Evaluation and Comparison between Multilevel Converters for Variable Speed Operation of Pumped Storage Power Plants with Full-size Converters

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***Abstract*—This paper compares the full-size converter topologies for the converter fed synchronous machines which can enable the fixed speed pumped storage power plant to variable speed operation. Three converter topologies: Neutral Point Clamped (NPC), Active NPC and Modular Multilevel Converter (MMC) topologies have been selected as suitable solution for this application. The characteristics of these topologies have been evaluated based on the startup torque required in pump mode, flexibility in fast transition from generating to pumping mode, number of semiconductor and passive components required and the efficiency of the converter. The review of the topologies shows that MMC can provide startup torque of about 35% whereas ANPC can yield about 60% of rated torque.**

***Index Terms*—Active Neutral Point Clamped Converter, Medium-voltage drives, Reversible pump-turbine, Pumped Storage Power Plants, Modular Multilevel Converter**

I. Introduction

Pumped storage power plants (PSHPs) are normally realized in two ways. First type, where the synchronous machine is connected to two different hydraulic machines: a Francis or Pelton turbine and a pump; also known as ternary set of machines. In this case, the electrical machine always rotates in the same direction and the generation and pumping action is managed by the turbine and pump respectively. Second type, where the synchronous machine is connected to a reversible pump turbine (RPT). In this case, the power is produced when the RPT rotates in one direction (when the water flows from upper to lower reservoir) whereas power is consumed, and the water is pumped when the RPT is rotated in opposite direction. The direction of rotation is changed by changing the phase sequence of the input power supply. In these both types of pumped storage plants, the set of machines run at fixed speed and the power in pump mode cannot be regulated. In addition, switching from pump mode to generation mode or vice versa is not seamless. It takes several minutes to start the set in pump mode as the turbine casing need to be dewatered and the machine set needs to be accelerated close to synchronous speed using auxiliary arrangement (pony motor or auxiliary turbine or coupling with the other machine in the same power plant). Such plants are, therefore, used for pumping the water with fixed power only for long term operation, e.g. weekly or seasonal in some cases.

However, it is well-known theory that the speed of the hydraulic machines (pump or turbine or RPT) need to be varied as the water flow and the head vary to achieve the best efficiency point of operation. In 90's, the variable speed operation of the pumped storage plant was introduced using doubly fed induction machine (DFIM) technology where the stator of the machine is directly connected to the grid as in case of fixed speed synchronous machine and the rotor winding is connected via a frequency converter of approximately 10 – 20% power rating of the machine. The speed of the rotor is controlled by controlling the slip frequency of the rotor supply, also known as slip power recovery. This technology was introduced to control the power in pump mode while keeping the base load plants which was nuclear power plants at relatively constant power generation. A list of large scale plants with DFIM technology is listed in [1]. Cycloconverters were mostly used in early days as the rotor power converter. In this case, the output frequency is approximately 1/3 of the input frequency. Therefore, it cannot be used as a startup converter since it cannot accelerate the machine close to the synchronous machine. Hence, an additional auxiliary arrangement similar to that in a fixed speed pumped storage plant is required to start the system. With the development of new type of semiconductor devices (like IGBTs), there are few new plants where two-level three-phase back-to-back converter topology is also employed. In this case, the rotor converter can be used to start the machine from standstill by short circuiting the stator winding. Like fixed speed PSHP, the water from the turbine housing need to the dewatered as the converter is not large enough to overcome the frictional torque produced by the rotation of the turbine in the water.

In the recent decades, the renewable energy sources like wind and solar have dramatically increased and the motive for operation of the PSHPs at variable speed has shifted from balancing the load to balancing the intermittent generation. As the world is moving towards the clean energy, the target is always to avoid curtailment of the production from these renewable energy sources. Therefore, it demands PSHPs to store and produce the power depending upon the status of these intermittently varying sources. This may need fast startup of the PSHPs and in some cases fast transition from generation to pump mode and vice versa. As described earlier, DFIM technology is unable to carry out fast start and mode transition. A full-size converter to the stator winding of the machine as in the case of industrial drives is the solution to this problem if the size of the converter for such application can be achieved. Considering the retrofit of the already existing fixed speed PSHPs, this solution is even more cost effective as it does not require the synchronous machine to be converted to DFIM by replacing with a new type of rotor and having a smaller converter. Such conversion of rotor to achieve variable speed operation has previously been demonstrated by ABB as a pilot project in one unit of 10 MW, 13.8 kV at Compuerto Hydropower plant in Spain [2]. Even though, DFIM can become a competitive solution in terms of cost, it cannot provide the dynamic features like fast startup and fast transition of the operational modes.

Therefore, full size converter for synchronous machine as shown in Fig. 1 will hereinafter, be considered as the scope of discussion in this paper. The semiconductor devices and industrial drives technologies are still growing towards high power converters. The commercially available industrial drives are still approaching 50 MW size. The thyristor based LCI converters in range of 100 MW already exists with some known issues of low order harmonics torque ripple and high amount harmonics current on the grid side; and therefore, has not been considered as a proper solution for hydropower application. In this paper, 100 MVA size converter has been taken as a reference and the possible solutions have been proposed and compared. A survey of the synchronous machines in hydropower plants around the world shows that the machines with 100 MVA rating has the stator voltage rating around 13 – 15 kV. The retrofit of the fixed speed plants to the variable speed should be carried out with minimum additional equipment. Therefore, the additional transformers to match the stator voltage and grid transformer voltage must be avoided to fit the converter. This leads to the fact that the full-size converter must achieve the output voltage equal to the rated voltage of the stator to deliver a transformerless solution.

The medium voltage industrial drives normally employ 3-level neutral point clamped (NPC) or active neutral point clamped (ANPC) converters for voltages in range of 3 – 6 kV because of the obvious limitations (high harmonics and high voltage steps) of the 2 – level converter for drives application. Matrix converter can produce the output voltage up to 86% of its input voltage [3], [4], and hence, cannot provide a transformerless connection in an existing setup. In [5], a comparison between NPC and ANPC converters have been carried out for the PSHPs and shows that ANPC can yield approximately double the torque that NPC can provide around zero speed, i.e. startup in pump mode. During the last decade, several studies have been carried out on employing the modular multilevel converter (MMC) for the drives application. Since the modular structure of MMC makes it easy to achieve any voltage level, it is an attractive solution provided the challenges of capacitor voltage swing at and around zero speed is addressed [6]–[8].

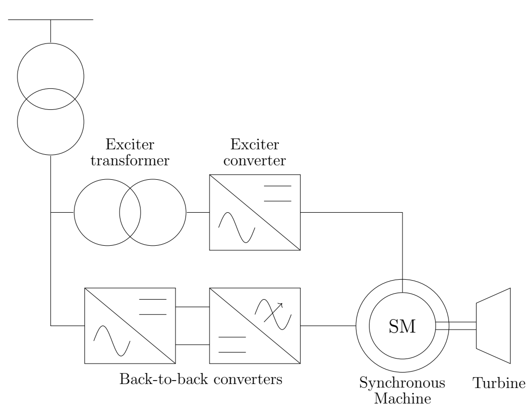

Fig. 1. Schematic of Converter Fed Synchronous Machine Technology.

The remainder of this paper is organized as follows. Section II explains the requirements that the full-size converter needs to fulfill to achieve the variable speed operation. A brief description of the NPC, ANPC converter and MMC topologies, and the overview of available devices are covered in Section III. The comprehensive evaluation and comparison of these topologies for pumped storage power plant application is carried out in Section IV. The most important attributes are summarized in Section V. Finally, Section VI highlights the major conclusions of this paper.

II. Application requirements

The pumped storage plants with fixed speed machines or with DFIM configuration takes more than 5 minutes to start the machine in pump mode [9]. In both of these cases, the water in the turbine casing needs to be depressed below the turbine level and the machine set is accelerated to synchronous speed before synchronizing to the grid. Therefore, fast startup is one of the major requirement of this application. The power plants with reversible pump turbines (RPTs) are normally optimized for pump operation and hence, are more efficient in that region. From the torque speed characteristics of a typical RPT presented Fig. 2, the torque required to start the RPT in pump mode from standstill is about 12% with minimum guide vane opening ($\alpha = 1°$), i.e. the converter needs to supply dc current around 12% of its rated current to start the RPT in pump mode when the turbine is submerged in the water. It can also be observed from the characteristics that the torque requirement increases at lower speed than at the rated speed for the same guide vane opening. It varies from 40 – 120% as the guide vanes opening varies from $5°$ to the rated opening of $30°$. Therefore, the transition of the operation mode from generation to pump to adapt fast variation of renewable sources can be demanding for many converter topologies and will be discussed in latter section.

In addition, matching the voltage level on the stator and the grid transformer side for a transformerless connection is also equally important as the space in the powerhouse cavern are limited in many cases to accommodate a large transformer.

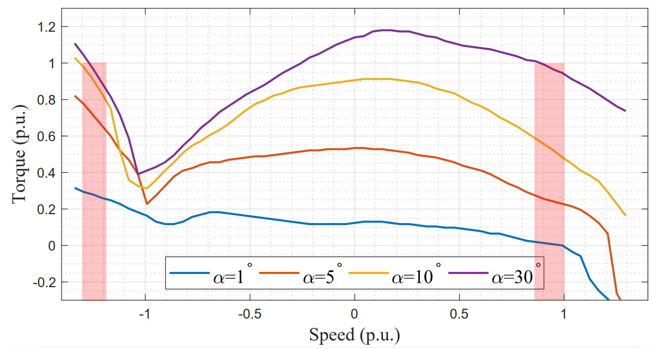

Fig. 2. Torque speed characteristics of a typical reversible pump turbine at different guide vane openings (α). The speed is positive in generating mode and negative in pumping mode. The shaded region shows the rated operating region. Courtesy: Water Power Laboratory, NTNU, Trondheim.

The minimum requirements for a full-size converter to achieve the variable speed operation can be listed as follows:

1) Transformerless connection of the stator to the grid transformer via back-to-back converters
2) Rated rms output voltage of 13 – 15 kV to meet the 100 MVA power rating
3) High torque at startup and in low speed region
4) High efficiency
5) Compact in volume
6) Cost effective

III. Converter Topology

The most popular and mature converter topology in medium voltage industrial drives is NPC topology in MW (upto 30 MVA) power rating. ANPC converter is also employed whenever high starting torque is required. Nonetheless, as the power rating increases, for instance, upto 100 MW, the requirements regarding the starting torque also increases. This is primarily because the combined inertia of the machine shaft and turbine becomes larger for larger hydropower machines. Thus, higher starting torque is the must to accelerate the machine quickly to the rated speed. An acceleration time of 30 – 60 seconds can be regarded as a very fast startup when compared to today's solution with DFIM technology.

Modular Multilevel converter is now widely used in HVDC application but yet to be widely introduced in the market for medium voltage drives application. There has been several research [6]–[8] carried out to address the issues of MMC for drives application.

Considering the suitability of these converters according the application associated requirements, these have been further discussed.

A. Neutral Point Clamped Converter

As discussed in [6], 3-level NPC converter configuration has been the major workhorse in the medium–voltage drives application. Many power drives with voltage rating up to 6.6 kV are widely used in industries employing NPC converter topology. The schematic of the topology is shown in Fig.3.

Although NPC converter topology can fulfil the rated voltage requirement for PSHP application, there is a drawback

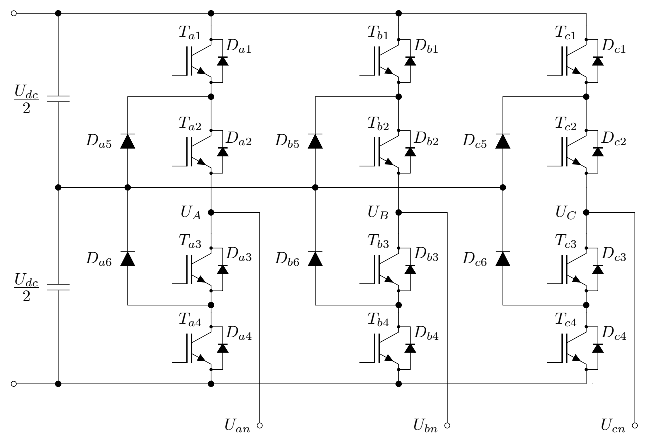

Fig. 3. Schematic of a 3-level 3-phase Neutral Point Clamped (NPC) Converter configuration.

associated with it regarding loss distribution among the semiconductor devices. In particular, at low speed operation, the clamping diodes (D_5) and (D_6) have higher losses which limits the dc output current. Therefore, when it is required to operate at low modulation index and low frequency during start-up, additional switches are added across these diodes to modify the topology, named as ANPC converter topology. The detail comparison is presented in Section IV.

B. Active Neutral Point Clamped Converter

The ANPC converter is a preferred solution over NPC converter where a single converter is required to achieve higher starting torque [10], [11]. The additional two switches across the clamping diodes in each bridge leg share the current flow and hence distribute the losses more evenly compared to that in the NPC converter. The schematic of the topology is presented in Fig.4.

As presented in [5], NPC converter with IGCTs as switching device can deliver around 33 % of rated torque at startup whereas ANPC converter with same device can deliver around 60 % in the same case.

An example of pumped storage hydropower plant with variable speed operation using ANPC converter is Grimsel 2 in Switzerland. This plant has a converter of 100 MW installed to one of its units. The solution consists of two parallel ANPC converters connected via transformers to both stator of the machine and grid side transformer [12].

C. Modular Multilevel Converter

MMC was first introduced in [13], [14] for the HVDC application but since then, there has been extensive research for employing it in drives application. The schematic of MMC is shown in Fig.5.

The arm currents in one bridge leg of an MMC can be expressed as follows:

$$i_u = \frac{1}{2} i_o + I_{z,dc} + i_{z,ac} \tag{1}$$

$$i_l = -\frac{1}{2} i_o + I_{z,dc} + i_{z,ac} \tag{2}$$

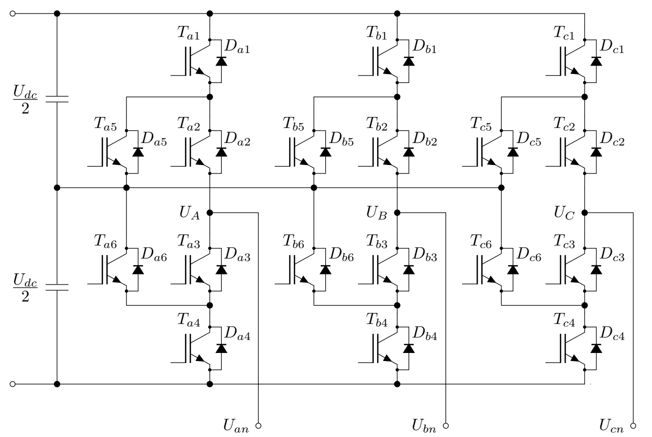

Fig. 4. Schematic of a 3-level 3-phase Active Neutral Point Clamped (ANPC) Converter configuration.

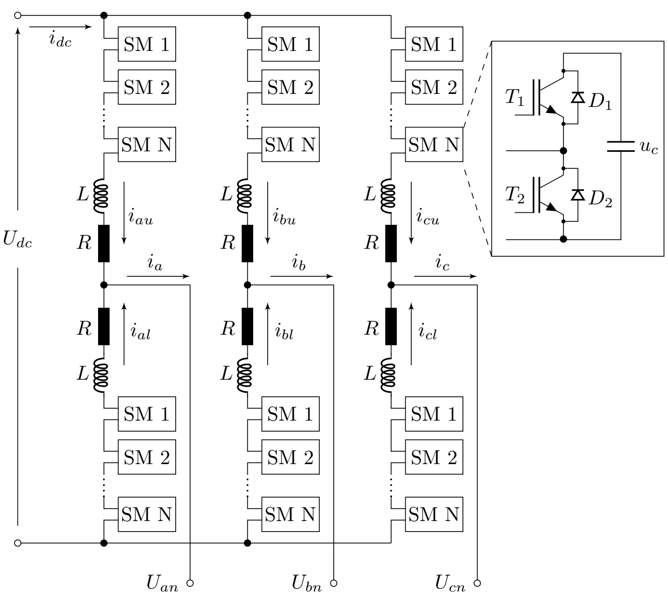

Fig. 5. Schematic diagram of a Modular Multilevel Converter with half-bridge sub-module configuration. A typical dc link voltage of 22 kV and ac output voltage is 13–15 kV (rms). In this figure, "SM" stands for Sub-module.

where,

$$i_o = i_u - i_l = \hat{I}_o \sin(\omega t + \varphi) \tag{3}$$

$$i_{circ} = \frac{1}{2}(i_u + i_l) = I_{z,dc} + i_{z,ac} \tag{4}$$

$$I_{z,dc} = \frac{M\hat{I}_o}{4}\cos\varphi \tag{5}$$

Here, $\hat{I}_o$ is the peak of output current, M is the peak of modulation index and $\cos\varphi$ is the power factor. The circulating current (i_{circ}) consists of dc component ($I_{z,dc}$) and ac harmonics component ($i_{z,ac}$) which predominantly consists of 2^{nd} harmonics of the output current in an open loop phase shifted PWM modulated MMC. There exists several control methods to eliminate these current harmonics, known as circulating current suppression (CCS) control [15]–[19] such that only the dc-component of the circulating current flows through the arms. Then the equations (1) and (2) becomes:

$$i_{u,l} = \pm\frac{\hat{I}_o}{2}\sin(\omega t + \varphi) + I_{z,dc} \tag{6}$$

The CCS control remains active in normal operation to eliminate the higher harmonics current through the arm which causes additional losses in the semiconductor devices and the passive elements in the arms.

In normal operation around nominal frequency, the voltage ripple in the capacitor of the submodules is controlled within 10% of its average voltage. But as the frequency decreases which is the case in drives application, the voltage ripple also increases to an unacceptable limit. In [6], sinusoidal injection method has been proposed to deal with this issue at low frequency operation. Later on, in [7], square wave injection method has been proposed to get higher torque than by sinusoidal injection method. Around 40% of load torque can be provided at startup by this method. In [8], a method to achieve full load torque through out the operating range has been proposed but this method needs around 3 times higher rating of the devices compared to HVDC counterpart as large circulating current is injected into the arms in low speed region.

D. Available devices

The IGCT devices performance is close to the physical limit possible using Silicon material, therefore, these devices could be the best candidate for high power devices based on Si material [20]. In future, high performance SiC devices might overcome and a smaller converter could be possible and a filter at output can be used to deal with high dv/dt. The devices available in the market at the moment with the highest voltage and current ratings to achieve a high power around 100 MVA is presented in Table I.

The devices with higher voltage ratings are not available with higher currents (e.g. 6500 V IGBTs) or with a matching high current diodes (e.g. 6500 V IGCTs) and thus, it cannot be an ideal selection to meet both high voltage and high power requirements. Therefore, IGCT 5SHY 65L4521 from Hitachi ABB with 4500 V and 6500 A and the corresponding diode FRD 5SDF 28L4520 have been considered for further evaluation in this paper.

TABLE I
MARKET OVERVIEW OF HIGH VOLTAGE AND HIGH CURRENT SEMICONDUCTOR DEVICES FOR HIGH POWER CONVERTERS [21]–[23].

Manufacturer	Device Type	U_{CE} $[V]$	U^*_{dc} $[V]$	Ic $[A]$
Hitachi ABB	IGCT (Presspack)	6500	4000	3800
		4500	2800	6500
		4500	2800	6000
	BIGT (Presspack)	5200	3400	3000
IXYS	IGBT (Presspack)	6500	3600	1890
		4500	2800	3000
Toshiba	IEGT (Presspack)	4500	2700	2100

The variables used in the table are: Maximum collector-emitter voltage of the device at 25 °C, U_{CE}; Permanent dc-link voltage, U^*_{dc}; Continuous collector current of the device, I_c. The device acronyms used are: Integrated Gate-Commutated Thyristor, IGCT; Bi-Mode Insulated Gate Transistor, BIGT; Insulated Gate Bipolar Transistor, IGBT; Injection-Enhanced Gate Transistor, IEGT.

IV. Evaluation and Comparison of Converter Topologies

The selected three converter topologies: NPC, ANPC converter and MMC are evaluated for this PSHP application based on the startup torque, the flexibility it can provide for fast transition from generation and pump mode, the number of semiconductor components and silicon area, requirements of passive components including dv/dt filter and the efficiency of the converters. The basis of evaluation has been followed as proposed in [24].

A. Converter Configuration for Transformerless Connection

One of the major requirements of a full size converter for PSHPs is the transformerless connection to the machine and grid side transformer. In other words, only the converter should be placed between the step-up transformer (the transformer which connects the machine to the grid) and the synchronous machine.

As the semiconductor devices are rated for their blocking voltage, the dc-link voltage of the converter is necessary to be determined for the ac voltage output of 13–15 kV. The relation between the ac output voltage and the dc-link voltage in a PWM modulated converter is as in (7) [25].

$$U_{ll,peak} = \frac{\sqrt{3}}{2} M \cdot U_{dc} \tag{7}$$

where, $U_{ll,peak}$ is the peak value of phase-to-phase ac output voltage, U_{dc} is the pole-to-pole dc-link voltage and M is the peak value of sinusoidal modulation index. With space vector PWM modulation or sinusoidal PWM with 3^{rd} harmonics injection technique, modulation index can be increased to $\frac{2}{\sqrt{3}}$ (≈ 1.1547) to achieve maximum output voltage for same dc-link voltage. In this case, the output voltage and dc-link voltage can be related as in (8).

$$U_{ll,peak} = U_{dc} \tag{8}$$

From (8), the dc-link voltage required for a 15 kV (rms) output is 21.2 kV. Normally, a margin of 4% is required to determine the dc-link voltage of the converters to drive the current through the machine at peak of the output voltage [26]. This gives a required dc-link voltage of 22 kV. The selected devices IGCT 5SHY 65L4521 and Diode FRD 5SDF 28L4520 have the voltage rating of 4500 V and a current rating of 6500 A. Therefore, with the permanent dc-link voltage (U^*_{dc}) rating of the selected device is 2800 V, at least 4 devices need to be connected in series at each position of the NPC and ANPC converter configuration shown in Fig. 3 and Fig.4 to block the half of the dc-link voltage. A dv/dt filter can also be required to filter the sharp and large voltage steps to protect the stator winding insulation.

In case of MMC, considering a maximum voltage ripple of 10% on the submodule capacitor in low speed region, the required dc-link voltage is 23.5 kV. The required number of submodules (N) will then be 8 in each arms of three phases with the selected IGCTs. As a general rule of reliability one extra submodule is added and this will lead to 9 in each arm, i.e. 18 submodules per bridge leg.

TABLE II
Number of devices per bridge leg for NPC, ANPC and MMC topologies for 15 kV rms output voltage.

Converter topology	Diodes	IGCTs	Remarks
NPC	30	20	
ANPC	30	30	
MMC	36	36	see note below

The number of devices must be multiplied by 3 for a three phase system to get the total number of devices in the converters. In case of MMC, 2N, i.e. 18 number of additional thyristors (one across each submodule) are required to protect the converter against the dc-link short circuit case.

B. Semiconductor devices

Following the number of IGCTs and diodes to be connected in series to achieve the transformerless connection and an additional semiconductor device for redundancy at each position in case of 3-level converter; and an additional submodule in case of MMC, the number of switches and diodes per bridge leg for different converter topologies are listed in the Table II.

C. Power Loss and Junction Temperature

Power loss analysis based on analytical loss equations is carried out for NPC and ANPC in [5] shows that for a junction temperature of $120°C$, these both converters can deliver an output current of 4000 A (peak) with IGCT 5SHY 65L4521 and Diode FRD 5SDF 28L4520. A similar analysis for MMC presented in [27] shows that MMC bridge legs can deliver upto 5500 A (peak). This corresponds to a power capacity of 73 MVA for 3-level converters whereas 100 MVA for MMC at 15 kV voltage output.

D. Device per kW

Since all three topologies are compared for high power application, the same type of semiconductor devices are considered for comparison. Hence, the device per kW indirectly provides the Silicon chip area used per kW in the converters. According to Table II, the total number of semiconductor devices used for NPC converter is 50 per bridge leg (i.e. 150 in total) and the power output is 73 MVA. Hence, the device per kW for this converter is 2.06 device/MVA (0.49 MVA/device). Similarly, the same value of ANPC converter is 2.47 device/MVA (0.41 MVA/device) which is about 20% higher than that of the NPC converter. The similar merit for MMC is 2.16 device/MVA (0.47 MVA/device), only 4.8% higher than that of the NPC converter if the thyristor for protection circuit is not considered (2.70 device/MVA including protection thyristors).

E. Harmonics in output

Comparing to 3-level converters, the shape of the output voltage of an MMC is close to sinusoidal and can directly be connected to the grid side or machine side without a passive filter. The voltage level of the MMC can also be chosen freely by adapting the number of submodules close to the rated voltage of the machine.

F. Startup torque

A typical torque-speed characteristics of an RPT is shown in Fig. 2. The startup torque (torque at zero speed) in pump mode is about 12 % with the turbine submerged in water.

ANPC converter can yield relatively very high torque compared to MMC topology. In [5], it is presented that ANPC converter can provide up to 60% torque at zero speed. And, according to [7], MMC can provide up to 40% if startup torque and the submodule capacitor voltages of the MMC can be kept within limit by injecting of square wave common mode voltage and a circulating current in each leg. Furthermore, an analysis based on power loss in the converter using the analytical loss equations exhibits that the MMC with IGCT devices can yield only upto 35% of torque at startup of the machine [27].

G. Fast transition from generation to pump mode

The fast transition from generation to pump mode or vice versa is important if the power plant is supposed to regulate the intermittent power generation from other renewable sources like wind and solar in a wide range of its operation. The transition from pump mode to generation mode is relatively easy as the water is flowing against the gravity in pump mode. Therefore, it takes shorter time to change the mode in existing power plants than to switch the mode from generation to pump mode. From Fig. 2, it can be observed that the torque requirement exceeds the torque in normal operating region around zero speed with maximum opening of the guide vanes. The converters rated for normal operating region cannot provide such torque. The converters need to be oversized to meet such requirement. As mentioned in [28]–[30], direct MMC with full-bridge submodules can be an alternative if fast transition at full opening is demanded by the system integration. This solution employs larger number of semiconductor devices and consequently, will be costlier solution.

H. Passive components

Passive elements in MMC are arm inductors and the submodule capacitors. In 3-level converters, the dc-link capacitor is series and parallel connection of several low voltage capacitors and the same can be imported to the MMC topology. The benefit of the application in MMC is that it does not have the risk of bearing uneven voltage sharing among the capacitors if the capacitance in the series stack differs by a small margin.

The size of the capacitor in MMC and 3-level are quite different. In 3-level, only the ripple current flows through the dc link capacitor whereas in case of MMC, the load current itself is modulated through the submodule capacitor. Therefore, MMC employs relatively larger capacitors compared to NPC and ANPC converters. In MMC, the normalized energy storage requirement is around 25 kJ/MVA [31].

I. Output (dv/dt or sine) filter

Three-level converters produce output voltage in steps of ($U_{dc}/2$) and lead to significant amount of harmonics (THD is 16.86 %) [32]. MMC has very small steps in voltage output (U_{dc}/N) and is quite close to the sinusoidal voltage. Therefore, the output filter can be avoided or a very small dv/dt filter can fulfill the cable reflection associated requirement in case of MMC. A relatively high voltage steps in 3-level needs a conditioning filter at the output. Especially, in case of retrofit projects, the space for the new converter for the synchronous machine may not be available just beside the machine and a cable of 50 – 60 m may connect these two. Such a long cable with fast switching devices can lead to voltage doubling at the machine terminals due to reflection in the cable and a dv/dt filter may be required at the output of the converter.

J. Control related issues

ANPC converter can be controlled at zero frequency the same way as it is controlled at rated frequency. MMC needs special control algorithm to inject high frequency common mode injection in low frequency operating region to control the submodule capacitor voltage within limit. This needs, for example, a common mode voltage injection of frequency around 45 Hz for a rated system of 50 Hz when operated below 15 Hz [7]. Higher the frequency of common mode voltage, better is the control of the capacitor voltage but this will lead to higher switching frequency and consequently, higher losses in the semiconductor devices.

Since the switching frequency needs to be very high in case of MMC to control in low speed region, MMC may not be advantageous to be employed in high power application using IGCTs. It can be considered as a topology for future when switching devices with low switching loss will be available in high voltage and high current rating.

K. Efficiency

Since the average and rms current through the device of MMC are relatively less than that in case of other topologies, conduction loss in the devices of MMC is significantly lower. The MMC yields higher efficiency than 3-level converters and reaches above 99 %.

V. Summary of comparison

The quantitative and qualitative characteristics of converters enlisted in Section IV can be summarized as in Table III. The summary table suggests that the all three converters meet the application associated requirements of Section II except ANPC has advantage of producing high startup torque compared to others.

VI. Conclusion

This paper presents the three possible converter solutions for executing the variable speed operation of a pumped storage plant with synchronous machines. All three converters meet the requirements for startup torque and an output voltage of 13–15 kV (rms) for transformerless connection. The comparisons show that all can meet the requirement of startup torque of 12% for fast startup with water in the turbine casing whereas ANPC is the best solution if fast transition from generation mode to pump mode is required because it can provide upto 60% torque at zero speed in contrast to 33 % and

TABLE III
SUMMARY OF COMPARISON OF CONVERTER TOPOLOGIES FOR PUMPED STORAGE POWER PLANT APPLICATION.

Converter topology	Startup torque	No. of devices	device/MVA	dv/dt filter	Harmonics
NPC	33 %	150	2.06	required	high
ANPC	60 %	180	2.47	required	high
MMC	35 %	270	2.70	can be avoided	low

35% from NPC and MMC respectively. Therefore, a controlled transition with partial flow can be executed. But, when it comes to the size of the converter, MMC can yield higher power capacity close to 100 MW whereas ANPC can yield upto 75 MW without paralleling of the IGCTs. In addition, MMC can be the solution without a dv/dt filter at the output or with a relatively very small filter, if needed, compared to the ANPC converter. And, unlike 3-level converters, MMC needs a special control strategy of high frequency common mode injection to operate at lower frequencies which demands a higher switching frequency operation to control the common mode current and hence, cannot be the best choice for high power application with devices like IGCTs.

Hence, looking into all the attributes of these converters, ANPC can serve the best with startup and fast transition of modes and can be regarded as the best alternative for variable speed operation of pumped storage plant.

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