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Multilevel Voltage-Sourced Converters for HVDC and FACTS Applications

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SUMMARY

The recent developments in the area of HVDC and FACTS are dominated by two new technology trends. One side is the introduction of 800 kV ultra high dc voltage systems for bulk power transmission, on the other side is the increased application of voltage sourced converters (VSC) in HVDC and FACTS schemes. Particularly, the VSC technology provides many attractive features to meet challenges in today's power industry, such as feeding megacities, connecting renewable energy from off shore wind farms and fast voltage regulation by compact static var compensator.

So far, the VSC for HVDC and FACTS applications uses mostly 2 or 3-level converters. However, it is well known that multilevel VSCs can provide some unique advantages with respect to the performance and harmonic impacts. This paper presents a modular multilevel VSC topology developed by Siemens for HVDC and FACTS applications. The basic concept and the technical performance of this innovative converter concept will be discussed in detail. The first application examples and experience of such multilevel VSC in HVDC, SVC and active filters will be presented and discussed as well.

KEYWORDS

HVDC – Voltage-Sourced Converter (VSC) – Multilevel Converter – Modular Multilevel Converter (MMC)
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1. **INTRODUCTION**

After successful broad application in traction and medium voltage drives for many years, VSC (**V**oltage-**S**ourced **C**onverter) utilizing modern IGBTs has become an important power electronic device in power transmission and distribution such as HVDC and FACTS applications. In comparison with traditional line commutated thyristor based converter, such self-commutated converters provide additional and advanced technical features, which are advantageous to meet today's technical challenges in power transmission industry [1]. VSC-based converter technology brings among others following technical benefits:

- Footprint requirements are lower.
- The active and reactive power can be controlled independently.
- An excellent dynamic response can be achieved, which is important to comply with the grid code requirements.
- Reliable operation at week or even passive system

The first application of VSC converters in power transmission system has been in the area of FACTS devices. While VSC in FACTS application had different topologies, the realized VSC converters for HVDC applications are all based on 2 or 3-level technology [1, 2], which enables to switch respectively two or three different voltage levels to the AC terminal of the converter (see Figure 1). Since the desired sine waveform at the AC terminal cannot be adjusted in terms of magnitude, special measures, such as PWM, are used to approximate the desired waveform. However, the difference between the implemented and the desired voltage waveform is an unwanted distortion which has to be filtered.

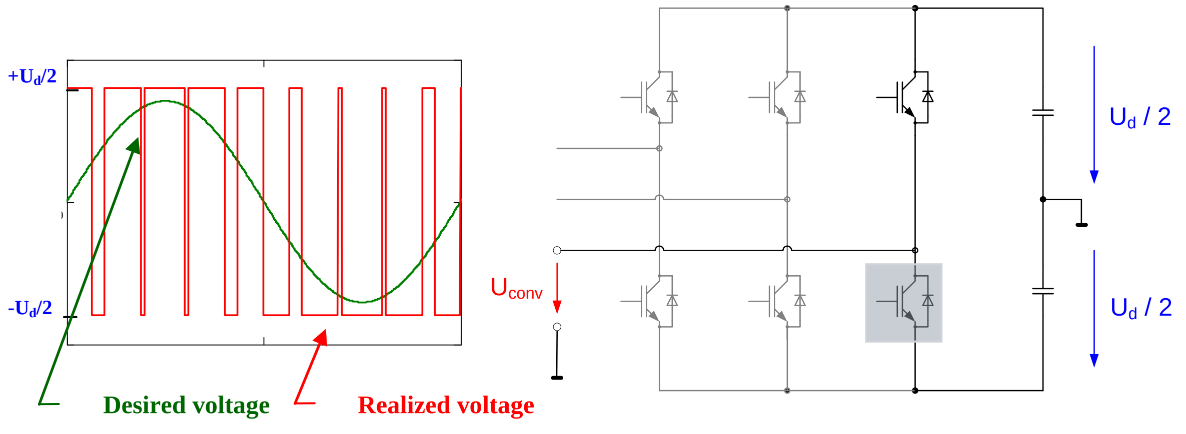

Figure 1 : Principle of control of converters based on two-level technology

For high voltage applications a large number of semiconductors need to be connected in series – up to several hundred per converter leg, depending on the DC voltage. To ensure uniform voltage distribution not only statically but also dynamically all devices connected in series in one converter leg have to switch simultaneously with accuracy in the microsecond range. As a result, high and steep voltage steps are applied at the AC converter terminals which require extensive filter measures. This effect becomes more significant with increased dc operating voltage.

Therefore it has been always desirable to have a simple multi-level VSC for high voltage applications like HVDC and FACTS, which can eliminate the drawbacks of two-level topology and provides significantly advantages with respect to the performance as well.

2. MODULAR MULTI-LEVEL CONVERTER (MMC)

2.1 Basic Principle

During last years a modular multilevel converter (MMC) topology has been introduced into HVDC and FACTS applications [3-6]. In this topology, the converter arms act as a controllable voltage source with a high number of possible discrete voltage steps, which yield approximately sine waveform in terms of adjustable magnitude of the voltage to the AC terminal. This principle is shown in Figure 2.

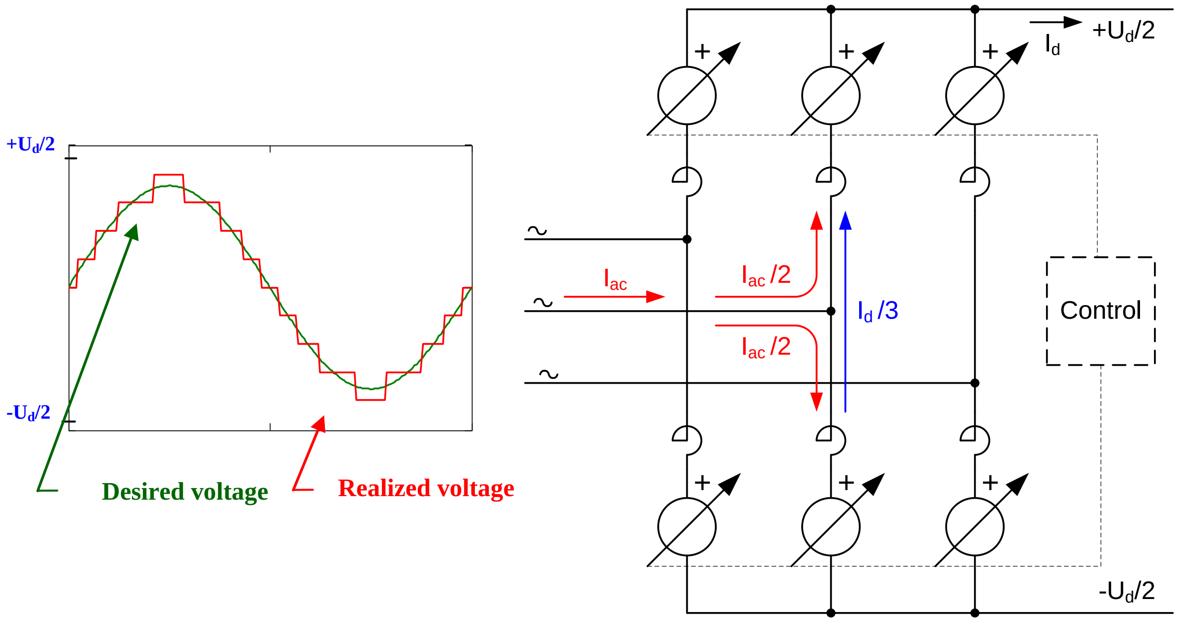

Figure 2 : Overview of MMC topology

Each of these variable voltage sources are designed with a number of identical but individually controllable submodules, as shown in Figure 3. Each submodule is a two-terminal component which can be switched between a state with full module voltage (IGBT 1 = ON, IGBT 2 = OFF) and a state with zero module voltage (IGBT 1 = OFF, IGBT 2 = ON) in both current directions. Dependent on the current direction, the capacitor can be charged or discharged if IGBT 1 is turned on. Besides auxiliary components and electronics, each submodule consists of an IGBT half bridge and a capacitor unit.

For some AC applications it is needed to have a full-bridge submodule instead of half-bridge, as illustrated in Figure 3 c).

By serially connecting many modules an elegant multilevel topology can be constructed. It is possible to individually and selectively control each of the individual submodules in a converter arm. The total voltage of the two converter arms in one phase unit equals the DC voltage, and by adjusting the ratio of the converter arm voltages in one phase module, the desired sinusoidal voltage at the AC terminal can be achieved.

In the event of a submodule failure during operation, this fault is detected and the defective submodule is short-circuited by a highly reliable high-speed bypass switch, which is connected in parallel to IGBT 2 (not depicted in Figure 3). This provides the fail-safe functioning, as the current of the failed module can continue flowing, and the converter operates without any interruption.

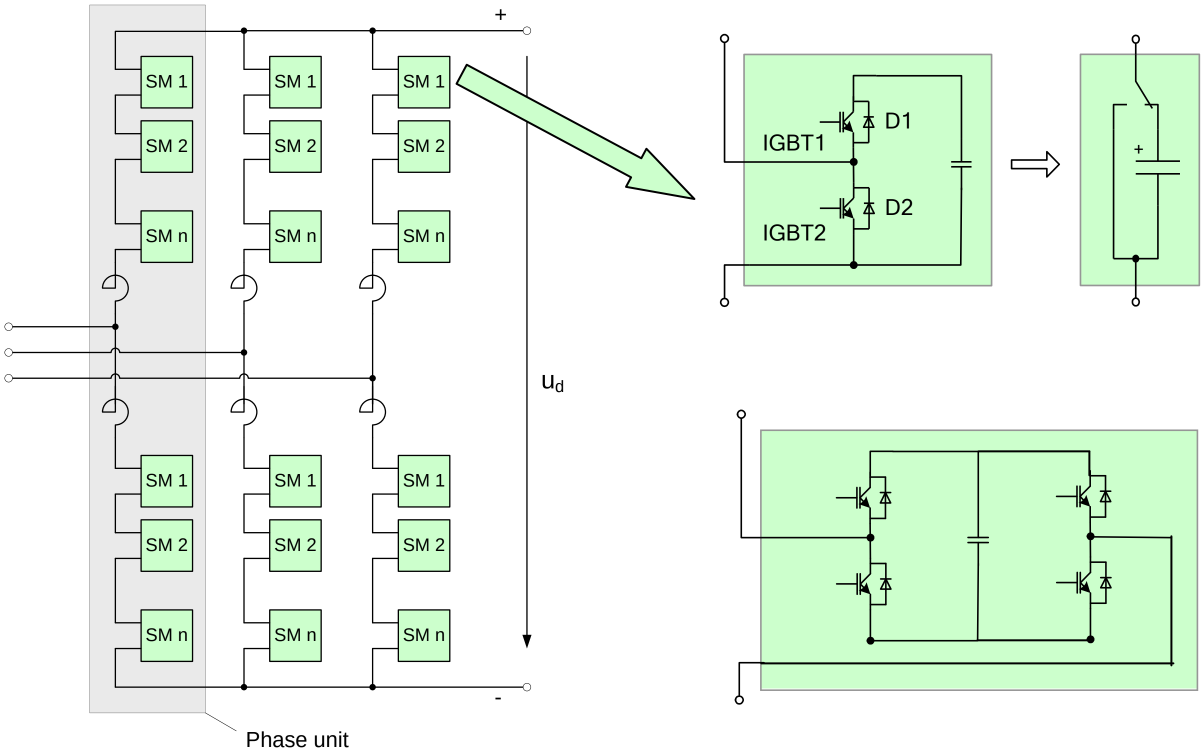

Figure 3 : a) Arrangement of MMC (left) b) principle design of a submodule and its electrical equivalent (right, top) c) H-bridge as sub-module for AC applications (right, bottom)

The converter reactors shown in Figure 3 have two functions:

– To damp the balancing currents between the individual phase units to a very low level and make them controllable by means of appropriate methods.
– To reduce the effects of faults arising inside or outside the converter. As a result, a short circuit in the DC circuit can be swiftly detected, and, due to the low current rise rates, the IGBTs can be turned off at absolutely uncritical current levels. Consequently, this feature provides very effective and reliable protection of the system, particularly for overhead line applications.

2.2 Technological Advantages of MMC

MMC retains all the existing advantages of VSC technology but with the additional benefits that come with the new topology:

Improved losses

The converter contains sufficient steps to generate high quality output waveforms without high frequency PWM device switching. This reduces the switching losses within the individual IGBTs (and diodes) - allowing higher steady-state currents and therefore requires fewer series connected levels for the same rating. Overall this means that the losses of MMC are less than an equivalent rated PWM converter.

Low dv/dt switching

Since each step in the multilevel output voltage is of the same small value the overall dv/dt remains low – irrespective of the number of series connected levels. This allows straightforward AC side connections to be made - high frequency blocking filters are not needed to protect the power transformer. The harmonic output is so low that AC filters are not required - this reduces the number of main circuit components and removes the risk of amplifying existing harmonics with passive filters.

Modular design with standard devices
A modular design approach has been applied to allow use of the latest technology in semiconductor devices and capacitors with easy replacement of the modules. Standard IGBT module is the preferred product in MMC application due to availability from many manufacturers and benefits from rapid technological developments.

Flexibility
Due to its modular construction the MMC converter is flexible in its connection arrangements. Many alternative topologies are available to the application designer to realize optimal project solutions possible. Modular design offers exceptional flexibility in valve tower arrangement and station layout. The highly modular design enables an excellent scalability in hardware and software as well.

Increased energy storage
With multilevel converters the storage capacitance is distributed across the complete converter and although this storage volume is necessarily high, it does yield other benefits:

- **imbalanced operation**
  Because there is no common dc capacitors shared by all phases each phase can operate independently without causing ripple voltage distortion across the other phases. Consequently the MMC can operate with a continuous voltage imbalance - for instance in the presence of very high negative phase sequence voltages across the AC network. For DC transmission, this gives a major advantage when operating into imbalanced network faults - especially long lasting events like single phase auto re-closure. The two unaffected phases can continue at full power transmission, limiting the net energy transfer deficit to about one third of the maximum value. This can particularly benefit weakened networks because it reduces frequency variations; avoiding the need for load shedding or generator tripping.

- **improved fault performance**
  In general the higher energy storage capacity gives improved performance during AC network faults because the DC voltage remains substantially constant allowing continuous, stable converter operation.

- **straightforward voltage balancing**
  A major challenge with high voltage VSCs is to ensure a tight voltage balance across all semiconductor device levels. With the PWM converter this relates to the balancing of the hundreds of simultaneously switching devices within a valve, this requires highly demanding electronic control accuracies – down to the tens of nano-second range. For MMC the equivalent task is to balance the voltages across the individual modules but at slower (millisecond) time scales.

Next to excellent on-state characteristics, the MMC topology also offers a strong dynamic behavior, which is essential to comply with the grid code requirements including fault ride-through capability in case of faults in the AC network.

Although the multilevel converter uses twice the number of semiconductors to support the same DC voltage as a PWM design, each arm of the converter conducts current continuously
– and with much lower device switching frequencies. When taken together this allows MMC based DC system to transmit almost twice the DC current when compared to a PWM design built with equally rated IGBT devices.

A larger valve hall is required for MMC due to the increased volume of capacitance, but this is a balanced against fewer outdoor components such as blocking filters – overall the MMC based station footprint should be reduced.

3. APPLICATION OF MODULAR MULTI-LEVEL CONVERTER FOR HVDC

As described in last section, MMC is perfectly suitable for high voltage applications. The typical arrangement of MMC based HVDC system is shown in Figure 3a). Recognizing the unique features of MMC Siemens has developed and introduced a VSC based HVDC system called HVDC PLUS (Power Link Universal System) into market. The first installation of such HVDC system is a 30 MW HVDC PLUS back to back system for demonstrating and testing purposes at Siemens power electronic laboratory. This system comprises 12 power modules per phase arm and can circulate up to 32 MW in loop. Starting from April 2008 this scheme has been demonstrated through various verification tests the adequate design of converter modules and the robustness of comprehensive controls. The first commercial application of HVDC PLUS system is the Trans Bay Cable link in the Bay of San Francisco. In September, 2007, Siemens secured an order to supply two converter stations based on MMC technology. The HVDC PLUS system in this project will transmit up to 400 megawatts at a DC voltage of +/- 200 kV. This 55 mile (88 kilometers) long HVDC PLUS system will be in service from March, 2010.

Comparing to the classic HVDC system, HVDC PLUS based on MMC provides the advantages of compact station design, lower converter losses, good dynamic response and excellent harmonic performance. Waveforms of a steady-state operation of a 400 MW converter with 200 submodules per phase arm and without any filter equipment are shown in Figure 4. The upper plot shows the DC voltages (+/- 200 kV) and the AC terminal voltages with respect to a virtual reference point. The plot in the middle illustrates the current in the AC terminals of the converter. The plot at the foot of the figure shows the six phase arm currents in the converter. Obviously, the voltage and current generated by such HVDC PLUS converter is almost free of harmonic distortion.

Besides the point-to-point HVDC application MMC is also advantageous for other DC applications like multi-terminal HVDC systems, particularly tapping existing HVDC system. Due to distributed capacitors in MMC the fault current in case of dc side faults will be easily manageable and restoration of operation after fault clearing can be done much faster than PWM type converters. This feature is specially advantageous for overhead line applications.

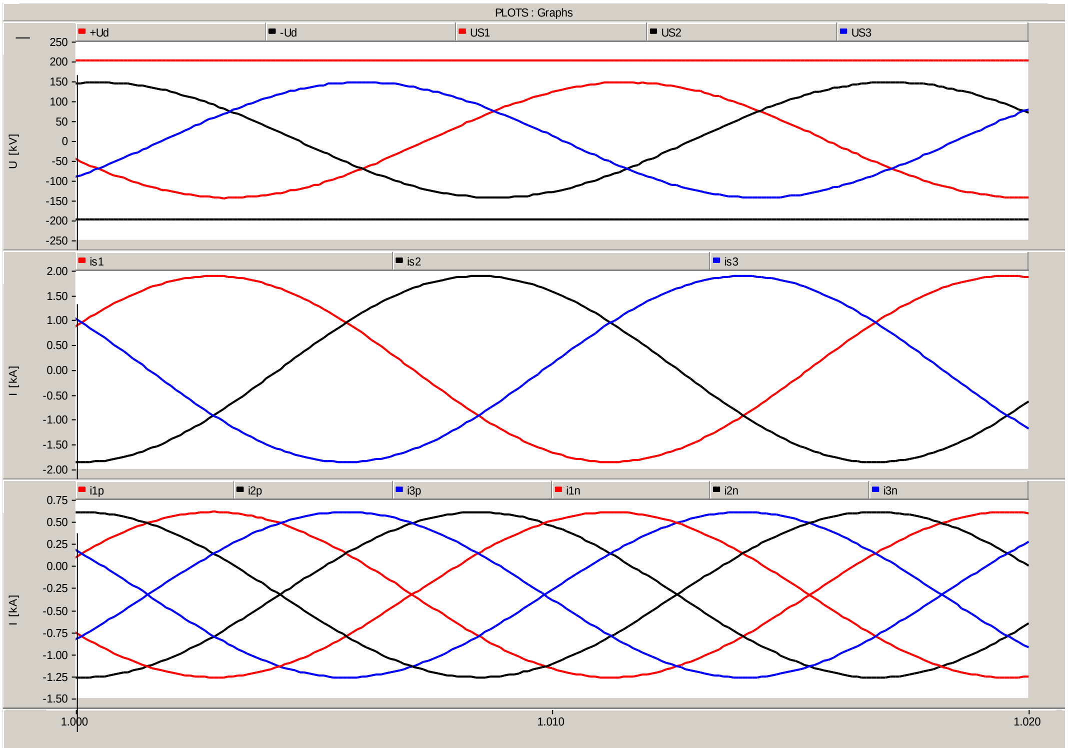

Figure 4 : Typical waveforms of a 400 MW VSC based on MMC topology - AC line-to-line converter voltages; AC converter currents; converter arm currents

4. APPLICATION OF MODULAR MULTI-LEVEL CONVERTER FOR FACTS

The self-commutated voltage sourced converter MMC is also an excellent choice for FACTS application like STATCOM. Due to AC application it is preferable to have full bridge power modules instead of half-bridge configuration. There are different possibilities to arrange a modular multilevel STATCOM. Siemens has developed and introduced a MMC based SVC system called SVC PLUS (Figure 5). The basic principle for module design and control of SVC PLUS is identical with those of HVDC PLUS system, so both solutions can maximize the synergy in technology and operating experience. Such SVC PLUS is high standardized and compact in design. It can be arranged into a standard container up to a rating of 50 MVAr, which enable a fast delivery time and almost “plug & play” capability during commissioning.

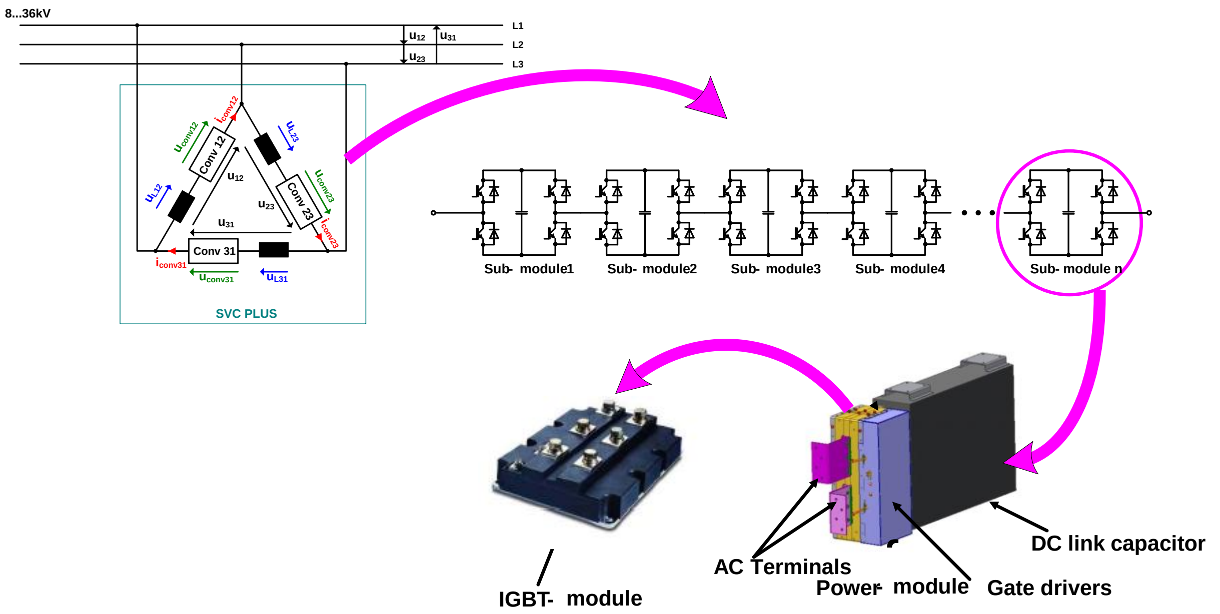

Figure 5 : SVC PLUS system based on MMC topology with same design principle of HVDC PLUS

MMC based SVC PLUS offers the same technical advantages as HVDC PLUS. Compact in design, fast dynamic response, and low operational losses and excellent harmonic performance are mentioned as examples. Although the number of module levels of a MMC in a FACTS application is considerably lower than HVDC applications, the harmonic performance is still exceptional. With adequate control algorithm the AC voltages generated by a SVC PLUS converter has such a low harmonic content that no or a small filtering circuit is needed to fully meet typical harmonic performance requirements (Figure 6).

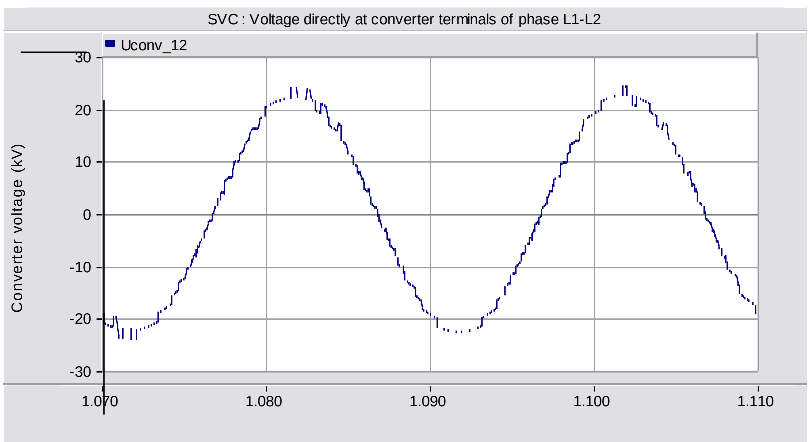

Figure 6: Simulation of AC terminal voltage of a SVC PLUS with 14 sub-modules per phase

5. OTHER APPLICATIONS OF MODULAR MULTI-LEVEL CONVERTER

The unique features of MMC technology can also be applied for other applications than HVDC and FACTS. In the area of power transmission and distribution two examples can be shown: A powerful and flexible active AC harmonic filter has been always desirable solution for HVDC system designers. The first MMC based active filters have already been in service with excellent filtering performance [6]. The latest new application of MMC is the static frequency converter SFC PLUS for connecting 16 2/3 Hz single phase railway system with 50 Hz three phase AC system. Based on the topology of HVDC PLUS (DC terminal in Figure 3a will be the 16 2/3 Hz AC terminals in this case) but with SVC PLUS modules the FSC PLUS combines the advantages of both schemes.

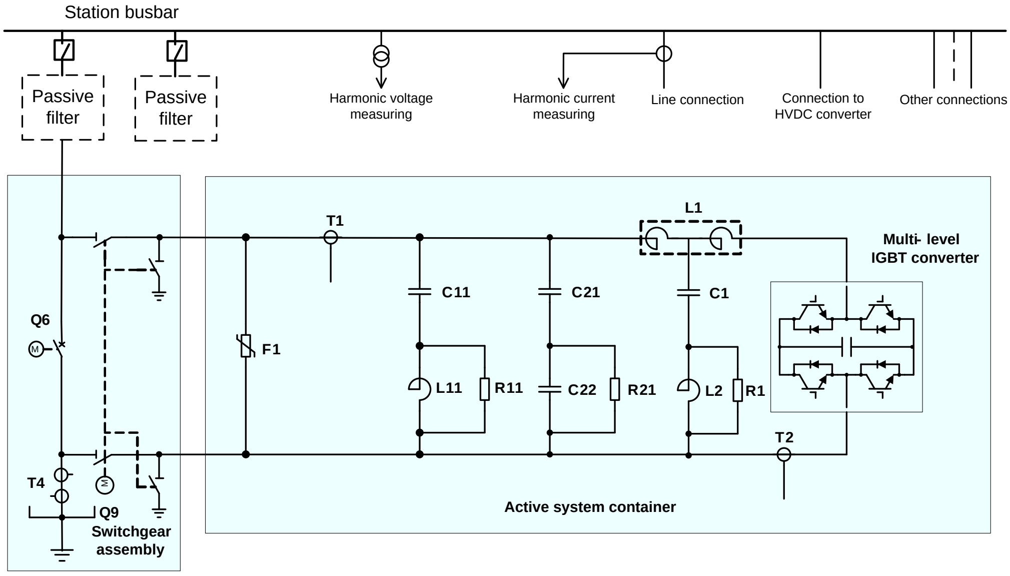

Figure 7: Active AC Harmonic Filter based on MMC, as implemented in Neptune Converter Stations

4. CONCLUSION

The MMC technology is ideally suitable for HVDC transmission system and FACTS devices. Compared with other VSC technologies, MMC offers additional benefits, particularly with respect to operational losses, EMC and suitability for HV applications. The topology is easy to scale with little engineering effort in the specific projects due to its modular design and mechanical construction.

This technology holds good for a wide range of different applications. Next to DC transmission systems MMC provides also excellent and unique features for STATCOM, active filter and frequency conversion applications. First commercial applications of MMC in HVDC, FACTS and Active filtering are already on the way to demonstrate the exceptional advantages of this technology.

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