Trans Bay Cable – A Breakthrough of VSC Multilevel Converters in HVDC Transmission

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SUMMARY
Trans Bay Cable is the first HVDC VSC scheme in the world which is based on modular multilevel converter (MMC) technology. Compared to two- and three-level topologies, which had been the standard for many years, the introduction of the innovative MMC topology has induced significant improvements and set groundbreaking milestones in HVDC transmission.

Low switching frequencies of the power semiconductors led to a considerable reduction of station losses. Due to the almost sinusoidal converter a.c. voltage and current waveforms special measures, such as extensive shielding and filtering, are no longer necessary to cope with the previously associated harmonic requirements. Less engineering, less space requirements and significant improvements in audible noise emission are some further advantages. Since the MMC topology is easily scalable towards higher voltages it has also paved the way of VSC technology towards transmission power in the range of up to 1000 megawatts and more.

The commercial operation of Trans Bay Cable started in November 2010. The paper covers operational experiences such as evaluation of station losses, harmonic performance and fault ride through capability.

With introduction of the MMC technology for grid access of offshore wind farms additional requirements arose, such as higher d.c. current capability and stricter grid code specifications. Further development aspects of the converter design to cope with these new requirements are presented.

KEYWORDS
Trans Bay Cable – HVDC – Voltage Sourced Converter – Modular Multilevel Converter – MMC

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1 First Application and Converter Principle

The Trans Bay Cable link is the first HVDC PLUS system in the world, based on modular multilevel converter (MMC) technology. Since November 2010 the link is in commercial operation and transmits up to 400 MW of real power from Pittsburg in the East Bay to Potrero in the centre of San Francisco (Fig. 1). It covers a distance of 85 km right across the bottom of the San Francisco Bay. The reactive power capability is +/- 300 MVar, limited down to +/- 170 MVar at rated real power transfer on Potrero station and +/- 145 MVar on Pittsburg station, respectively. The DC link voltage is +/- 200 kV.

Fig. 1: Trans Bay Cable Link, San Francisco, USA

The basic topology of the modular multilevel converter (MMC) and its generic design are shown in Fig. 2. An MMC consists of six phase arms. Each of these comprises of several submodules (SM) and one converter reactor connected in series. Each submodule comprises of an IGBT half bridge and a submodule capacitor for energy storage purposes. The latter ensures a low inductive commutation of the semiconductors within one submodule. With individual control of the submodules each phase arm can be operated as controlled voltage source and sinusoidal a.c. voltages and smooth d.c. voltages be achieved [1], [2].

Fig. 2: HVDC PLUS - Basic scheme
2 Operational Experience

2.1 Converter Control Performance

Fault Ride Through Capability

The Trans Bay Cable Converters have demonstrated an excellent fault ride through (FRT) behavior in many situations during commissioning and commercial operation. They provide continuous variable active and independent reactive power for control purposes in a very smooth and, if necessary, high dynamic way. Fig. 3 shows an example of the response to an a.c. under-voltage caused by a phase to phase fault event, which occurred on March 18th, 2011 in Potrero (inverter).

Fig. 3: Fault ride through behavior of Trans Bay Cable MMC Converter, a.c. line-to-ground voltages (top), phase arm currents (middle), AC converter currents (bottom)

Inner Converter Control Variables

The basic control principle of modular multilevel converters was described in the past [1]. Important converter control variables, beside voltages and currents, are for e.g. the inner phase arm energies $w_{kz}$, i.e. the energy stored in submodule capacitors of each phase arm. The index $k \in \{1, 2, 3\}$ is related to the converter phases, index $z \in \{p, n\}$ describes the upper, lower phase arms, respectively.

Fig. 4: Measured phase arm energy (normalized) \{$w_{1p}, w_{2p}, w_{3p}, w_{1n}, w_{2n}, w_{3n}$\}

Vertical Balancing of one phase (left) and Horizontal Balancing (right)
Of course the energy of all series connected capacitors within each phase arm has to be balanced. But in addition to that, the phase arms have to be balanced vertically and horizontally in terms of their energy $w_{1p}$, $w_{2p}$, $w_{1n}$, $w_{2n}$, as well. Fig. 4 shows the excellent step response of the converter control with respect to the phase arm energies [3]. It’s worth mentioning that the a.c. converter currents are not influenced by the balancing control.

**Harmonics**

Due to the high number of series connected power modules within one phase arm, the MMC concept results in almost linear control capability. Each phase arm acts as a quasi continuous voltage source. Harmonic distortion as a result of the switching of single power modules are therefore of minor importance. Harmonic filters have become a thing of the past – on the AC side as well as on the DC side.

The measuring results shown in Fig. 5 were performed during the commissioning period of the scheme. The frequency range under consideration is from 120 Hz to 3 kHz for a.c. voltage distortions and from 60 Hz to 5.1 kHz for d.c. current distortions.

The fluctuations are caused by a variation of real and reactive power.

**Fig. 5:** Harmonic Interference Levels – Pittsburg Conv. Station – total harmonic distortion of converter a.c. voltages (top) – d.c. equivalent disturbing current (bottom) – Feb. 1st, 2010

**2.2 Losses**

Converter losses are very important in the field of energy transmission. The MMC technology has led to a significant reduction of losses compared to two or three level converters concepts. The main reason is that two or three level converters work with considerably higher switching frequencies in the order of one kilohertz compared to 100 to 200 Hz for MMC.
Actual system losses, including cable losses of the Trans Bay Cable project are determined by direct measurement. As the station auxiliary power demand is drawn from the tertiary windings of the converter transformers, this demand is included in the measured results (Fig. 6).

The fluctuation of the losses corresponds to the variation of the reactive power, as depicted in the bottom of Fig. 6.

**Fig. 6:** Systems losses (top) and reactive power (bottom) as a function of time

### 3 Further Development Aspects

As shown in Fig. 1 the MMC topology consists of phase arms with a series connection of submodules, each of them consisting of an IGBT half bridge and a submodule capacitor. The main aspects of current developments are to increase the power capability of the submodules, to reduce losses and to investigate alternative configurations instead of half bridges.

#### 3.1 Half Bridge Submodules

Since the introduction of the MMC topology requirements to increase the transmission power arose from the market. As an example, in Germany several large offshore wind farms are already under construction and further clusters with a capacity of more than ten giga watts are in a planning stage. For most of these installations HVDC is the only solution to transmit the power to the shore, requiring a transmission power of up to one giga watt and more per system. Due to the limitation of the d.c. voltage capability of the XLPE cables, the required d.c. current increase in a range of up to 2 kA. A single IGBT module of the industrial standard type in the voltage class of 4.5 kV does not have such a current capability. Therefore a parallel connection of IGBTs within the submodule is the most reasonable and economic solution to fulfill these requirements.

**Fig. 7:** Half bridge submodule design with parallel connections of IGBTs
The parallel connection of IGBTs can easily be handled because the saturation voltage has a positive temperature coefficient in a wide current range and ensures good current sharing of the devices. Apart from power transmission applications the parallel connection of IGBTs has successfully been employed for many years, e.g. in traction drives.

3.2 Full Bridge Submodules
For static var compensation full bridge modules (FB-SM) were developed. With a series connection of these full bridge submodules connected between the three phases, the topology was introduced as SVC PLUS some years ago as a containerized solution. If the full bridge submodules are arranged in a B6 configuration, an alternating voltage can be generated instead of a d.c. voltage. This topology was introduced by Siemens for static frequency converters (SFC PLUS) to exchange power between the national three phase grid (50 or 60 Hz) and the single-phase railway grid operated with 16 2/3 Hz.

![Fig. 8: Full bridge submodule (FB-SM)](image)

Utilizing full bridge submodules in a B6 configuration could also be used for HVDC. In that case, a short circuit between the d.c. poles does not lead to a fault current driven from the grid because the current can be turned off immediately with the IGBTs. In some cases this might be advantageous compared to half bridge submodules, where the a.c. circuit breaker has to be opened to clear the fault. However, the utilization of full bridge submodules causes higher losses of the converter, since the phase arm current has to flow through two instead of one power semiconductor in case of half bridge power modules.

3.3 Submodule with d.c. Short Circuit Turn-Off Capability
The clamp-double submodule (CDSM) offers higher efficiency than the full bridge submodule including the capability to turn off a d.c. fault current. It has double the voltage capability compared to full bridge submodules and has therefore to be compared with two full bridge submodules in series. The voltage output of the CDSM is \(0; U_c\) or \(2U_c\) but the current flows through only three semiconductors during steady state operation. During normal operation, the IGBT in the centre of the module is always turned on, only in case of a short circuit between the d.c. poles of the converter that IGBT has to be turned off and the d.c. fault can be cleared without opening of the a.c. circuit breaker.

![Fig. 9: Clamp-double submodule (CDSM)](image)

However, the losses of a converter equipped with this kind of submodules dissipates higher losses than a converter with half bridge modules and might therefore be of interest for overhead line applications only.

3.4 DC Chopper Submodule
When offshore wind farms are connected to the onshore power grid, utilities demand compliance to stringent requirements regarding fault ride through capability as per grid code. One of the requirements is that in case of an a.c. line fault in the onshore power grid the offshore wind farm must not be turned off immediately. Typically there are requirements that if the a.c. fault is cleared within about one second the HVDC converter has to restore the power transmission within some ten to hundred milliseconds. This means, in case of an onshore a.c. fault the wind turbines and the HVDC transmission has to be kept in operation for up to two seconds. The transmitted energy has to be
dissipated during this fault time. This can be achieved by dynamic braking chopper in the HVDC inverter station. A series connection of the braking chopper submodules are connected between the d.c. poles on the inverter station and absorb the transmitted energy, if necessary.

Fig. 10: Braking chopper submodule

3.5 Submodules with an Internal Series Connection of Semiconductors

It is obvious, that in all of the presented submodule types a series connection of several semiconductors can be realized. In case of the half bridge submodule, the basic configuration is shown in Figure 11. Compared to the previous half bridge submodule a semiconductor fault usually does not lead to a discharge of the submodule capacitor because the remaining healthy devices should be able to block the applied voltage. However, some aspects should be considered:

A faulty semiconductor has to have the capability to carry the full submodule current. That might be critical since IGBT devices consist of an internal parallel connection of small chips. If one chip fails the full load current flows through the faulty chip which might cause an overheating of the silicon or the internal connection to the chip. One possibility to overcome that challenge is to apply a bypass device for each semiconductor.

The voltage of the half bridge submodule with one or two faulty devices bridged has to be reduced accordingly to ensure that the devices are operated within their specified voltage limits. However, if the voltage is decreased linear with faulty devices per submodule the remaining semiconductors are stressed higher because the effective stray inductance per healthy semiconductor became higher.

Additionally it shall also be considered that a short circuit of a whole half bridge can occur. This might happen as a result of a failure in the control system or of semiconductor failures with a domino effect in the series connection. In that case the fault current would be in the order of several hundred thousand amps and the mechanical design of the submodule should be capable to handle that fault current without excessive impact to the neighbored submodules accordingly.

Multilevel concepts with internal series connection of IGBTs utilize the blocking capability of the semiconductors in a reduced way and the switching frequency is typically higher to achieve the same performance. Therefore the losses of multilevel concepts with internal series connection of IGBTs are expected to be higher compared to topologies without series connection.

Fig. 11: Half bridge submodule with internal series connection of semiconductors

REFERENCES

