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White Paper

POWER CONVERSION

MMC FOR HYDRO

The advantage of Modular Multilevel Converter topologies for medium-voltage, high-power applications.

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PURPOSE

Introduction and background

Pumped hydro storage plants (PHSP) have been introduced end of the 19th century and have been primarily used to store energy.

Since the beginning of the 20th century the total installed capacity of PHSP has drastically increased, also driven by increased installation of intermittent renewable energy sources as wind and solar. In the 1930s the first variable speed PHSP has been developed. However, it took more than 60 years to have a first commercial unit commissioned [1]. The worldwide installed capacity of pumped hydro storage plants in 2020 was 159.5 GW [2]

PHSP have been used mainly for balancing the power production and load demand in the grid. With this it was possible to run conventional power plants in their maximum efficiency points even when demand for electricity was low. In case of an over-production of the conventional power plants the power is used to pump water [3].

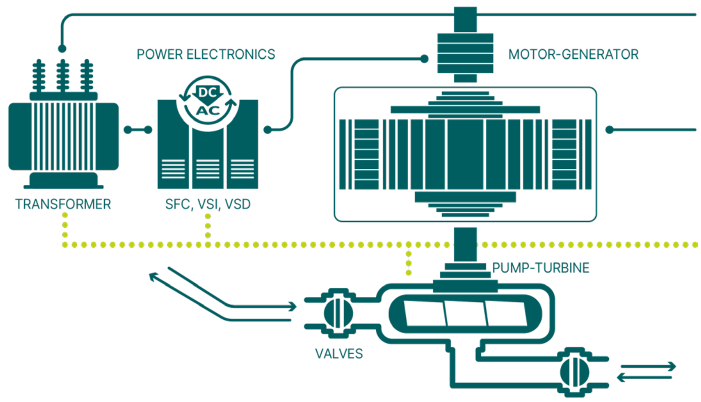
Principle

A pumped hydro storage plants (PHSP) acts as a giant energy storage system. It contains an upper gate and depending on the type of PHSP a second lower reserve or a river. During periods of low power consumptions or low cost of electricity water is pumped to an upper gate.

The water in the upper reservoir is released when the demand for power is high. In some few cases a PHSP is equipped with a pump and a separate turbine on the same shaft of a motor-generator (ternary system).

As this type of PHSP topology is quite rare the focus of this whitepaper is on fixed and variable speed systems utilizing a so-called pump-turbine.

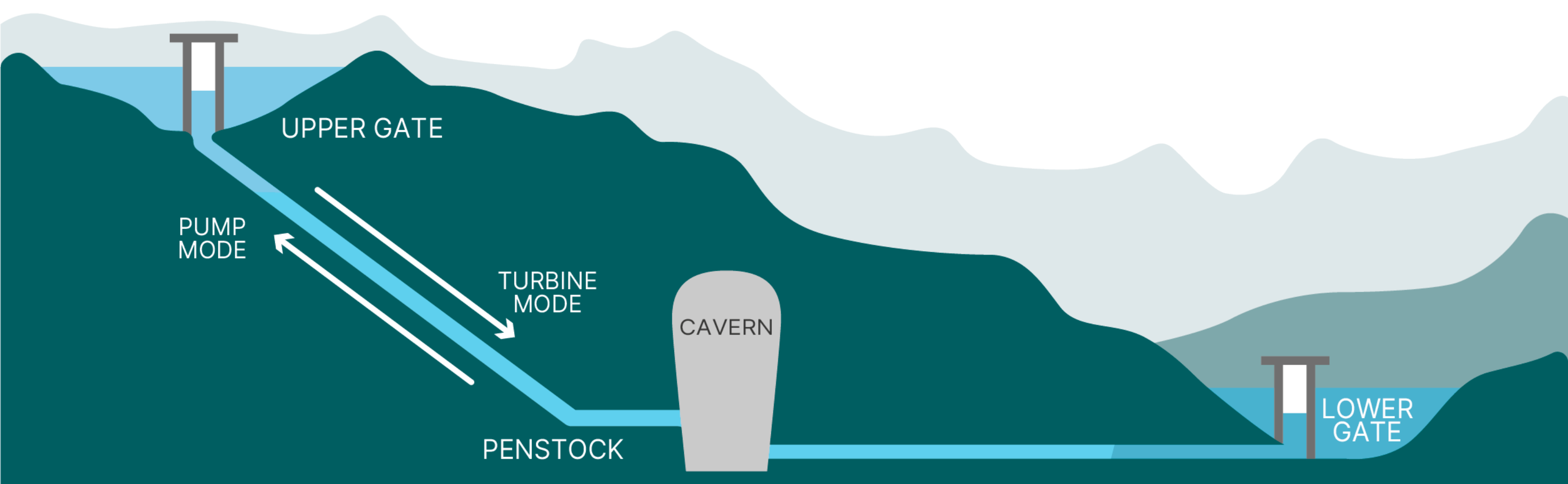
The pump-turbine is connected to a motor-generator which can be either a synchronous motor or an induction motor. Depending on the type of generator different power electronic systems are connected to the motor-generator.



Two different topologies are mainly used in a PHSP:

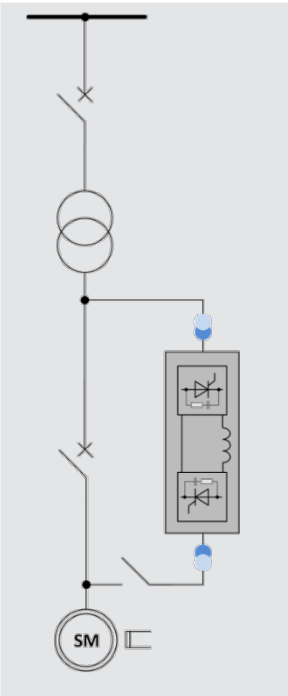
- Fixed Speed PHSPs
- Variable Speed PHSPs

The structure of these topologies are described in the next chapters.



PHSP with fixed speed pump-turbines

Most existing PHSPs utilize fixed speed pump-turbines. These turbines are connected to synchronous motor generators in combination with a start-up converter or so-called SFC's.



The generator is started via the SFC and once the generator (synchronous machine) is at rated speed and synchronized to the grid the SFC will be bypassed via a bypass switch. The synchronous machine is connected to the grid, the pump-turbine can generate power or consume power from the grid. As the SFC is only used for start-up of the machine, the power rating of the SFC can be lower than the rated power of the machine.

Although the structure of this type of topology is quite simple there are some disadvantages linked to this topology. One disadvantage is clearly that the power during pump mode (power consumption from the grid) is limited to a fixed value at a given head of the reservoir. Additionally, the usable head range is limited with a fixed speed.

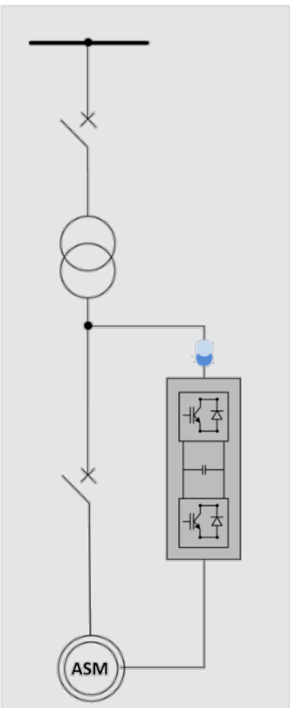
Another disadvantage of fixed speed systems is given at deviations in the head and power compared to rated valuta, which can lead to a significant reduction of efficiency [3].

Power adjustment in pump mode with fixed speed systems can be achieved by using multiple smaller fixed speed systems and control the power in pump mode by activating/deactivating several systems to adjust the power of the entire power plant.

However, this results in multiple start/stop sequences and well-balanced control of the multiple systems [4].

PHSP with variable speed pump-turbines

Variable speed (VarSpeed) PHSP utilizes pump-turbine operating at various speed values. For this a power electronic converter system is needed. There are two different approaches given:



1. Doubly Fed Induction Machine

VarSpeed systems based on doubly fed induction machines (DFIM) have a power electronic converter system connected to the rotor of the DFIM. These converter systems (also known as AC Excitation systems) are either voltage source inverters (VSIs) or cycloconverter.

The converter rating is significantly lower than the rating of the generator as only the required rotor current or power is provided by the converter system. Due to the lower power rating of the converter system this topology is the preferred solution for large hydro power plants with rated power up to 120MW.

A major drawback of this system is the use of slip rings to provide current or power to the rotor.

As all VarSpeed PHSP, this solution provides major benefits. Firstly, power during pump operation can be adjusted. Furthermore, a higher head range can be used which also lead to a higher energy storage capacity. Primary frequency control during pump operation is given for all VarSpeed PHSP [3].

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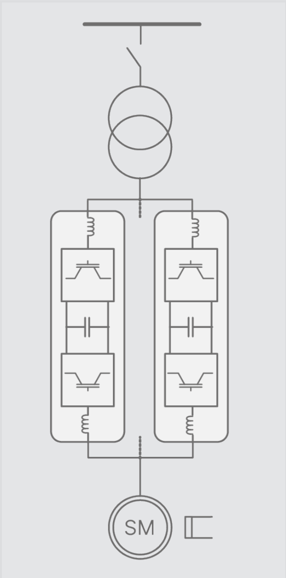


2. Fully Fed Synchronous Machine (FFSM) — the 'so-called' Fully Fed Solution

Synchronous machine (SM) with a power electronic converter system connected to the stator of the SM are so called Fully Fed Synchronous Machine (FFSM). The first FFSM have been put in operation in 2013.

Is it obvious that converter rating must be same as the rating of the synchronous machine. Thus, the amount of installed power electronic components is higher compared to DFIM solutions. However, this also means some advantages especially in starting the machine. Compared to DFIM, FFSM can be started without dewaterimg because of the possibility to provide significant torque at zero speed [3].

There are running FFSM based on conventional VSI topologies but the recent development in the power electronic sector led to a change of used converter topology.

FFSM WITH MODULAR MULTILEVEL CONVERTER

The Modular Multilevel Converter (MMC) was introduced in the early 21st century and has primarily been employed for large HVDC transmission systems.

Nowadays, an increasing number of Fully Fed Synchronous Machines (FFSMs) are being implemented using MMC technology. The key benefit of MMC technology lies in the modularity and scalability it offers for the converter system.

Challenges with conventional VSI Systems

Conventional VSI Systems are designed for a specific voltage and power rating. Thus, the design of the motor generator is somehow linked to the given converter output voltage.

Especially high power FFSM require a stator voltage that is typically higher than the output voltage of conventional VSI. To achieve the desired power of the PHSP converter currents are increased leading to a parallel connection of several VSIs with an interconnection between converter and generator designed for very high currents.

Moreover, conventional VSI produce a significant amount of current harmonics on the generator side which can lead to additional losses in the generator. This could either be compensated by increasing the effective switching frequency of the converter, by increasing switching frequency of the semiconductor devices, by adding interleaving reactors/transformers, or by implementing appropriate filters on the output of the converter.

Both solutions would decrease the harmonic content in the generator current but also mean additional components or higher losses in the converter. This can be omitted when a multilevel converter is used.

Benefits of Multilevel Converters

Multilevel converters have a smoother output voltage waveform with lower total harmonic distortion (THD) resulting in lower harmonic content of the output or generator current.

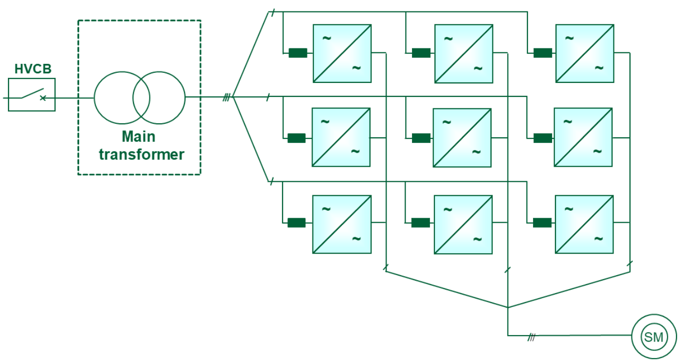
MMC converter are used in different topologies. With all topologies each phase leg (so-called arm) consists of several identical submodules.

These can be realized either in a full-bridge configuration with four power semiconductors (typically insulated gate bipolar transistors or integrated gate commutated thyristor) together with a DC capacitor or in a half-bridge configuration with just two semiconductor devices per submodule and a DC capacitor.

The Modular Multilevel Matrix Converter (M3C)

The so-called Modular Multilevel Matrix Converter (M3C) is used for a direct AC/AC conversion.

Two AC systems, the grid and synchronous machine, are directly interconnected without the need for AC to DC and then DC to AC conversion. It is employed to connect two AC systems with different frequencies, such as in newly built Fully Fed Synchronous Machines (FFSM) PHSP or Rail power supplies.



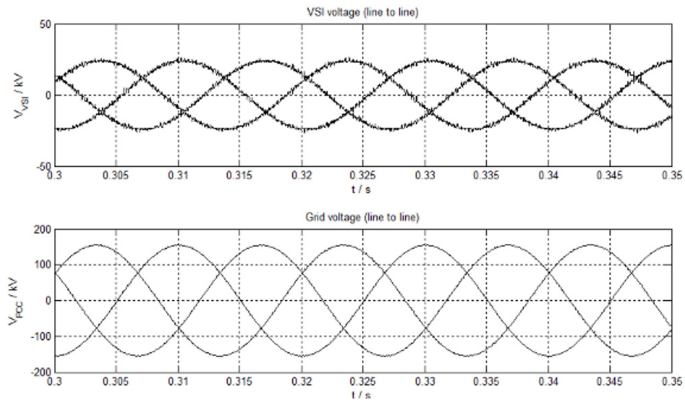
The two AC systems must have different frequencies to limit voltage fluctuations on the individual submodule capacitors. This implies that also the maximum frequency of the SM needs to be below the grid frequency.

The maximum rated SM frequency and therefore also speed of the SM is limited to ~2/3 of the grid frequency. It becomes obvious that this kind of topology is not suitable for SM with rated frequencies of 50/60Hz and thus cannot be used for a modernization or an upgrade of an existing PHSP with fixed speed pump-turbines.

Enhancing efficiency and modularity for PHSP

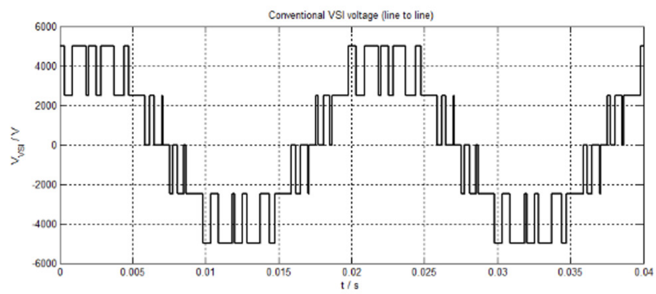
Power Conversion introduced the MMC technology as the product MM7 in 2020 for different applications. In 2021 MM7 for pumped hydro storage plants has been introduced. The MM7 for PHSP is specially designed for high efficiency and modularity for new PHSP based on FFSM. It utilizes the above shown topology (M3C).

Due to the high scalability of such a system higher SM voltage can be achieved and thus higher output power ratings without the need of parallel connected converter units can be reached. Converter ratings of up to 100MVA can be achieved without parallel connection.



Due to the multilevel structure of the MM7 an almost sinusoidal voltage waveform can be achieved.

A case study for a 60 MVA MM7 system connected to an 110kV grid has been conducted and the expected voltage at the point of common coupling (110kV High Voltage side) and the converter input voltage are depicted. The MM7 consists of thirteen submodules per arm and leads to minimized total harmonic distortion (THD). The calculated THD value on the 110kV is 0.2%.



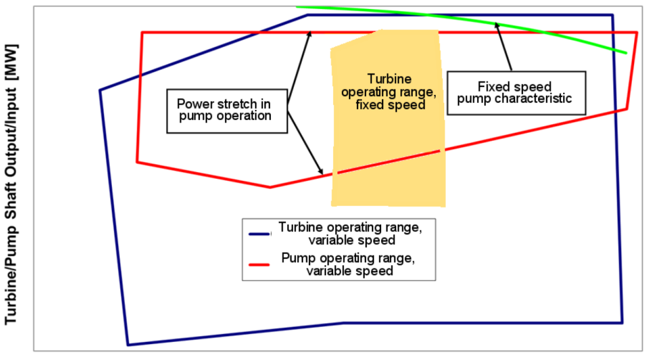
A similar case with a conventional VSI solution (based on 3-level VSI) is also shown. **It is obvious, that the THD of the converter voltage is significantly higher.**

The calculated THD of an individual converter is approximately 30%: Overall system THD with multiple converter units in parallel can be reduced to single digit values. However, this is still 10-times higher compared to a modular multilevel converter. These voltage harmonics cause high frequency currents that produce additional losses and thus lowering the overall efficiency of the power plant.

UPGRADING EXISTING FIXED SPEED PUMP-TURBINES

Most existing PHSPs utilize fixed speed pump turbines with all the known and described disadvantages (e.g., no power regulation in pump mode and significantly reduced efficiency in partial load).

Upgrading an existing fixed speed pump-turbine to VarSpeed eliminates these disadvantages and brings additional benefits to the power plant operator.



The operating range (Power output vs. net head) in turbine and pump mode can be stretched (see figure [5]).

Ancillary services as frequency regulation in pump mode or an increased Spinning reserve in generation or turbine mode can be utilized when upgrading PHSP from fixed Speed to VarSpeed. Frequency regulation means that the power of the PHSP will be adjusted to keep grid frequency in a well-defined range whereas Spinning reserve means a spare generation capacity which can respond rapidly to a sudden loss of the generating unit [6].

Two scenarios for upgrading an existing fixed speed pump-turbine into an VarSpeed pump-turbine are presented in the following sections:

- Upgrade with exchange of synchronous machine and pump-turbine
- Upgrade without exchange of synchronous machine and pump-turbine

Generally, a potential upgrade includes several studies as identifying system needs, hydraulic and electric study [4]. All this is not scope of this whitepaper.

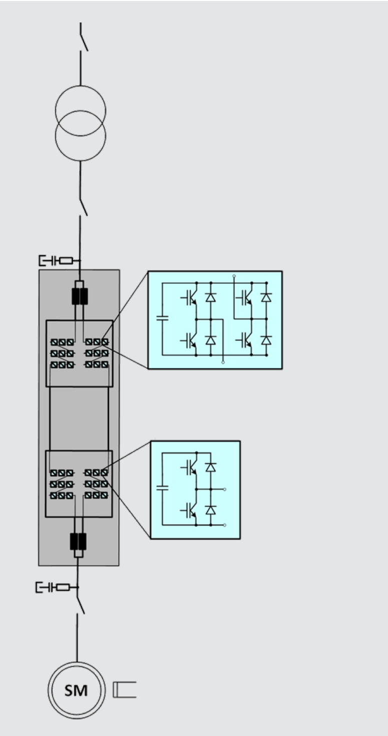
Upgrade with exchange of synchronous machine and pump-turbine

Upgrading an existing PHSP to VarSpeed operation by replacing the synchronous machine (SM) and, if necessary, the pump-turbine can improve the efficiency of both components and increase the achievable output power.[7].

Additionally, the selection of SM parameters (e.g., voltage and frequency) can be adopted to the converter resulting in an overall optimized systems with increased efficiency. Selecting voltage and frequency values enables the use of a direct AC/AC MMC topology as shown on p5. However, this means a major upgrade with new added components and thus high CAPEX.

Upgrade without exchange of synchronous machine and pump-turbine

Upgrading an existing PHSP to VarSpeed operation without changing the synchronous machine (SM) renders the use of the MMC topology described on p5 (direct AC/AC conversion) impractical due to the matching frequencies of the generator and the grid. Therefore, an alternative topology or technology must be adopted.



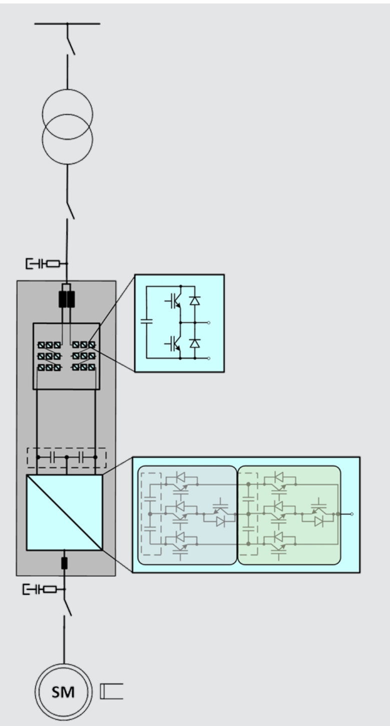
Generally, a conventional VSI can be used. Conventional VSI solutions do not have the restriction of unequal frequencies and thus are suitable for this kind of application. Due to the high harmonic content of the VSI harmonic filter (e.g., sine filter) must be installed on the output and input of the converter.

As previously described MMC produce significantly lower harmonics and can be used for an upgrade. A possible configuration of a MMC based solution is shown here.

The synchronous motor has been originally designed for an operation at a grid and thus is not optimized for operation with a variable frequency drive. Thus, stringent requirements in terms of voltage harmonics, common mode voltages and rise times (dv/dt) must be met by the converter.

The shown MMC topology uses a mixture of full-bridge and half-bridge submodules to ensure start-up without the need of dewatering and to minimize common mode voltage stress of the machine insulation [8]. Furthermore, it might be necessary to install small filters on the converter in- and output to limit stress of the insulation of transformer and SM.

Synchronous machines designed for direct online operation are aligned with specific voltage levels, reducing the demand for scalability and flexibility. This allows for a simpler converter topology to be employed when upgrading fixed-speed pump-turbines to VarSpeed operations.



A combination of a modular multilevel converter together with a conventional VSI can reduce the complexity of the converter system.

The shown converter topology consists of a MMC Active-Front-End (AFE) and a 5-Level Machine Converter. Due to the topology of the machine converter (MC) the AFE can be equipped with half-bridge modules. The machine converter topology is a so-called nested NPP topology [9].

The complexity of this converter topology is notably lower when compared to an MMC-based design (with half-bridge and full-bridge submodules), given an assumed grid and machine voltage of 13.8kVAC. A full MMC solution (a combination of half- and full-bridge submodules) requires nearly 60% more semiconductor devices than a mixed MMC/VSI solution. The machine converter can achieve equivalent torque characteristics to other conventional VSI topologies.

As the machine side converter is a 5-Level VSI, an output filter will be needed to achieve an output voltage with similar characteristics as the grid.

Topology	Full MMC	MMC-VSI combination
Type of converter AFE	Full-bridge MMC	Half-bridge MMC
No of arms	6	6
No of submodules per arm	9	9
Type of converter MC	Half-Bridge MMC	5-level VSI
No of arms	6	3
No of submodules per arm	9	2
No of semiconductors per submodules	2	16
Total installed semiconductors	324	204
	159%	100%

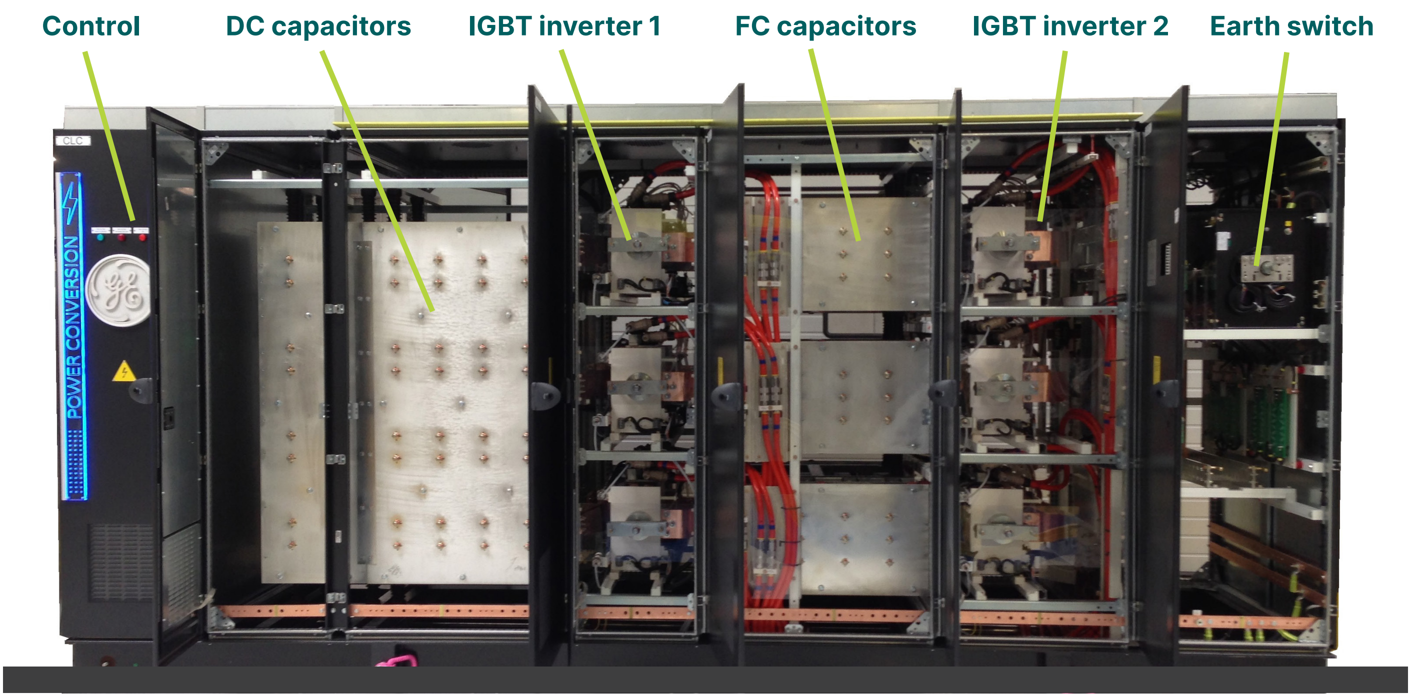
Power Conversion introduced this kind of mixed topology in 2021. The solution is called Hybrid MM7 and is available for machine voltages of 11kVAC and 13.8kVAC. The machine converter consists of proven 5-Level technology and is part of the MV7 product offering.

The figure shows the machine converter of the hybrid MM7 utilizing a 5-Level nested NPP topology.

The 5-level inverter is built of two 3-level cells (IGBT inverter 1 and 2). These inverter cells are connected via a so-called flying capacitor.

Conventional two or three level topologies require many IGBTs or IGCTs connected in series. Due to the nested NPP structure a series connection of only four IGBTs is needed to achieve an output voltage of 13.8kV.

With the MMC topology acting as an active front end (AFE) the voltage of the AFE has low harmonic content and harmonic filters are not needed.



CONCLUSION

Upgrading PHSP based on fixed-speed pump-turbines into variable speed enables a much wider operating range in pump and turbine modes.

For this a converter is needed to adjust the speed of the synchronous machine. Although this means an additional CAPEX additional benefits as ancillary services can be offered.

Modular multilevel converters are the best choice for converter-fed synchronous machine offering a modular and thus scalable converter solution.

Upgrades of PHSP without an exchange of the machine and the pump-turbine have the difficulty that the machine will be operated at grid frequency and that the converter must have similar voltage characteristics as the grid. Modular multilevel converter have the advantage of low harmonic content. However, special converter topologies must be used to ensure high torque at almost zero speed. A hybrid solution combining modular multilevel converter and conventional VSI topologies eliminates the complex structure of a purely MMC based solution for this kind of application.

Glossary of terms

MMC: **Modular Multilevel Converter**
VSI: **Voltage Source Inverter**
PHSP: **Pumped hydro storage plant**
AFE: **Active Front End**
MC: **Machine converter**
SM: **synchronous machine**
FFSM: **Fully Fed Synchronous Machine**
DFIM: **Doubly fed induction machine**
HVDC: **High Voltage Direct Current**

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