Introduction
Cell-based, multilevel converters provide an attractive solution in the design and application of medium voltage drives. They offer several benefits such as: scalable motor-friendly voltage, virtually sinusoidal load- and motor-friendly output current, modular and easy to maintain design, cell bypass and redundancy, and low fault energy. This makes cell-based, multilevel converters the best solution for most medium voltage drives applications.

A medium voltage drive using Modular Multilevel Converter (M2C) technology provides the same superior performance of cell-based, multilevel converters while adding the flexibility and configurability of a drive with a common DC link.

In 2002, Prof. Rainer Marquardt, a former Siemens employee, laid the foundation for this innovative engineering by presenting the M2C technology for the first time. Today this topology has proven beneficial not only in high voltage current (HVDC) transmission projects with hundreds of cells, but also in medium voltage drive technology.
This document explains M2C cell-based, voltage source inverter topology and how it is applied in a medium voltage drive. The M2C topology can be used as an Active Line Module or as Motor Inverter (also called a Motor Module). In addition, it is also possible to implement the M2C on the line and motor side as both the converter and the inverter circuit, as shown below.

**Operation principle**

The M2C topology used in medium voltage drives connects low voltage power cells in series to produce a medium voltage output. Each phase consists of two arms and their associated arm inductors.

In the simplest case, the power cell consists of two IGBTs and one capacitor bank. Such power cells are also called “single submodules” whereas the “double submodule” or “twin submodule” consists of four IGBTs and two capacitor banks. The difference between the single and the double submodules are the number of possible output steps as shown in Figure 4.

In the following description it is assumed that the inverter configuration uses single submodules only, unless otherwise noted.
In the case of medium voltage drives (See Figure 4), each power cell has two terminals (X1 and X2) and is equipped with low voltage (LV) IGBTs and self-healing film capacitors. There are many applications including LV drives that use LV IGBTs, which is why they are manufactured in very high quantities. This helps ensure the highest possible quality and reliability at a reasonable cost. Furthermore, all new technologies (e.g. new IGBT and diode generations, new module technologies with higher load cycling capabilities) are introduced into the LV market first. All these developments are driven by high volume applications, such as the wind power industry where they require very high quality standards. Therefore, MV drives using LV devices can benefit from the fast innovation cycles, highly reliable components and long-term availability of spare parts.

**Single phase operation**

It is possible to separately and selectively control each of the individual power cells in all phases. The two converter arms of each phase represent a controllable voltage source. The total voltage of the two arms in each phase equals two times the common DC link voltage. By adjusting the ratio of power cells activated in the upper and lower arm, the desired sinusoidal voltage at the midpoint AC terminal is achieved.

Example: The DC link voltage is 4 kV. Each power cell can store 1 kV. The output voltage can be adjusted to +2 kV and -2 kV related to the midpoint of the DC link voltage, as long as the total stored voltage in all power cells of one phase is 8 kV.

The control ensures that only half of the cells in one phase are activated and provide voltage to the DC link. Further protection concepts ensure that higher DC link voltages will always trip the drive.

To simplify, it is assumed that all cells are charged equally (with “+1”) and the cells have enough capacity (no pulse width modulation is shown) to support the voltage. Half of the cells in one phase are always activated. This is required so that the DC link voltage of the infeed (e.g. diode front-end [DFE]) is not higher than the voltage contributed by all activated cells. By activating all cells in the top half of one phase, the minimum peak voltage (in this example “-2”) can be reached, or vice versa by activating all cells in the bottom half the maximum peak voltage can be reached (in this example “+2”), as shown in Figure 5.
For the same output voltage (e.g. “+1”) different patterns of "active" and "passive" cells are possible. The selection of active cells is done according to their capacitor voltage level.

Various combinations of active cells are possible, as shown in Figure 6.

**Three phase operation principle**

The motor only sees the phase to phase voltage (purple line in Figure 7) but does not recognize the phase to middle point voltage at its terminals. This also means that the number of levels achieved is nearly doubled (nine levels instead of five in this example) compared to single phase operation.

Two different switching states are illustrated in the following figures. The zero-volt output voltage is achieved if the phase to middle point voltage is the same in two phases. Whereas the highest output voltage is achieved if all cells in the top of one phase and all cells in the bottom of the other phase are activated.

Same concept is applied to a drive configuration with double submodules. The number of resulted levels increase and each step size decrease. This results in a more sinusoidal looking voltage waveform.
Flexibility
The common DC link in the M2C topology allows for a separate rectifier. This makes the use of a standard DFE possible as well as the integration of a braking chopper for dynamic braking operation. Compared to cascaded H-bridge topology where the rectifier is an integral part of the cell, the M2C topology uses a stand-alone rectifier. This topology offers the possibility to select the number of line-side pulses since it is not dependent on the number of cells available in the motor-side inverter. This also allows for the use of a separate standard converter transformer.

Figure 8: M2C topology and its common DC link allows using different line front ends and a central braking chopper
**Redundancy**

As is true in all technical systems, random failures of individual components, even with the most meticulous engineering and one hundred percent testing are unavoidable. However, if a single component failure occurs, it should not impact the operation of the system. In a medium voltage drive this means there is no interruption of the energy transfer and the system should continue to operate until the next scheduled maintenance shut-down.

The M2C technology provides the ability to integrate redundant power cells into the drive, unlike other topologies such as 3-Level NPC or 5-Level NPC topologies. Drives can now be designed so that, upon failure of a power cell in one arm, the remaining power cells are not subjected to a higher voltage stress. The inclusion of the redundant power cells merely results in an increase of the drive dimensions.

In the event of a power cell failure during operation the fault is detected and the defective power cell is shorted out by a highly reliable high-speed bypass switch, as shown in Figure 9. Such switches can react in less than one millisecond which means, when combined with cell redundancy, that there is no loss of motor torque or speed. Therefore, full functionality is maintained and the drive continues to operate without any interruption.

![Figure 9: M2C Module equipped with redundant cells (n+1), each cell requires a cell bypass switch](image)

Depending on the location of the cell failure, several cells can fail without a reduction of output power. A drive with n+1 redundancy is shown in Figure 10. Only if two cells fail in the same arm does the full output power become unavailable and the drive will trip (if the full output power is required for keeping the process alive.) This is the reason why the drive MTBF (mean time between failures) increases by a factor of approx. 1.7 compared to a drive without redundancy.
**Scalability**

Scalability is the ability of a system to grow with the demand.

Cell-based topologies using LV components have an advantage in scalability, as they can cover a larger range of output voltages with only one power cell design. The output voltage and power of the drive using M2C topology can be easily increased by adding cells connected in series.
The cell based M2C topology used in HVDC applications demonstrates true scalability with more than 200 cells per arm reaching an output voltage of 400 kV. This is possible since each cell does not need to be connected to a transformer's secondary winding.

Medium voltage levels are obtained by adding together the outputs of multiple power cells. This is possible due to their smaller output voltage steps compared to drives using MV components. For example: the 24-cell configuration produces 33 line-to-line levels, the 36 cell configuration generates 49 line-to-line levels, and the 66 cell configuration results in 89 line-to-line levels. The more output levels the drives have, the better waveform the motor sees. To show the quality output waveform produced by an M2C drive, a simulation was done with the 36-cell configuration. As demonstrated in Figures 12 and 13 below, both the output voltage and current are almost sinusoidal and therefore produce no additional heating with minimal torque pulsations (less than 1%).

Figure 12: Phase to phase voltage (t)  
Figure 13: Phase current (t)

**Low fault energy**

The M2C topology does not need a centralized DC link capacitor. Its capacitors are distributed within the cells of the drive. This results in a very low energy level stored in each cell. This also means that in case of a short circuit in one semiconductor, the energy feeding into the fault is very small. Also, the motor does not feed into the fault as the voltage at the motor terminal hardly changes. Additionally, the grid has no direct connection to the M2C cells (if used on the motor side as inverter) and therefore cannot feed into the fault. Cumulatively, this results in an improved fault behavior as compared to other drive topologies.

Figure 14: Decentralized energy storage in the M2C topology
Siemens products using M2C topology
Siemens has more than six decades of experience manufacturing nearly every type of medium-voltage converter or inverter that exists today. SINAMICS PERFECT HARMONY drives using multi-cell topologies offer superior output waveform, increased reliability with cell bypass technology and cooling method flexibility that does not exist anywhere else. The SINAMICS PERFECT HARMONY GH150 uses a state-of-the-art DFE and the M2C topology on the motor side. The SINAMICS PERFECT HARMONY GH150 series of drives has expanded with the introduction of an air-cooled design variant. The air-cooled design is the largest single-channel, air cooled variable frequency drive and can produce up to 45,000 HP and 13.8 kV output voltages.

SINAMICS PERFECT HARMONY GH150 Benefits:
• Line-friendly: Achieves a near-unity power factor by eliminating harmonic voltage and current distortion
• High availability: Provides fault tolerant operation with cell redundancy and cell bypass, easy repair, and high-efficiency
• Motor-friendly: Eliminates harmonic heating and insulation stress
• Load-friendly: Eliminates significant torque pulsations

SINAMICS PERFECT HARMONY GH150 air-cooled drive reduces operating cost and improves Total Cost of Ownership (TCO) with:
• Cooling method flexibility: Duct air outside, use of integral or separate air-to-air or integral air-to-water heat exchanger
• Heat exchangers: 95% of heat losses rejected outside or into the water
• IP 54 rating with heat exchanger configurations: Superior protection from contaminates in the environment
• Best in industry: 10-year blower life design
• Reduced maintenance: Eliminate replacing filters, ionizer tank or adding water to the drive
• Robust design for the most demanding ambient conditions: Simple single loop cooling with easy high temperature derating and no glycol limits for cold climates

For more Information on other products using M2C Topology:
• SINAMICS PERFECT HARMONY GH150: Medium Voltage Converter,
  http://www.siemens.com/sinamics-perfect-harmony-gh150
• SINAMICS SM120 Cabinet Modules: Modular Medium Voltage Converter,
  http://www.siemens.com/sinamics-sm120-cm
• HVDC PLUS: Power transmission system,
• SVC PLUS: STATCOM (Static Synchronous Compensator),
Literature


• An Innovative Modular Multilevel Converter Topology Suitable for a Wide Power Range, 2003, A. Lesnicar, and R. Marquardt


• M. Hiller, R. Sommer, M. Beuermann; “Medium-Voltage Drives - An overview of the common converter topologies and power semiconductor devices”; IEEE Industry Applications Magazine; Mar/Apr 2010

• MTBF comparison of cutting edge medium voltage drive topologies for oil & gas applications, PCIC Europe 2015, Dr. M. Hiller, Dr. K. Kahlen, P. Himmelmann, S. Busse

• A new Modular Multilevel Converter for Medium Voltage High Power Oil & Gas Motor Drive Applications, EPE2016, P. Himmelmann, M. Hiller, D. Krug, M. Beuermann

• Complete Performance Test of MV Drive with Modular Multilevel Topology for High Power Oil & Gas Applications, PCIC 2016, D. Krug, S. Busse, M. Beuermann
In order to protect plants, systems, machines and networks against cyber threats, it is necessary to implement – and continuously maintain – a holistic, state-of-the-art industrial security concept. Siemens’ products and solutions constitute one element of such a concept. For more information about industrial security, please visit https://www.siemens.com/industrialsecurity.

This document contains a general description of available technical options only, and its effectiveness will be subject to specific variables including field conditions and project parameters. Siemens does not make representations, warranties, or assurances as to the accuracy or completeness of the content contained herein. Siemens reserves the right to modify the technology and product specifications in its sole discretion without advance notice.