speed as the flow through the turbine varies in either turbine or pump mode. The first commercial unit with variable speed capability using Doubly Fed Induction Machine (DFIM) technology was commissioned at the Yagisawa Pumped storage power plant in 1990 [1] with the aim to balance the slow regulating thermal power plants with PSHPs.

In recent years, the integration of renewable energy sources like wind and solar to the grid have followed an unprecedented increasing trend and are continuing to do so. As these sources are very intermittent in nature, a very large and dynamic energy storage system is becoming inevitable to fully utilize these pollution free energy. Even though, the variable speed operation of PSHP exists with DFIM technology, it takes several minutes (5–10 minutes) for start up of the system in pump mode as the water inside the turbine casing needs to be blown down below the turbine level; and even longer to switch the mode from generation to pump mode. Therefore, the demand to make the system dynamic to fully utilize the renewable energy is going to be the ultimate objective. Since the DFIM technology which needs a converter of about 30% of the stator power rating is not enough to serve this purpose, full-size converter is the way forward to achieve this goal.

The semiconductor devices technology is rapidly increasing and manufacturers are continuously improving the rated capacity of high voltage - high current devices. This has led to achieving high power converters with multilevel converter topologies. Hence, a full size converter to the stator of existing synchronous machines in the fixed speed PSHPs can make the plant dynamic and more efficient. The first of this type is installed in one of the 100 MW units of Grimsel-2 PSHP, Switzerland to run in pump mode [2].

Even though the full-size converter technology for PSHPs is the most sought topic in the energy storage market recently, the control associated challenges have not been thoroughly discussed in literature. The control strategy for a PSHP with DFIM technology has been investigated using simulation tools in [3]. The higher level control strategy in pump mode for a Modular Multilevel Converters (MMC) based full-size converter is discussed with simulation results in [4].

The full-size converter configuration consists of back-to-back converters. The converter on the grid-side and machine-side can have any type of topology depending upon the power and voltage level of the unit. In this paper, a set of outer layer (secondary) control strategies for both grid-side and machine-side converters separately for generating (turbine) mode, pumping mode and fast transition from turbine to pump mode and vice versa have been proposed for the dynamic control of power in both modes. The control strategies are validated using experimental results from a laboratory prototype consisting of 100 kVA converter fed synchronous machine and an Induction machine of similar size to emulate reversible pump turbine (RPT).

II. Converter Topologies

With the development of high voltage high current devices like IGCTs [5], high power converters of up to 100 MVA are commercially viable. In Grimsel-2, two 50 MVA 3-

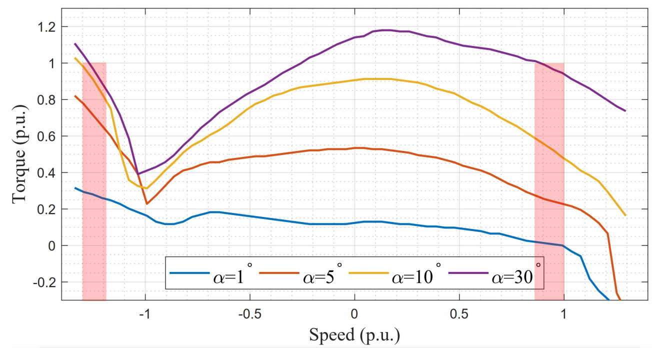

Fig. 1. Torque - Speed characteristics of a reversible pump turbine at varying guide vanes openings (α). The speed is positive in turbine (generating) mode and negative in pumping (motoring) mode. The shaded regions show the rated operating area in respective mode. Courtesy: Water Power Laboratory, NTNU, Trondheim.

level ANPC converters are installed to enable variable speed operation of one of the four 100 MVA units [6].

Considering the commercially available semiconductor devices in the market at the moment, converter of size up to 100 MVA has been considered for discussion in this paper. For a 100 MVA unit of PSHPs, the stator voltage rating of the synchronous machines are in the range of 13–15kV. There does not exist any commercial converter of this voltage level in the market but it is not due to the technological limitation but due to the lack of demand by any application. Converter topologies with 3-level NPC and ANPC are the most popular medium voltage industrial drives and hence, can also be used in this application for both grid-side and machine-side. Since the grid-side converter is connected to an almost fixed frequency AC grid, 3-level Neutral Point Clamped (NPC) converter or Modular Multilevel Converter (MMC) can be a preferred choice. But on machine-side, the output frequency varies as the speed varies from +100% in turbine mode to -100% in pump mode (speed in pump mode may go up to -120% depending upon the net head). The load torque also varies with the speed of rotation of the RPT as presented in Fig.1. The torque required with minimum opening of guide vanes are typically around 13 % which has been considered as the startup torque requirement for the converters to start the RPT in pump mode from standstill. This torque is sufficient to accelerate the RPT with water in the turbine casing which is not the case in any existing pumped storage plants.

As discussed in [7], around 100 MVA of 3-level Active Neutral Point Clamped (ANPC) can be achieved in a single converter block. And, such converter provides a starting torque of around 60% of rated torque. In the past decade, numerous research has been carried out to apply MMC in drives application and has shown promising results that it can provide a starting torque up to 40% of rated torque [8]. Hence, MMC can also be considered as an alternative for both the grid-side and machine-side converters.

III. Control Strategy

The proposed full-size back-to-back converter fed synchronous machine includes hierarchical control structure where the lower most control layer (primary control) is the inner current controller which uses pulse width modulation, hysteresis control loop or direct torque control (DTC). The outer control loop (secondary control) is the layer which interacts with other systems, e.g. Transmission System Operator (TSO) in this case and it generates the references for the primary layer with the logic based on the mode of operation. The upper most control layer (tertiary control) includes the global frequency or voltage regulation of a system normally controlled by a TSO in a large integrated grid network or by an automated system in a relatively smaller system.

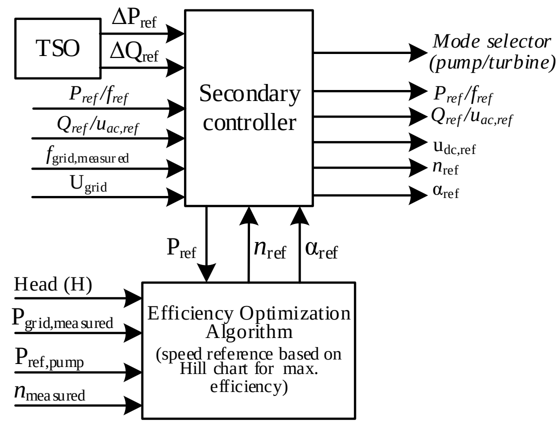

Fig. 2. Schematic showing Secondary layer control strategies for the full-size back-to-back converters. The plant operator normally sets the active and reactive power references (input to Secondary controller). The TSO provides an incremental changes dynamically according to the instantaneous grid parameters. The Efficiency Optimization Algorithm processes the net head (H), Power reference (P_{ref}) in both turbine and pump mode and determines the speed of rotation of the RPT. The references produced by the secondary controller is passed to the converter controllers. A set of converter controllers are activated depending upon the mode of operation (pump / turbine).

A. Secondary Controller

The secondary controller serves as the local controller of the plant and provides frequency and voltage references for the grid-side converter, speed and dc-link voltage references for the machine-side converter, and the speed and guide vanes set-point to the turbine governor. The startup in turbine or pump mode and the transition between these modes is initiated by this controller. The overview of the interaction of secondary controller with the other systems is shown in Fig. 2.

B. Efficiency Optimization Algorithm

The main motivation of variable speed operation of hydropower plant is to run the turbine at maximum possible efficiency depending upon the available head and the water flow through it. Normally, the efficiency curves for a turbine or reversible pump-turbine at varying speed (n), flow (Q) and head (H) is provided by the manufacturer or is determined experimentally using a down-scaled prototype as presented in [9]. The characteristics are popularly known as efficiency Hill chart. The data points in the Hill chart is tabulated to build an Efficiency Optimization Algorithm (EOA) as part of secondary controller or as a different entity in the outer layer of the

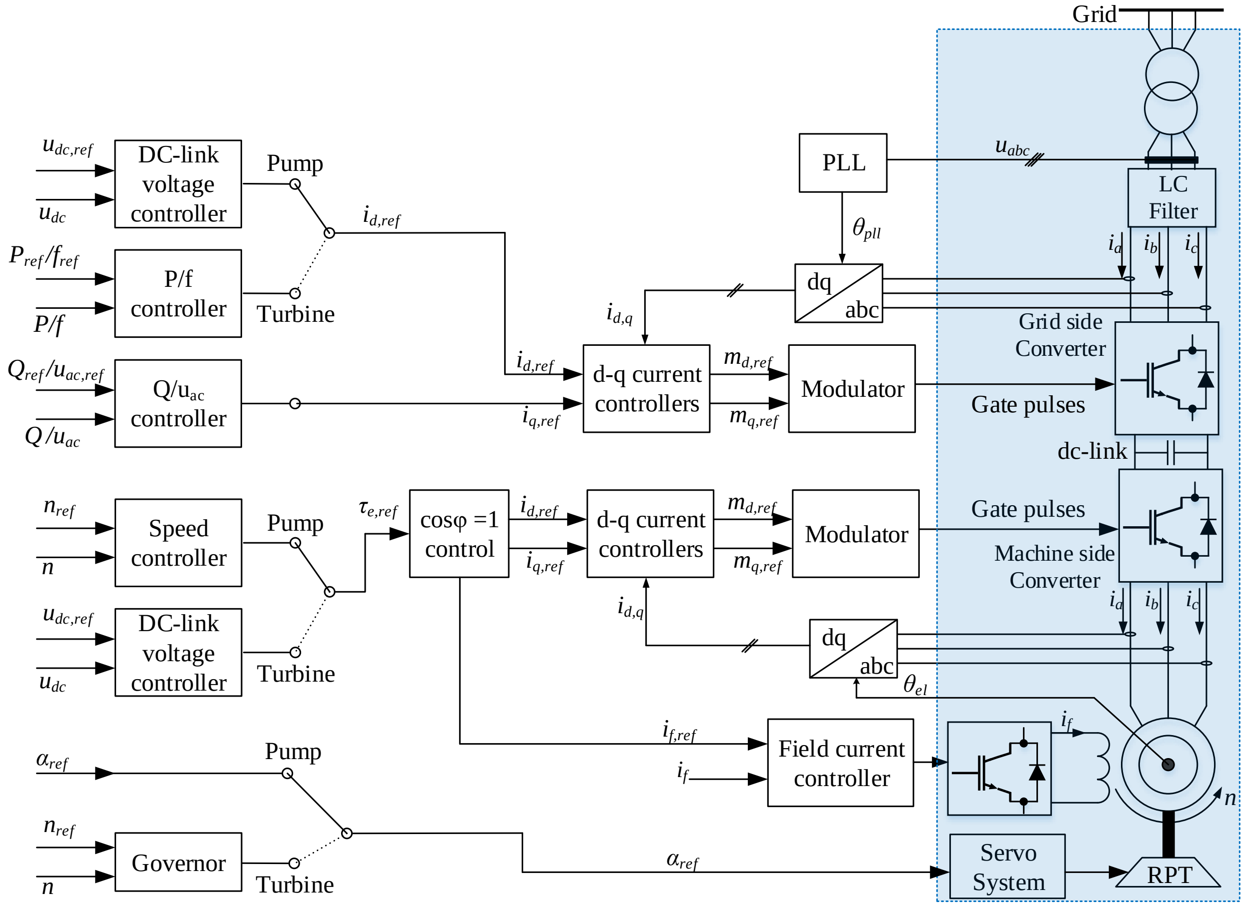

Fig. 3. Schematic of the overall control of the full-size back-to-back converters. All the references to the controllers (on left side of the figure) come from the secondary controller and the Efficiency Optimization Algorithm. All the controllers are proportional - integral (PI) controllers. The shaded region consists of the physical components of the power plant.

control system. The EOA generates the speed reference both in turbine and pump mode to run the machine at maximum possible efficiency. In turbine mode, the speed reference is followed by turbine governor. The governor control system produces guide vane opening angle reference (α_{ref}) for the servo system to control the water flow to achieve the reference speed. In pump mode, the speed is controlled by the machine-side converter. The guide vanes are normally kept fully open and the pumping power is controlled by varying the speed.

Overall control strategy for the control of the grid side converter, machine side converter and governor control is presented in Fig. 3.

C. Grid-side Converter

In a conventional power plant, the synchronous machine is directly connected to the grid and the inertia of the turbine-generator set contributes to the stability of the grid. In case of full-size converter fed system, the machine setup is isolated from the grid such that the rotational speed of the turbine is independent of the grid frequency and vice versa. The grid side converter also known as active front end (AFE) converter is now the gateway to the power flow from the machine to the grid. Utilizing the modern fast and robust control methods, virtual inertia and damping are implemented in the grid-side converter control system in order to contribute to the stability of the grid.

The AFE can run in different modes as demanded by the secondary layer controller. In pump mode, the AFE delivers the pumping power to the reversible pump-turbine. In this mode, it controls the dc-link voltage (U_{dc}) and supports the grid with the reactive power demanded by TSO via secondary controller. This mode of AFE has also been referred as grid following mode in literature. In turbine mode, the control variables AC voltage (U_{ac}) and frequency (f) is set by the secondary controller and the variables are controlled using synchronously rotating frame of reference as shown in Fig. 3. The control of U_{ac} in droop mode controls the reactive power (Q) flow towards the grid whereas the frequency (f) in droop mode controls the active power (P). This mode is known as virtual synchronous machine (VSM) or grid forming converter. In some cases, the active power (P_{ref}) and the reactive power (Q_{ref}) are set by the plant operator via secondary controller and the converter follows these references if the grid voltage and frequency are within the prespecified limit.

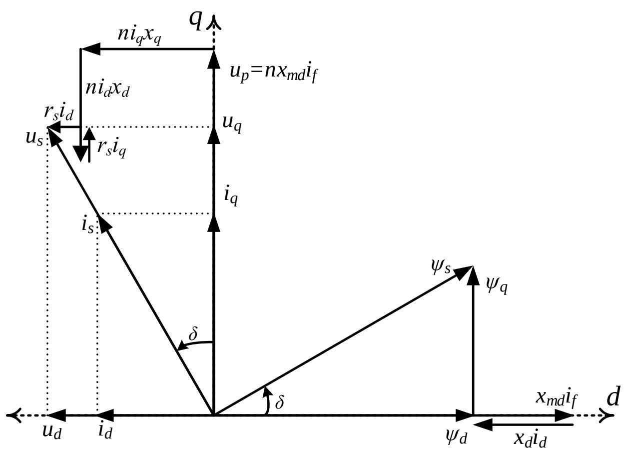

Fig. 4. Unity P.f. control of salient pole synchronous machine. The magnetic pole is aligned along d-axis and the induced emf (u_p) is along q-axis.

D. Machine-side Converter

The machine side converter controls the synchronous machine in a PSHP the same way as it is done in normal industrial drives. The field oriented control (FOC) or direct torque control (DTC) method can be employed to control the machine.

In pump mode, the speed of the machine is controlled to control the pumping power. The speed reference (n_{ref}) generated by the EOA is followed to achieve maximum efficiency.

In turbine mode, the speed is controlled by the turbine governor system and the direction of power flow changes. Since, the grid-side AFE runs as VSM, the machine-side converter needs to control the dc-link voltage.

In either mode of operation, the torque reference generated by the speed controller or dc-link voltage controller is executed by the inner current controller.

E. Inner Controller for Machine-side Converter

The inner controller for the machine-side converter is a torque controller. The torque reference produced by the speed or dc-link controller is translated to stator current reference using (1). The position of the stator current vector to acheive $\cos\varphi = 1$ is determined by (2) . Finally, the d- and q-axes current references from (3) are controlled based on sinusoidal PWM or space vector modulation technique. This control method is best suited for a converter fed synchronous machine since it produces the required torque with minimum possible stator current and converter current. Hence, the method leads to the least possible loss in the machine and the converter with the expense of varying field current.

The governing equation for the torque control to achieve unity power factor ($\cos\varphi = 1$) is as follows based on the phasor diagram presented in Fig. 4 [10]:

$$\tau_e = \pm\psi_s i_s \tag{1}$$

where, τ_e is the electrical torque, ψ_s is the stator flux linkage and i_s is the stator current of the machine in per unit. The current out of the bridge-leg of the converter is considered positive. Consequently, the active power is positive in pump mode and negative in turbine mode. Therefore, when the speed is positive in turbine mode, the torque is negative to inject power to the grid. And, when the speed is negative in pump mode, the torque is still negative to draw power from the grid.

The position of voltage and current vector (δ) w.r.t. the positive q-axis is calculated as:

$$\tan\delta = \pm\frac{x_q i_s}{\psi_s} = \frac{\tau_e x_q}{\psi_s^2} \tag{2}$$

The d- and q- axes current references are then calculated to pass through the current controllers to achieve the torque reference.

$$\begin{aligned} i_d &= -\, i_s \cdot \sin\delta \\ i_q &= \quad i_s \cdot \cos\delta \end{aligned} \tag{3}$$

The field current (i_f) required to maintain the stator flux and the stator current to the reference value for $\cos\varphi = 1$ control can be derived from Fig. 4. Neglecting the relatively small value of the stator resistance, the field current reference is dynamically set as expressed in (4) [10]:

$$i_f = \frac{1}{x_{md}} \frac{\psi_s^2 + x_d x_q i_s^2}{\sqrt{\psi_s^2 + x_q^2 i_s^2}} \tag{4}$$

where, x_d and x_q are reactances along d- and q-axes respectively. x_{md} is the mutual inductance between field winding and d-axis winding. The field current is controlled by a separate full-bridge dc-dc converter.

IV. Experimental Setup and Results

As discussed in Section II, there exist various types of converters which can serve the purpose of full-size converter in a back-to-back setup. The secondary control strategy can be developed such that it is independent of the type of converter installed for the grid-side and machine-side converters. Therefore, to validate the overall system level of control, a two-level back-to-back converter setup has been chosen as the laboratory prototype for this work as shown in Fig. 5.

The down-scaled laboratory setup consists of a synchronous machine as in the case of fixed speed PSHPs and a 2-level 3-phase back-to-back converter set to verify the proposed control principles of this paper. The field current is controlled by a separate full-bridge dc-dc converter and the field current reference ($i_{f,ref}$) is set to the converter from the SM converter over CAN bus. Another 2-level 3-phase back-to-back converter set but with induction machine (IM) is connected via gear box (left half from gear box of Fig.5) to emulate the reversible pump-turbine (RPT). The model of the RPT, waterway, governor control and efficiency optimization algorithm are simulated in real time simulator (OPAL-RT with MATLAB Simulink models). The model also serves as secondary controller as presented in Fig. 2 and initiates the transition of operation mode (turbine to pump or vice versa) and generates references and control mode of operation for the converters. The speed reference in turbine mode and the torque load in pump mode is transferred to the IM converter set over high speed optical fiber link. The IM drive control is tuned to accurately follow the simulated speed of the RPT model. The overall laboratory setup follows the control structure shown in Fig. 2 and 3 except the efficiency optimization part. The main objective is to validate that the control principles works as proposed. The specifications of converters and the electrical machines are presented in Table I.

TABLE I
SPECIFICATION OF ELECTRICAL EQUIPMENT OF THE EXPERIMENTAL SETUP

Converter Specification - Grid side	
Rated Power	100 kVA
Rated dc-link voltage (U_{dc})	650 V
dc-link capacitor (C_{dc})	1.5 mF
Switching Frequency (f_{sw})	8 kHz
AC side capacitor(C_{ac})	27.9 $\mu F \Delta$
Induction Machine Specification	
Rated Power	90 kW
Rated voltage	400 V
Rated current	165 A
Power factor (p.f.)	0.83
Rated speed	1482 rpm
Synchronous Machine Specification	
Rated Power	100 kVA
Rated voltage	400 V
Rated current	144.3 A
Rated speed	428.57 rpm
x_d	1.27 pu
x_q	0.75 pu
Rated field current (I_f)	56 A

All converters are identical. The machine-side converter outputs are directly connected to the machines whereas that of the grid-side converter are connected to the grid via L-C-L filter.

The following control strategies with full-size converter setup has been experimentally verified for the control of the PSHP:

1) start the machine in turbine mode and load it to steady state load via grid side converter
2) start the machine in pump mode from standstill with water in the turbine casing and load it to the steady state value
3) switch the mode of operation from pump to turbine mode without disconnecting from grid
4) switch the mode of operation from turbine to pump mode without disconnecting from grid

In electrical terms, the turbine and pump mode can be interchanged with generation mode and motoring mode respectively. The positive speed of the synchronous machine is considered for turbine mode whereas the negative for pump mode (also shown in Fig.1).

A. Startup in turbine mode from standstill

The startup process in turbine mode can partly be similar to the conventional way of startup where the guide vanes opening is set to a fixed opening optimized for a particular setup (also known as idle position) and let the machine to accelerate to nominal speed. The excitation system is then turned on. Since the rated voltage is available at the terminals, the dc-link capacitor is charged to the peak value of ac voltage through diode rectification. The machine-side converter for synchronous machine can now be set to run state (start switching) to reach the reference dc-link voltage (which is around 0.9 - 1.0 pu). With a stable dc-link voltage, the AFE can be started and synchronized to the grid. The startup process in turbine mode is presented in Fig. 6, and the response of dc-link voltage controller is presented in Fig. 7.

The list of symbols used in Figures are as in the Table II.

TABLE II
LIST OF SYMBOLS USED IN FIGURES

Guide vanes opening	α
Water flow through the RPT in per unit	q_{pu}
Speed of the RPT in per unit	n_{pu}
Electrical torque produced by the synchronous machine in per unit	$\tau_{e,pu}$
Electrical power produced by the synchronous machine in per unit	p_{pu}
dc-link capacitor voltage reference	$u_{dc,ref}$
Measured dc-link capacitor voltage	$u_{dc,meas}$

B. Startup in pump mode from standstill

Startup in pump mode from standstill is the major challenge of the state-of-the-art pumped storage hydropower plants. In existing power plants, the water from the turbine casing is compressed below the turbine level so that it needs less torque to accelerate the machine to synchronous speed. There exists several methods to execute this; for example, soft starter, Load Commutated Inverter (LCI), pony motor, auxiliary turbine, using rotor converter and short circuiting the stator in a DFIM setup and some others [11], [12].

In a plant with full-size converter fed synchronous machine, the AFE is started first in dc-link control. After the dc-link voltage stabilizes to its reference value, the SM machine-side converter is started in speed control mode. The RPT needs a starting torque around 13 % of its nominal torque at standstill. The machine setup is accelerated up to rated speed at a desired rate by controlling the reference from the secondary controller. As the speed increases, the torque capability of the converters also increases and the speed reaches to steady state value within 5 – 6 mechanical time constant. The guide vanes are then opened to pump the water to the upstream. The speed is adjusted to control the water flow and consequently, the active power consumed from the grid as presented in Fig. 8.

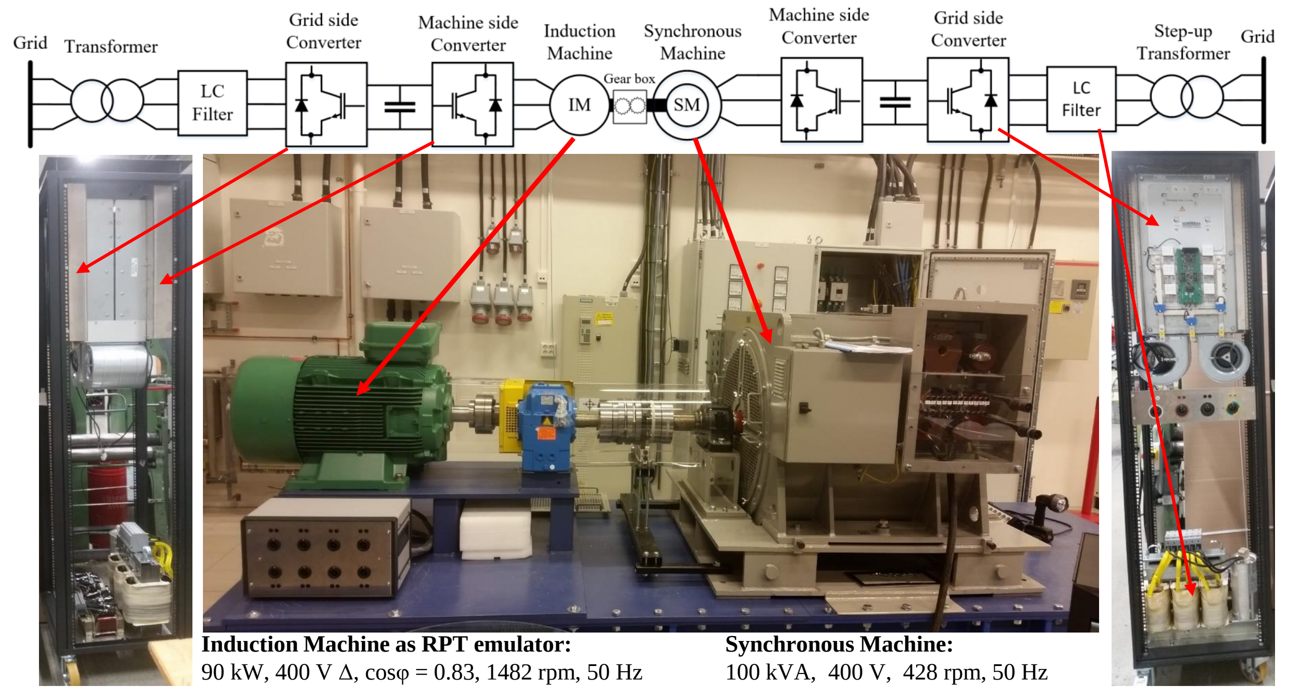

Fig. 5. 100 kVA laboratory prototype. The right half of the gear box with synchronous machine and back-to-back converter is the setup for which the control strategies have been proposed and tested. The left half of the setup with the Induction machine and the back-to-back converter is emulating the Reversible Pump-Turbine as is the case in a PSHP.

C. Transition from pump to turbine mode

This transition is faster even in fixed speed PSHP as the water flows from headrace to tailrace once the pumping power is disconnected. The controlled transition in a converter fed operation has been tested as follows and presented in Fig. 9:

The system is running in pump mode with AFE in dc-link control mode and SM drive in speed control with the speed in range of -1.1 pu. When the transition of operation mode is initiated, the speed is decreased to the value where the load torque due to pumping action is minimum, i.e. water flow is zero, and the guide vanes are closed to the minimum level (the opening level used at start in generation mode) so that the pumping power consumed from grid is close to zero. The secondary controller which initiates the mode transition changes the speed reference to 1.0 pu to turn the rotation to direction of turbine operation. The SM drive ramps up the speed in positive direction to the reference value. Now, the control mode of the converter is changed. The SM drive controls the dc-link voltage and the AFE remains synchronized to the grid, but now controlled as a virtual synchronous machine. The turbine governor is then enabled to control the speed of the machine to the reference value generated by the efficiency optimization algorithm. The power to the grid is now controlled by AFE running in power control mode or in frequency droop to the grid.

D. Transition from turbine to pump mode

When the transition of operation mode from turbine to pump mode is initiated, the AFE regulates the power to the grid close to zero and accordingly, the guide vanes come to its minimum position as the the load is minimum. The control mode of converters are then switched such that AFE controls the dc-link voltage and SM drive controls the speed. Now, the speed reference is set to -1 pu and the SM drive slowly ramps down the speed to the reference value to turn the rotation to the direction of pump mode. In the experimental setup, -0.93 pu is the zero water flow point so the speed is set to this value but higher value is also allowed since the guide vanes are closed. The guide vanes are slowly opened to its maximum opening. The speed is adjusted to control the pumping power to the available power from the grid or to the power set point ($P_{ref,pump}$) provided by the plant operator via secondary controller. Since the torque loading is steep in pumping mode (as shown in Fig. 1), a small change in speed leads to significant change in water flow and hence in pumping power.

The change of control mode of SM drive should always be carried out when the speed is positive and around 0.5 pu because crossing zero speed with AFE in dc-link is not possible. The rotor at zero speed does not have any power to put into the dc-link to keep the voltage to the reference value.

V. Conclusion

The proposed control strategies for a full-size back-to-back converter enables a very fast control of the variable speed operation of the pumped storage plant. The startup of the plant in pump mode, which is challenging in a fixed speed PSHP or plant with DFIM technology, is very rapid with this method. The plant can be started within 5-6 mechanical time constant of the turbine-generator system. This control strategy can

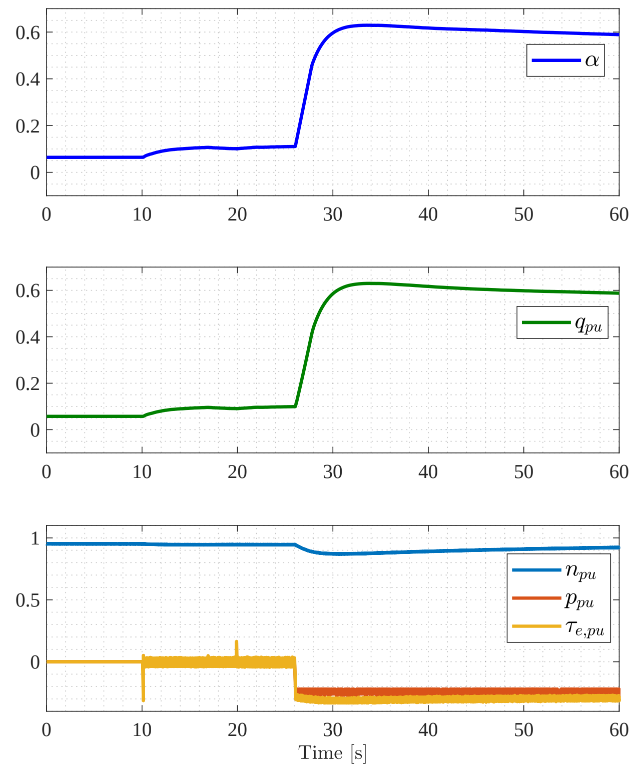

Fig. 6. Startup in turbine mode from standstill. From $t = 0s$ to $t = 10s$, turbine governor controls the guide vanes (α) to run the turbine to 1 pu speed. At $t = 10s$, the machine side converter is started and the charging of dc-link capacitor is the reason of transient in the torque. The water flow (q_{pu}) increases to cover the losses in the machine and the converter. At $t = 20s$, the grid converter is started and synchronized to the grid. At $t = 26s$, a power output of -0.25 pu was injected to the grid using grid-side converter. The recovery of speed takes around 60 seconds which is completely acceptable since the grid frequency and turbine speed are decoupled.

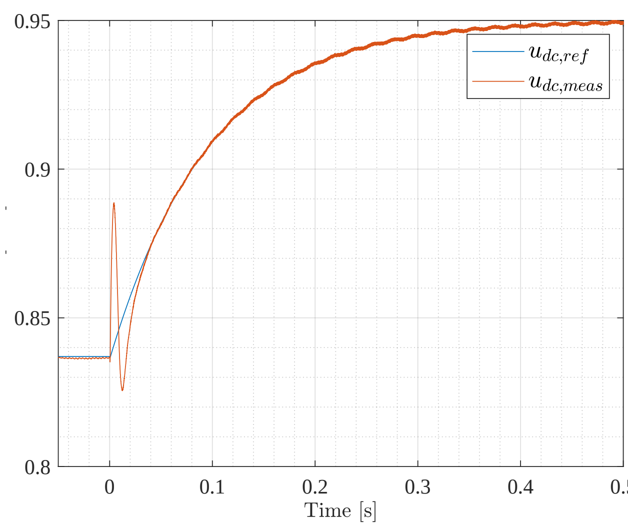

Fig. 7. Startup of synchronous machine-side (SM) converter in dc-link control. The dc-link voltage is controlled without pre-charge which is the case during black start of the power plant. The dc-link voltage before $t = 0s$ is from the diode rectification of the converter. The switching is enabled at $t = 0s$ and the reference voltage (0.95 pu) is passed through a filter. The switching event leads to oscillation in the voltage due to saturation of the controller, which is difficult to avoid since the dc-link voltage is already at the peak of ac voltage.

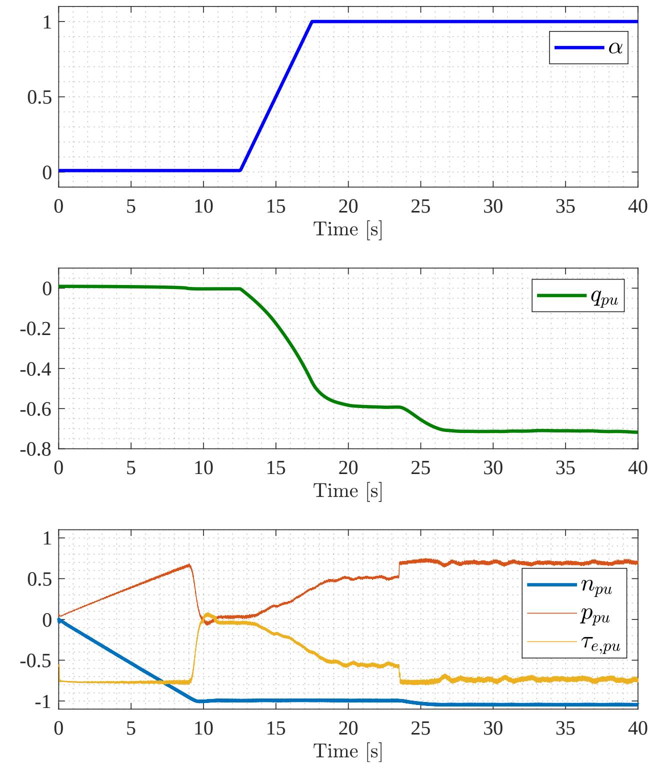

Fig. 8. Startup in pump mode. From $t = 0s$ to $t = 10s$ pump speed is accelerated to -1 pu. At $t = 12.5s$ guide vanes have started to open and the torque loading on SM increases and consequently, the power consumption increases. The water flow increases to -0.6 pu. At $t = 23.5s$, the speed is further increased to -1.05 pu to increase the water flow, and hence the torque loading and the power on the machine increases. The load changes sharply in this region as expected from the torque-speed characteristics shown in Fig. 1. The oscillation in the water flow reflects on the torque and power of the synchronous machine. It takes several minutes for the water to stabilize.

easily integrate the efficiency optimization algorithm which provides high energy savings during steady state operation compared to a fixed speed power plant. The dynamic transition of the mode of operation from turbine to pump and vice versa within 100 seconds can lead to highly efficient integration of renewable energy sources to the grid.

The experimental results show that the system can be started in turbine mode without the requirement to pre-charge the dc-link capacitor, which resembles to the black start capability of a fixed speed power plant.

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REFERENCES

[1] World's First Adjustable-Speed Pumped-Storage Generating System. [Online]. Available: https://www.world-nuclear.org

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

[3] Y. Pannatier, B. Kawkabani, C. Nicolet, 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 Transactions on Industrial Electronics*, vol. 57, pp. 3039–3049, 2010.

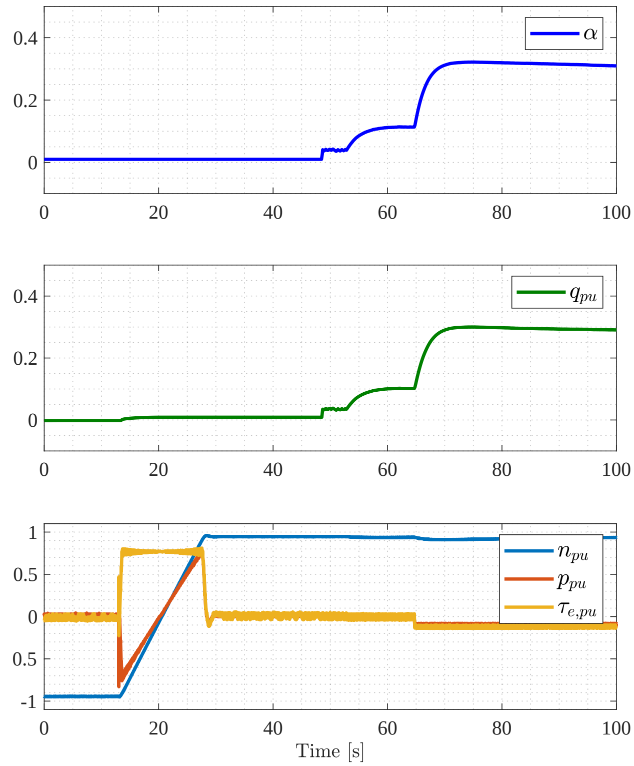

Fig. 9. Transition from pump to turbine mode. From $t = 0s$ to $t = 13s$, the RPT is running in pump mode and the guide vanes have been closed to initiate the transition of mode of operation from pump to turbine. At $t = 13s$, the secondary controller changes the speed reference from -1 to 1 pu to turn the machine to the direction of turbine mode. At $t = 48s$, the control mode of SM converter is switched from speed control to dc-link control and the same of the grid-side converter from dc-link control to grid connected u_{ac} and f_{grid} control. At $t = 65s$, the machine is loaded using grid connected AFE.

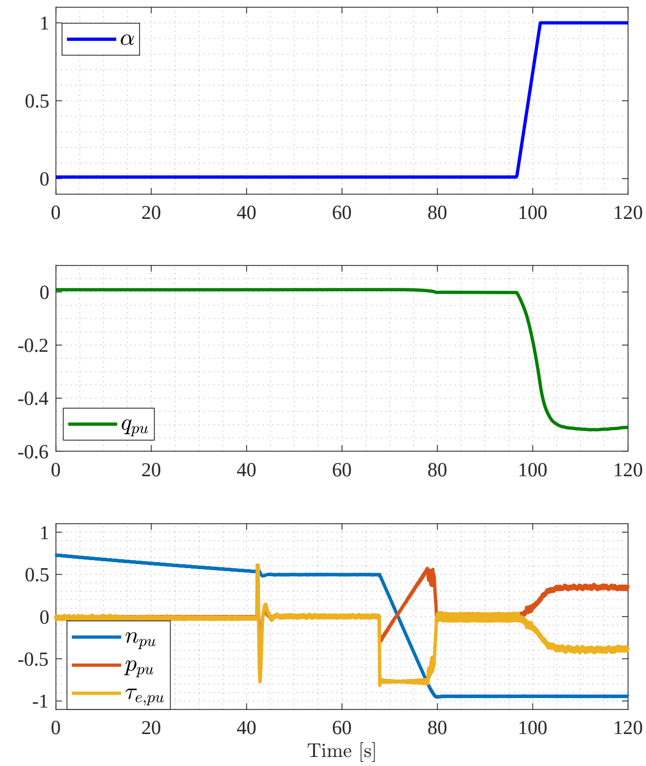

Fig. 10. Transition from turbine to pump mode. From $t = 0s$ to $t = 42s$, the RPT is running in turbine mode and the guide vanes are closed to initiate transition of mode from turbine to pump mode. At $t = 42s$, the control mode of SM converter is switched from dc-link control to speed control and the same of the grid-side converter from grid connected u_{ac} and f_{grid} control to dc-link control. At $t = 68s$, the secondary controller changes the speed reference from 0.5 pu to -0.93 pu to turn the machine to pump mode direction. At $t = 97s$, the guide vanes are opened to pump the water.

[4] M. Basić, A. Schwery, and D. Dujić, "Highly flexible indirect modular multilevel converter for high power pumped hydro storage plants," in *IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society*, 2020, pp. 5290–5295.

[5] "Asymmetric and reverse conducting (IGCTs) | Hitachi ABB," [online].

[6] P. K. Steimer, O. Senturk, S. Aubert, and S. Linder, "Converter-fed synchronous machine for pumped hydro storage plants," in *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2014, pp. 4561–4567.

[7] R. Tiwari, R. Nilsen, and A. Nysveen, "Active NPC Converter for Variable Speed Operation of Pumped Storage Hydropower Plant," in *IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society*, Singapore, 2020, pp. 1211–1216.

[8] M. Hagiwara, I. Hasegawa, and H. Akagi, "Start-up and low-speed operation of an electric motor driven by a modular multilevel cascade inverter," *IEEE Transactions on Industry Applications*, vol. 49, no. 4, pp. 1556–1565, 2013.

[9] P. Guo, Z. Wang, L. Sun, and X. Luo, "Characteristic analysis of the efficiency hill chart of francis turbine for different water heads," *Advances in Mechanical Engineering*, vol. 9, no. 2, p. 8, 2017. [Online]. Available: https://doi.org/10.1177/1687814017690071

[10] H. Bühler, *Einführung in die Theorie Geregelter Drehstromantriebe: Band 2. Anwendungen*, ser. Lehrbücher der Elektrotechnik. Birkhäuser Basel, 1977. [Online]. Available: https://www.springer.com/gp/book/9783034864428

[11] T. J. Hammons and J. Loughran, "Starting methods for generator/motor units employed in pumped-storage stations," *Proceedings of the Institution of Electrical Engineers*, vol. 117, no. 9, pp. 1829–1840, Sep. 1970.

[12] K. Gamlesaeter, "Starting methods for pump stoarge units." Paris, France: Cigre, 1991.