Multilevel voltage source inverters in medium voltage drives

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Bachelor's thesis
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ABSTRACT

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This bachelor's thesis makes literature review in to medium-voltage drive markets and the objective of this study is to find out what kind of multilevel inverter topologies are used in medium voltage drives today. This study also investigates the traditional medium voltage inverter topologies and how those different topologies work and what are the pros and cons in them. Main sources of information used in this study are scientific articles and literature. This study also uses material provided by manufactures.

The main benefit of using multilevel inverters in medium voltage drive systems is that multilevel inverter improves the quality of output voltage waveform which is fed into the motor. This increases the lifespan of motors and increases productivity of the process. Multilevel inverters also increase the total efficiency of the drive system. The most used inverter topologies in the medium voltage drive markets are NPC and ANPC and the most used switching device is IGBT. Market review suggests that FC topology is not used in the medium voltage drives alone anymore. It has found its place as a part of hybrid topologies which have developed enough to reach into the markets. The development of hybrid topologies has led to that M2C topology is found in the medium voltage dive markets today and ANPC has become more and more used in medium voltage converters.

TIIVISTELMÄ

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Tässä kandidaatin työssä on tavoitteena selvittää, millaisia monitasoisia vaihtosuuntaajia käytetään keskijännitteisissä sähkökäytöissä. Työssä tutustutaan perinteisten monitasoisten vaihtosuuntaajien rakenteisiin, niiden toimintaperiaatteeseen sekä hyviin ja huonoihin puoliin. Työssä tutkitaan myös millaisia monitasoisia vaihtosuuntaajarakenteita eri valmistajat käyttävät keskijännitealueelle tarkoitetuissa taajuusmuuttajissaan. Tutkimus on suoritettu käyttäen tutkimusmenetelmänä kirjallisuustutkimusta, tieteellisiä artikkeleja, kirjoja sekä valmistajien tuottamaa materiaalia.

Monitasoisten vaihtosuuntaajien etuna on parempilaatuisen syöttöjännitteen luominen säädettävälle moottorille, mikä pidentää moottorin elinikää ja parantaa tehokuutta sekä koko käytön hyötysuhdetta. Markkinoilla käytetyin vaihtosuuntaaja on NPC ja ANPC. Suosituin kytkinkomponentti on IGBT. Markkinatutkimuksen perusteella on nähtävissä, että FC topologian vaihtosuuntaajia käytetään oikeastaan enää vain hybridivaihtosuuntaajien yhtenä osana. Hybridivaihtosuuntaajien kehityksen myötä M2C on kehittynyt markkinoille asti yltäneeksi tuotteeksi ja ANPC vaihtosuuntaajan viisitasoinen hybridiversio on yleistynyt taajuusmuuttajissa.

CONTENTS

Symbols and abbreviations

LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating current
ANPC	Active Neutral-point clamped
CHB	Cascaded H-bridge
DC	Direct current
DTC	Direct tongue control
FC	Flying capacitor
GCT	Gate commutated thyristor
GTO	Gate turn off thyristor
IGBT	Insulated gate bipolar transistor
MV	Medium-voltage
M2C	Modular multilevel converter
NNPC	Nested neutral point clamped
NPC	Neutral-point clamped
PWM	Pulse width modulation
SCR	Silicon-controlled rectifier
SHE	Selective harmonic elimination
SVM	Space vector modulation
THD	Total harmonic distortion

Subscripts

dc	Direct current
x	Phase
y	Switching device

1. INTRODUCTION

The mid-1980s marks the starting point of medium-voltage drives development, when gate turn off thyristors (GTO) became available in commercial markets. GTO was industry standard for medium voltage drives until the high-power insulated gate bipolar transistors (IGBTs) and gate commutated thyristors (GCTs) became commercially available in late 1990s. (Wu 2006; Rizzo 2004; Steimer 1999)

In the low voltage category, converters that use two-level voltage source inverters have dominated the electrical drives. If we look at the medium and high voltage category, the markets have been divided between many different topologies which have their own unique features to suite better in different industrial applications that use medium voltage drives (Rodriguez et al. 2010). Medium voltage drives can be found in a wide range of industrial applications. They can be used in the field of transportation, energy conversion, manufacturing, mining, among others. The current industrial applications demand continuously increasing production rates, cost reduction and efficiency which has led to the demand of higher power and higher power quality requirements to medium voltage drive systems (Rodriguez et al. 2009).

In the field of high-power conversion systems there have been two types of approaches for developing new inverters that are capable of handling the increasingly higher power rates, with better quality. The first way of approaching this problem was to start developing new high-voltage semiconductor technology that has the capability for higher nominal voltages and currents. The positive aspect of this approach is that well known circuit structures and control methods can be used. The negative aspect in this approach is that the new semiconductor technologies are more expensive. It is also difficult to meet other power quality requirements when going for higher power rates. The second way of approaching this problem was to start developing new topologies which can use already existing components that are on the market. These inverters are called multilevel inverters. The benefit of this approach is that we can use matured and cheaper semiconductors. But negative aspect of this approach is that the new topologies are more complex, and this brings challenges for the implementation and control. This complexity also brings a new kind of freedom for control that can be used to improve power quality and efficiency by using redundant states. (Rodriguez et al. 2009)

This bachelor’s thesis makes a literature review in medium-voltage inverter topologies and looks at what topologies are currently available in the market of medium-voltage drives today. Main sources of information for this thesis are scientific articles and literature. This review also uses material provided by manufactures. The focus of this thesis is in finding out how different topologies work and what are the positive and negative properties in each topology. This review has been restricted to deal with multilevel voltage source inverters. The second chapter contains information about positive aspects and challenges with medium voltage drives and introduces traditional medium voltage inverter topologies neutral-point clamped (NPC), flying capacitor (FC) and cascaded H-bridge (CHB) and discuses briefly about active neutral point clamped (ANPC) topology and modular multilevel converter (M2C). The second chapter also looks at the grid connection of medium voltage drive systems. The third chapter gives an overview of current medium voltage drive products of different manufactures in the market and an analysis of different electrical specifications which manufacturers have used in their products. The fourth chapter looks at topologies which are not found in the market and discusses the reasons why those topologies have not broken through. The fifth chapter presents the conclusions and relevant remarks of this study.

2. MEDIUM-VOLTAGE INVERTERS

Medium voltage (MV) drives typically operate in the power levels of 1 MW to 4 MW power range with voltages range from 3.3 kV to 6.6 kV, but power levels can be extended up to 100 MW. Development of high-power converter technology has led to use of variable speed MV drives. MV drives have become more common and accepted in industrial solutions. Many MV motors have been driven with fixed speed which leads to substantial and unnecessary energy losses. Installing variable speed MV drive system, the energy losses can be reduced substantially. Medium voltage variable speed drive makes industrial processes more energy efficient, because variable speed drive makes it possible to adjust the motor speed to suite the demand of the process rather than driving it at full speed all the time. This leads to substantial energy savings in different industrial applications and reduces the cost of production. In some industrial applications the use of medium voltage drive has led to increased productivity by reducing stoppage times that are caused by maintenance breaks. (Wu et al. 2017)

Block diagram of MV drive system is illustrated in Figure 1. Medium voltage drive system contains a transformer. The transformer creates the needed voltage level to the secondary winding and required phase displacement between primary and secondary for cancellation of harmonic content that line-side contains. The transformer also creates isolation between the rectifier circuit and the electrical grid that feeds drive system. For the AC to DC conversion MV drive system has a rectifier circuit which is composed of multi-pulse diode or silicon-controlled rectifiers (SCR) (Wu et al. 2017). With different topologies this rectifier circuit can be replaced with the same inverter topology that is used in DC to AC conversion (Rodriguez et al. 2009). The main function of DC filter is to act as an energy storage and filter out harmonic content that line current fed from the rectifier circuit contains. For DC to AC conversion there is an inverter that can generate output voltage with variable frequency which is fed into the load. The filters in line- and motor-side are optional. The use of the filters depends on the requirements different applications have.

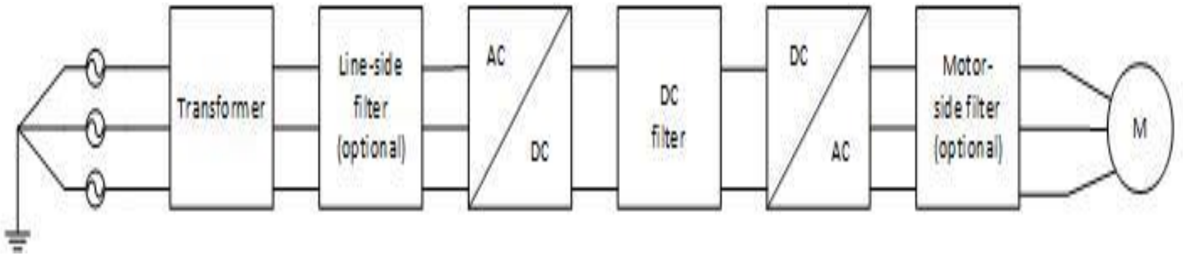

Figure 1 Medium voltage drive system

The use of multilevel inverters in medium voltage drive leads to more sinusoidal output voltage fed to motor that drives the industrial process. Multilevel inverters produce output voltage waveforms which have lower total harmonic distortion (THD), du/dt and leads to reduced common mode voltages. This is made possible by composing output voltage waveform from multiple levels. The multilevel inverters also make possible the use of drive system in fault conditions. Various multilevel inverter topologies also introduce modular structure which makes it possible to reduce manufacturing costs and makes maintenance quicker and easier (Rodriguez et al. 2007).

With medium voltage drives there are a lot of different challenges that must be taken into account when designing drive system. These challenges can lead to premature failure of insulation or the bearing system in motor or incapability to operate the system with full capacity. Fast switching speeds results in high du/dt in the output of the inverter. This can lead to discharges and a premature failure of insulation in motor windings. The discharges can lead to the bearing currents flowing into the bearing system. These currents cause wear in the bearings system and may eventually lead into the failure of the bearing systems. High du/dt also produces electromagnetic emissions in the cables that connects motor and inverter. The switching action of the inverter and rectifiers that feed dc link generates common mode voltages in the system. This can lead to noise between neutral and ground of the motor which can result in the failure in insulation of the motor. Inverters also generate large a number of harmonics in to the voltage and current waveforms which causes power losses in the windings and magnetic core of motor. (Wu et al. 2017)

Traditional multilevel inverter topologies that are used in MV drives are represented in this section of this thesis. This section focuses on how those traditional topologies operate and what are the pros and cons of these different topologies. This section also takes a brief look at the more recently developed active neutral point clamped and modular multilevel converter topologies and how the MV drive system is connected to the grid. This section also takes a look at what kind of modulation methods are used with different topologies.

2.1 Neutral-point clamped inverter

Neutral-point clamped inverter uses clamping diodes and capacitors to produce multilevel waveforms for output voltage. The NPC is composed of switches, clamping diodes and series connected dc capacitors (Wu 2006). NPC can be thought as two two-level inverters piled one over each other, where the negative bar of the upper inverter is connected to the positive bar of the lower inverter to form phase output. The original phase outputs of the two-level inverters are connected through clamping diodes into dc link to form a neutral-point. The neutral point divides the dc link voltage into two. Because the dc link has been divided into two, the voltage of each power device has to block is halved instead of needing to block the total voltage that is fed to the inverter (Rodriguez et al. 2009). This means that it is possible to double the power rating of the inverter with the same semiconductor technology. Figure 2 illustrates the three-level neutral point clamped inverter circuit topology.

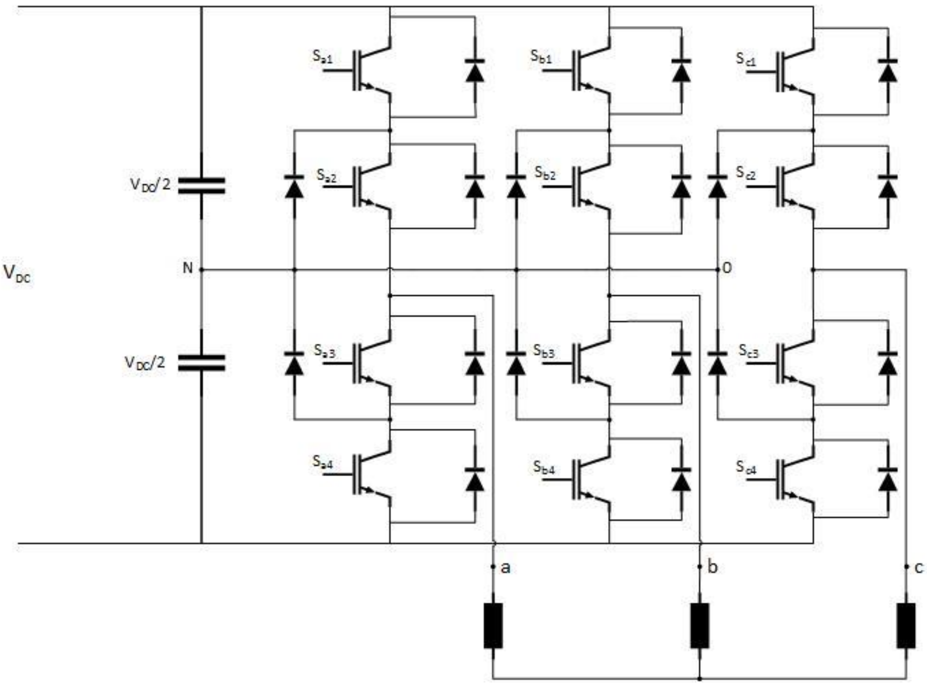

Figure 2 Three-level three phase NPC topology

In the Figure 2 each phase of the NPC is composed of active switches S_{xy} where x represents the phase and y is the number of the switch. Each phase is composed of four switches and two clamping diodes that form the neutral-point with dc link. The three-level NPC can generate three different voltage-levels depending on the switching states that the switches are on. Every phase output is formed by a particular set of control signals for the switching devices (Wu 2006). The operating principle of the switches is that when the S_{a1} gets gate signal to turn on, the switch S_{a3} gets an inverted gate signal and when the S_{a2} gets gate signal to turn on the switch S_{a4} gets a gate inverted signal. The NPC uses only two control signals per phase. The inverted gate signals are used to avoid a short-circuit in the dc link (Rodriguez et al. 2009). Table 1 illustrates three different switching states of phase a and Figure 3 shows the equivalent voltage level.

From the Table 1 it can be observed that the combination where S_{a1} gets gate signal to turn on and S_{a2} gets gate signal off is not used. The combination is not used because it does not allow current to flow in to the load. Switching between states +E and -E is also forbidden because it involves that all switches are commuted either on or off at the same time which means that dynamic voltage with each switch cannot be kept same. It also doubles the switching losses in inverter (Wu 2006). All the switching states that are represented in Table 1 can be applied for other phases in the inverter.

Table 1 Three-level NPC switching states and equivalent output voltage-level. Number 1 represents on state and number 0 represent off state

Output Voltage	Switching device			
V_{aN}	S_{a1}	S_{a2}	S_{a3}	S_{a4}
+E	1	1	0	0
0	0	1	1	0
-E	0	0	1	1

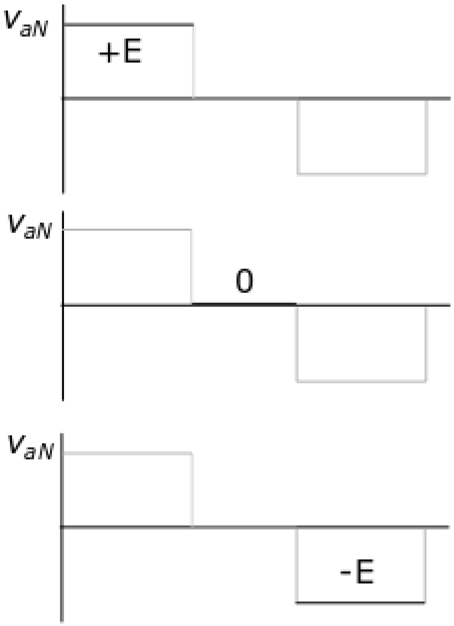

Figure 3 Output voltage levels from NPC with different switching states

The pros for the NPC topology are that it provides increased power rates. The increased power rates are made possible by getting more switching devices connected in series during commutation, which makes it possible to double output voltage. The power rates can be further increased by connecting two NPC inverters parallel or adding a step-up autotransformer to the output of the inverter (Wu et al. 2017). The NPC also makes static voltage equalization possible. It can be achieved when leakage current of the top and bottom switches is chosen lower than switches in the middle have. The NPC also provides lower THD and du/dt because the line-to-line voltages are composed of a greater amount of voltage levels (Wu et al. 2017). The NPC topology is also suitable for regenerative applications because it has a structure that makes back-to-back connection possible (Rodriguez et al. 2009).

The cons of the NPC topologies are that they lack modularity and even though it is possible to extend the NPC for higher levels, the structures provide higher losses in switching devices and the losses are unevenly distributed in outer and inner devices. Unevenly distributed losses cause uneven temperature distribution in semiconductor junctions, which leads to unequal utilization of switching devices (Wu et al. 2017). When the NPC is extended in higher levels it is necessary to use more clamping diodes connected in series to be able to block higher voltages (Wu et al. 2017). This introduces more conduction losses and produces reverse recovery currents during commutation (Wu 2006). Increasing levels in the NPC also makes the dc link capacitor voltage balance unobtainable with convention modulation methods (Kouro et al. 2010).

For the NPC, multiple different modulation strategies can be used. The strategies are carrier-based pulse width modulation (PWM), space vector modulation (SVM), selective harmonic elimination (SHE), and discontinuous SVM (Wu et al. 2017). These modulation methods can be used either in the motor side inverter or the active front end. The control methods that are commonly used with the NPC are linear controller with PWM, direct torque control (DTC) and predictive torque control (Rodriguez et al. 2010).

2.2 Flying Capacitor inverter

The flying capacitor inverter topology uses multiple dc capacitors and switches to create multilevel output voltages. When Figure 2 and Figure 4 are compared it can be seen that the FC topology resembles the NPC topology substantially. The difference between the FC inverter and the NPC inverter is that the clamping diodes that are used to create neutral-point in the NPC are replaced with flying capacitors and a neutral-point which divides the dc voltage in the NPC is removed. Because the neutral-point has been removed it is not possible to connect load directly into the neutral-point to create output voltage level zero. The output voltage level zero is created by connecting load either into the positive or negative bar of the inverter through flying capacitor (Rodriguez et al. 2009). The three-level flying capacitor inverter topology is illustrated in Figure 4.

Each phase of the three-level FC inverter is composed of four switches S_{xy} where *x* represents the phase and *y* the switching device and one FC which can been seen in Figure 4. For commuting the three level FC needs two gating signals for each phase. Two signals are needed to avoid short-circuit between the dc-link and the flying capacitor. With this topology, switches are controlled in pairs. The pair is controlled so that one switch from the pair gets an inverted signal (Rodriguez et al. 2009). In Figure 4, the switches S_{a1} and S_{a3} form one pair and switches S_{a2} and S_{a4} the second. One major advantage in the FC control for the NPC is that the FC allows four combinations between the S_{a1} and S_{a2}. The switching states and equivalent voltage levels are presented in Table 2. From the Table 2 it can be observed that there is more than one combination that can create output voltage level zero.

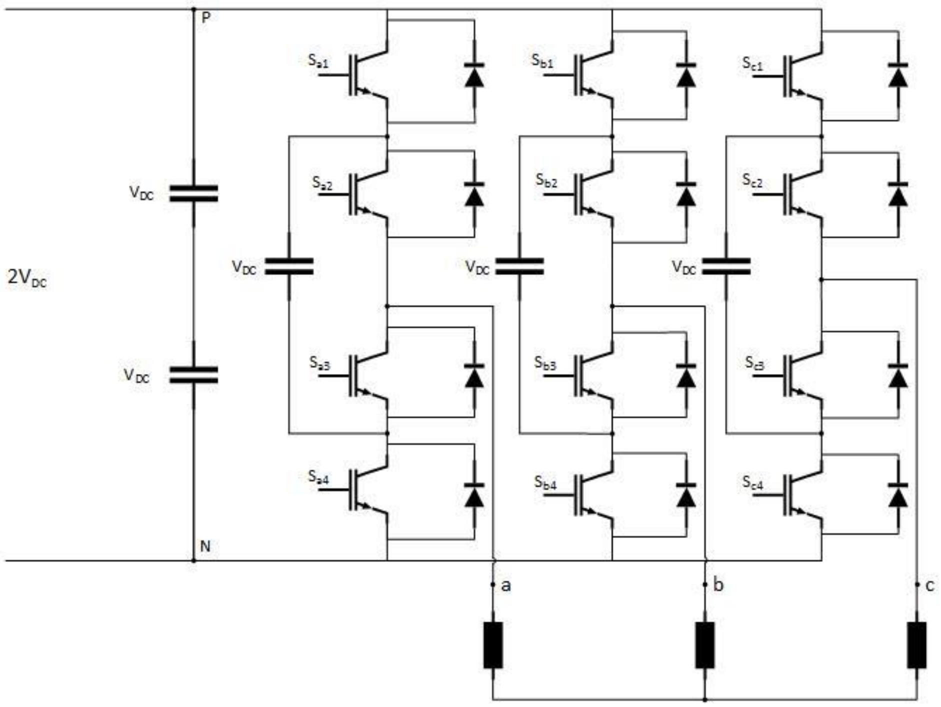

Figure 4 Three level flying capacitor topology

The flying capacitor voltage is varying depending on the way the current is flowing through when zero voltage is created. The behaviour of this changing phenomena is illustrated in the Table 2 column charge. The three voltage levels which the three level FC can create are the same as the NPC has and are illustrated in Figure 3.

Table 2 Switching states of three level flying capacitor and output voltage levels and capacitor charge. Number 1 represents on state and number 0 represent off state, C represents charging and D discharging.

Output Voltage	Switching device				Charge	
V_{aN}	S_{a1}	S_{a2}	S_{a3}	S_{a4}	i > 0	i < 0
+E	1	1	0	0	-	-
0	1	0	1	0	C	D
	0	1	0	1	D	C
-E	0	0	1	1	-	-

The flying capacitor topology has a modular structure. One power cell is created by capacitor and a pair of switches. These power cells are easily connected into each other to extend the FC and provide additional voltage levels. Each power cell also provides additional redundancies that can be used as in control design. With the FC inverter, bipolar phase-shifted modulation techniques can be used. (Rodriguez et al. 2009) When a proper control method is used with the FC, it has naturally the capability to keep its flying capacitor balance in control. To keep the balance switching frequencies should be greater than 1200 Hz, but this limits the use of the FC in high power applications because the frequencies are not feasible in high power applications (Kouro et al. 2010).

The benefits of the FC topology are that it provides many redundancies in the switching states and when the topology is extended it provides more degrees of freedom for control design and makes it more tolerant to faulty operations. The modular structure makes it possible to extend this topology much easier. The output voltage waveform which the FC creates is composed of multiple levels which lead into reduction of du/dt and the THD.

The downsides of the FC topology are that it needs large numbers of dc capacitors with separate pre-charge circuits. Also, for keeping capacitor voltage in balance it requires complex control schemes to tightly control for voltage deviations with inverters that have more than three levels (Wu 2006). Flying capacitors have high expense at low and medium carrier frequencies and FC requires lots of cells (Rodriguez et al. 2007).

2.3 Active neutral-point clamped inverter

An Active neutral point clamped inverter topology has been developed to cope with the uneven power losses distribution in the switches of the NPC topology. The ANPC can be either a three or five level inverter. The ANPC topology is a modified three level NPC topology where the clamping diodes are replaced with active switches which make it possible to control the uneven power loss distribution in each leg of the inverter (Wu et al. 2017). Five level ANPC uses the Flying capacitor power cell cascaded to thee level ANPC to create those two extra voltage levels (Wu et al. 2017). Because the ANPC solves the power loss distribution issue, it is possible to increase output power from the inverter. The ANPC also increases the complexity and the cost of the system, because it uses switches instead of diodes in clamping circuit (Wu et al. 2017).

The three level ANPC topology is illustrated in Figure 5. Each phase of the ANPC is composed of active switches S_{xy} where *x* represents the phase and *y* is the number of the switching device. Each phase is composed of four switching devices and a clamping circuit which is composed of two active switches. It can be observed that it is almost identical with the NPC topology which is represented in Figure 1, with the exception of the clamping diodes which have been replaced by switches S_5 and S_6 in every phase.

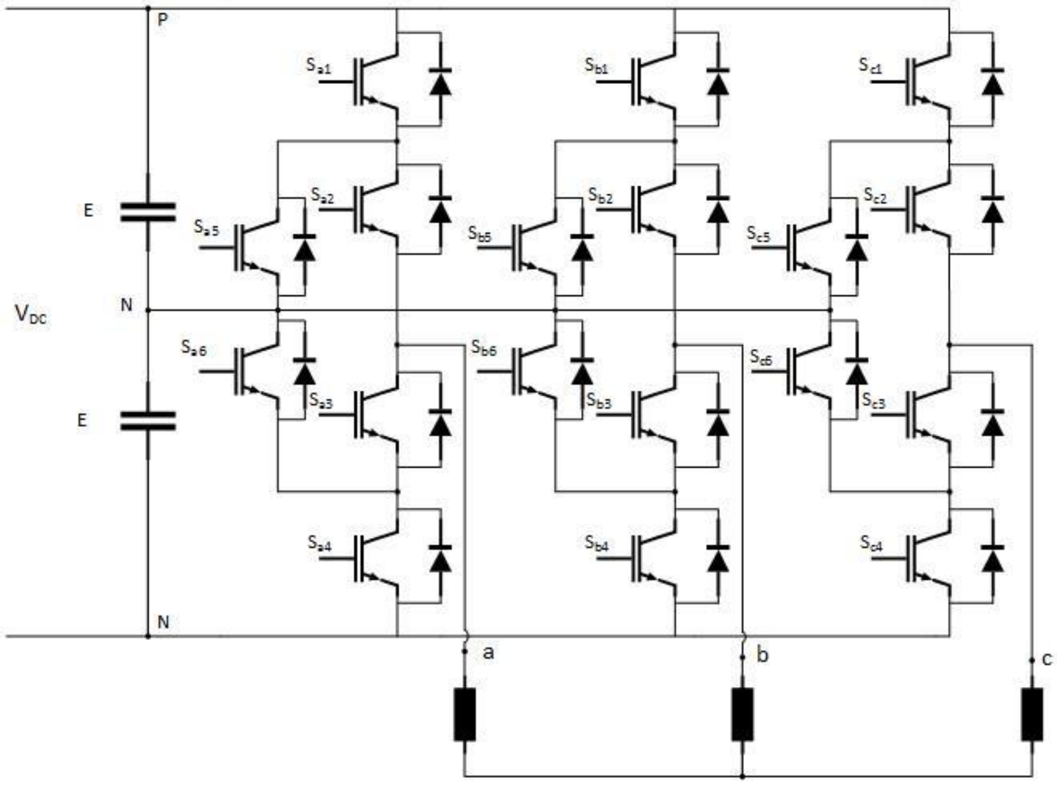

Figure 5 Three level Active neutral point clamped inverter topology

Three level ANPC has six different switching states. Those states are represented in Table 3. From Table 3 it can be observed that the ANPC has four redundant states to create voltage level zero. These redundant states make the control of uneven power losses possible by selecting the suitable state for the switches to redistribute switching losses equally during commutation (Wu et al. 20017). When either positive or negative output voltage is created, it can be observed that one of the active switches in clamping circuit is conducting. One switch in the clamping circuit is turned on because it makes it possible to share dc bus voltage equally between the other two switches that are not conducting (Wu et al. 2017).

Table 3 Switching states of ANPC inverter and equivalent output voltage levels. Number 1 represents on state and number 0 represents off state.

Output Voltage	Switching device					
V_{aN}	S_{a1}	S_{a2}	S_{a3}	S_{a4}	S_{a5}	S_{a6}
+E	1	1	0	0	0	1
0	0	1	0	0	1	0
	0	1	0	1	1	0
	0	0	1	0	0	1
	1	0	1	0	0	1
-E	0	0	1	1	1	0

2.4 Cascaded H-bridge inverter

A Single-phase H-bridge inverter is composed of independent isolated dc voltage supply and four switching devices. Each H-bridge inverter corresponds to two voltage source phase legs. The output voltage generated by the H-bridge inverter is equal to the line to line voltage. The single H-bridge can generate three voltage levels (Rodriguez et al. 2009). A Cascaded H-bridge inverter is obtained when two or more H-bridge inverters are connected in series. The total output voltage is generated as the sum of different output levels that each individual h-bridges generate (Malinowksi et al. 2010). Figure 6 represents single H-bridge inverter.

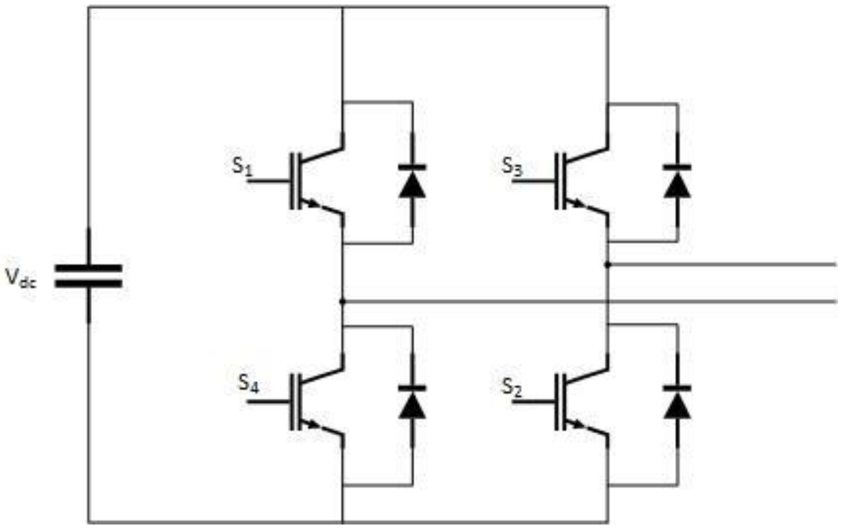

Figure 6 Single H-bridge inverter

Each leg of the H-bridge is composed of two switches which can be observed from Figure 6. The switching devices in the same leg conduct complementary to each other to avoid dc link short circuit (Rodriguez et al. 2009). When the S_{a1} gets gating signal on, the S_{a4} gets an inverted gating signal. The different switching states for one H-bridge inverter are presented in Table 4. One H-bridge inverter has four different switching states. From Table 4 it can be observed that there are two redundant states in one H-bridge inverter. Which means that same voltage level can be created with more than one combination. In case of single H-bridge output voltage level zero can be created with two different combinations. All three voltage levels that single H-bridge inverter can create are illustrated in the Figure 3 and are the same as in the NPC and the FC. The CHB drives have naturally lots of redundant states. Each H-bridge have one redundant state and when multiple H-bridges are connected in series the redundancies increase (Wu et al. 2017).

Table 4 Switching states of one H-bridge inverter and equivalent output voltage levels. Number 1 represents on state and number 0 represents off state.

Output Voltage	Switching device			
V_{aN}	S_{a1}	S_{a2}	S_{a3}	S_{a4}
+E	1	0	0	1
0	0	0	1	1
	1	1	0	0
-E	0	1	1	0

The CHB inverter can be composed of H-bridges that have equal dc voltage or with unequal dc voltages. The CHB with unequal dc voltages makes it possible to increase voltage levels of the inverter without increasing the number of power cells and to create more steps in the output voltage waveform (Wu et al. 2017)

The benefits that come with using the cascaded H-bridge inverters are that H-bridges brings natural modularity into the structure of the inverter. The H-bridges which are cascaded have lots of redundant states which enable fault-tolerant operations. The H-bridges make the increase of the output voltage and power possible and effective, since all the semiconductors must only block V_{dc}. (Rodriguez et al. 2009). The CHB creates an output voltage waveform from multiple levels which reduces the THD content in the output and reduces du/dt. The CHB makes high voltage operation possible without using switching devices in series. (Wu 2006)

The downsides of the cascaded H-bridge are that each H-bridge inverter requires isolated dc source, which is usually provided by a three-phase transformer (Rodriguez et al. 2009). This transformer must have multiple secondary windings which lead to a bulkier system and increases the component count of the system (Wu 2006). With unequal dc voltages this topology makes the design of switching patterns more difficult because it reduces the number of redundant states. This also takes away benefits that modular structure allows (Wu et al. 2017).

The modulation methods that can be used with the CHB are bipolar and unipolar PWM, but the unipolar modulation method is more commonly used with the CHB. Phase- or level-shifted PWM, SHE modulation, space vector modulation schemes are used with CHB. For asymmetric CHB the hybrid PWM is used. (Wu et al. 2017)

2.5 Modular multilevel converter

The Modular multilevel converter topology (M2C) is a topology that uses multiple submodules connected in series in each of the converter arms. Each submodule can differ in design. The submodules can use a neutral point clamped, flying capacitor, h-bridge or half-bridge design. The main difference between the M2C and the CHB topology is that when the CHB needs an isolated dc supply for every power cell it contains, the M2C does not need separate isolated power supplies for every submodule. In the M2C the isolated dc supplies are replaced by flying capacitors which make it possible to connect the M2C straight to the common dc bus. Figure 7 illustrates the modular multilevel converter topology. In each phase there are six submodules and each phase is divided into two arms – upper and lower – which contain three submodules and an inductor. The function of the inductor is to limit the inrush, circulating and surge currents during different stages of operation. (Wu et al. 2017)

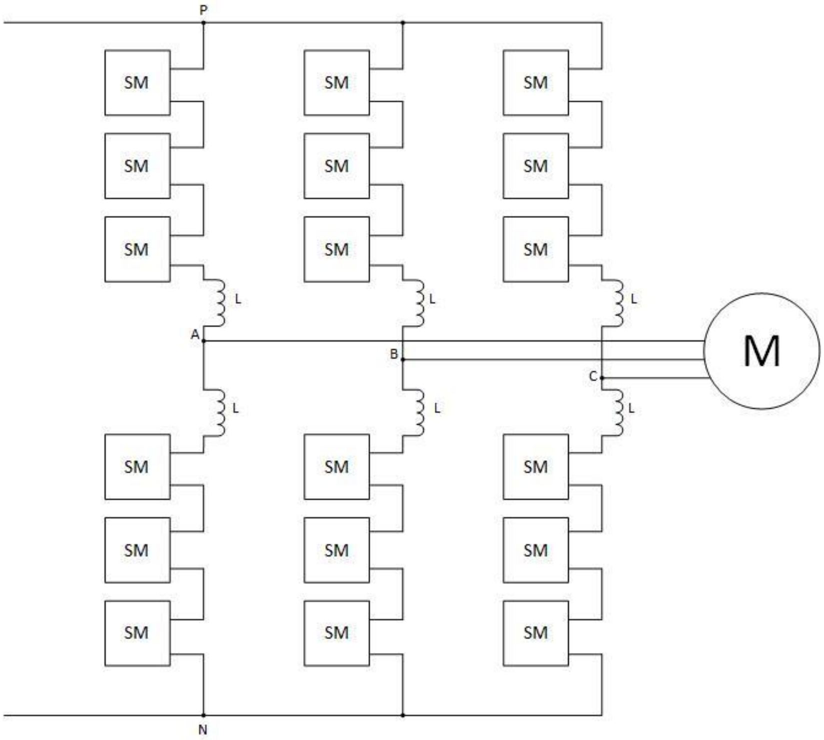

Figure 7 Modular multilevel converter fed drive system

The voltage levels that the M2C can create depends on how many submodules there are in each arm of the converter. This topology is easily extended to higher voltage and power levels, because of the modular structure. The simplest submodule structure with the M2C is the half-bridge, which is illustrated in Figure 8.

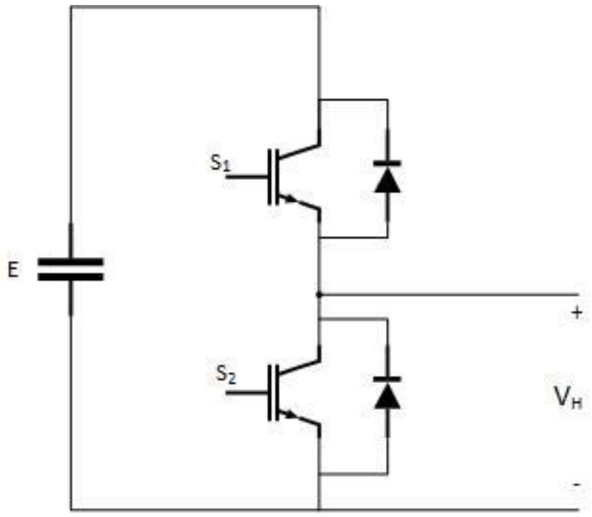

Figure 8 Half-bridge submodule

This submodule contains two switching devices and one flying capacitor. The different voltage levels and states are illustrated in Table 5. From the Table 5 it can be observed that the switching devices get inverted gating signals relative to each other. The half-bridge submodule can be in two different states which are the on state and the bypass state (Wu et al. 2017). The state where the switching device S_1 is conducting is called the on state, which means that output voltage from the submodule is equal to voltage from the flying capacitor. When the S_1 is not conducting the state of the submodule it is called the bypass state. In the bypass state, the output voltage from the submodule equals to zero. This submodule is the simplest, because it has the least number of components and the simplest structure, which lead to lower conduction losses during commutation (Wu et al. 2017).

Table 5 Switching states of half-bridge inverter and output voltage levels. Number 1 represents on state and number 0 represent off state.

Output Voltage	Switching device	
V_H	S_1	S_2
E	1	0
0	0	1

The benefits in this topology are that it creates the output voltage waveform from a large number of voltage levels which lead to lower du/dt and the THD especially in high voltage applications when there are many identical submodules in series (Wu et al. 2017; Debnath et al. 2015). The M2C offers high efficiency because it allows the use of simple structured submodules and lower conduction losses. Because the M2C submodules use flying capacitors instead of isolated dc supplies, it does not need dc link capacitors which reduces the number of components needed and removes the need for a transformer with big secondary winding to feed the submodules. This reduces the overall cost of the system.

The cons in this topology are that when the motor is running at low speed there is a disproportionate high voltage ripple in the flying capacitors. At low frequencies the ripple can be reduced by increasing the size of the flying capacitor, which increases the total cost of the system. Other solution for managing the ripple is to inject high frequency common mode voltage signals in to the PWM signals. This method generates more common mode voltage stress into the stator winding which can lead to the premature failure of stator if not handled properly. With this topology, circulating currents occur in the inverter circuit. This is caused by a difference in the capacitor voltages in the upper and the lower arms of the converter. These currents increase conduction losses in the switching devices. These currents can be minimized by increasing inductance in arms and using closed loop control scheme (Debnath et al. 2015; Akagi 2011). This topology also needs a high number of flying capacitors which increases the complexity of the controls schemes to the control capacitor voltages in the submodules. (Wu et al. 2017)

2.6 Grid connection

The medium voltage drive system is connected to the electrical grid through a transformer which feeds the rectifiers as shown in Figure 1. In the MV drive systems the transformer is usually a phase shifting transformer, which is usually connected either wye to zigzag or delta to zigzag configuration (Wu et al. 2017). The phase shifting transformer helps in the cancellation of common mode voltages that the rectifiers and the inverter are generating (Das et al. 1998). The phase shifted transformers are also used to reduce the THD content in line currents that are fed to the multi-pulse rectifiers. (Wu et al. 2017)

The rectifiers which are used in the medium voltage drive systems are usually multi-pulse diode rectifiers especially in the voltage source inverter drives. The multi-pulse rectifiers are usually 6-, 12-, 18- and 24-pulse rectifiers depending on the specifications which drive system must meet. The higher pulse rectifiers are created connecting six pulse rectifiers together. The main function of the rectifiers besides converting AC to DC is to reduce the harmonic content in line current that is fed to the DC filter. The harmonic content is reduced every time when the number of pulses is increased in the rectifier. The multi-pulse rectifiers can be divided in to two types of rectifiers, which are the series type and the separate type. The difference between the series and the separate types are that in the series type, all six-pulse rectifiers are connected in series and they feed single dc load while in the separate type six pulse rectifiers feed different dc supplies. The series type rectifiers have a lower ripple in current and a better power factor compared to the separate type. But the separate type rectifier contains better THD profile. (Wu et al. 2017)

3. MANUFACTURERS

In the field of medium voltage drives there are many manufactures that offer different medium voltage drive systems for different applications. This section looks at the medium voltage drive market and creates an overlook into electrical specifications different manufacturers have on their products and which topologies and switching devices are used in their products. This section also looks at which application these products are marketed for.

3.1 ABB

ABB is one of the major manufacturers in the field of medium voltage drives. Their ACS drive family ranges from 200 kW to 36 MW with output voltages from 6 kV to 13.8 kV (ABB 2019a). They use two different inverter topologies at their ACS products, which are the NPC and the ANPC. ABB prefers to use the IGCT as a switching device in their medium voltage inverters (ABB 2018a, 2017, 2015). ACS2000 is the only converter where the IGBT is used as a switching device (ABB 2018b).

ACS1000 is a drive which has a power range from 0.315 to 5 MW and an output voltage from 2.3 - 4.16 kV. According to ABB (2016, page 2), ACS1000 has two possible options for cooling: air or water. The power range of the ACS1000 depends on how it is cooled. With air cooling, the power range is from 0.315 to 2 MW and with water cooling, the power range is from 1.8 to 5 MW. According to the ABB (2018a, page 12) in the topology of the ACS1000 they are using the NPC or the ANPC topology at their inverter because there is a connection to the neutral point at the middle of the dc link from the inverter. If we look at the more detailed electrical specifications of this ACS1000 from ABB (2018a, page 18) and compare it to the table from Wu et al. (2017, page 296) which lists the main specifications of the three level NPC drive that uses the GCT, we see that the electrical specifications for the ACS1000 are almost identical. This suggest that ABB is more likely to use three level NPC topology in this product. ABB (2014, page 3) says that in this product there is three level voltage source inverter, which suggests that it is a three level NPC. Another product that uses the NPC topology is the ACS6000. The ABB (2015, page 18) brochure says that there is a three-level voltage source inverter. Because common dc bus where multiple inverters can be connected is discussed in ABB (2015, page 16). That suggests that they are using the NPC topology. The ACS600 has a power range from 5 to 36 MW and output voltage range from 2.3 to 3.3 kV and it is water cooled according to ABB (2015, page 20).

The ACS2000 is a drive which has a power range from 0.25 to 3,68 MW and output voltage range from 4.16 to 6.9 kV. ABB offers the ACS2000 only with air cooling according to ABB (2016, page 2). This product is one of the drives in the ACS family that uses the ANPC topology. According to ABB (2018b, page 13) topology presentations there is a connection from the inverter to the middle of the dc link. ABB (2014, page 2) provides information that there is a five-level voltage source inverter in this product and that it creates nine level output waveforms. From this information it can be reasonably said that in this product ABB is using an inverter which has five level ANPC topology. Another product that uses five level ANPC topology is the ACS5000 from ABB (2017, page 16). It can be said that the single converter unit is either NPC or ANPC but ABB (2014, page 2) gives same information that it uses a five-level inverter and creates a nine-level output, which means that it has the five level ANPC. The ACS5000 has power range from 2 to 36 MW and output voltage range from 6 to 13.8 kV (ABB 2017). ABB offers the ACS5000 with two different cooling systems: air and water (ABB 2017). According to ABB (2016, page 2) the power range with air cooling is 2 to 7 MW and with water cooling 5 to 36 MW.

The ACS1000 and the ACS5000 are only available with diode front end which allows two quadrant operations, which means that they are not suitable for regenerative applications (ABB 2016). The ACS2000 and the ACS6000 can be configured with an active front end which allows four quadrant operations and makes them suitable for regenerative applications (ABB 2016). The whole ACS family uses a direct torque control method and is marketed for the drive systems that use induction motors. ACS5000 and the ACS6000 have also the capability to drive synchronous and permanent magnet motors. The ACS1000, the ACS2000, and the ACS5000 are marketed for the pump, fan, conveyor, extruder and compressor applications. The ACS6000 is mainly marketed for mills and marine applications but can be used in same applications than other products in this family. (ABB 2016)

3.2 Danfoss

Danfoss manufactures numerous converters in the low voltage category, but they have one medium voltage converter in their product portfolio, which is Vacon 3000. Danfoss is using a three-level neutral point clamped inverter in their Vacon 3000, according to Danfoss (2017, page 9). This inverter unit is capable of output power rates from 2 to 3 MW and nominal voltages are 3.3 and 4.16 kV. 4 MW and higher power rates can be achieved by paralleling inverters (Danfoss 2017). Danfoss offers the Vacon 3000 only with liquid cooling system and according to Danfoss (2017, page 18) the cooling solution is glycol-based water solution.

The Vacon 3000 is available with a diode front end and an active front end which makes it capable for nonregenerative and regenerative applications as is said in Danfoss (2017, page 11). Danfoss uses the IGBTs as their switching device (Danfoss 2017). This converter is designed only for induction motor drives according to Danfoss (2017, page 11). Danfoss is using vector control as a control method in this product according to Danfoss (2017, page 16). Danfoss is marketing the Vacon 3000 for various applications where the induction motor is needed to drive fans, pumps, conveyors, compressors, and propulsion according to Danfoss (2017, page 3).

3.3 Delta electronics

Delta electronics manufactures three medium voltage drive systems for high power motor drives. The medium voltage drive family, which is called MVD consists of MVD1000, MVD2000 and MVD3000. Delta electronics is using cascaded h-bridge topology in the inverter units in their medium voltage drive products. Delta electronics is using the IGBTs in all the MVD products as switching device and all the MVD products have voltage range from 3.3 to 11 kV. Delta electronics is using vector control as a control method in all products on MVD family (Delta electronics 2014a, 2014b, 2013). Because Delta electronics is using cascaded inverter topology, voltage and the power range of the system depends form the amount of the power cell units used in the inverter.

The main differences with these three different drives are the power they are capable of transferring to the motor, with certain rated voltages and their overload capabilities. The MVD1000 has power range from 160 kW to 12.8 MW and it has an overload capability of 120% for one minute at every 10 minutes (Delta electronics 2014a). The MVD2000 has a power range from 183 kW to 10.2 MW with constant torque and 229 kW to 12.8 MW with variable torque load (Delta electronics 2014b). The MVD3000 has a power range from 315kW to 5.3 MW (Delta electronics 2013). The MVD2000 and the MVD3000 are capable of overloads 150% for one minute at every 10 minutes (Delta electronics 2014b, 2013). The MVD 3000 is the only product in Delta electronics medium voltage drive portfolio which can be configured with an active front end which makes it capable to be used in regenerative applications. All products in the MVD family are using forced air-cooling system according to Delta electronics (2014a, 2014b, 2013).

The MVD products are marketed for various applications to different industries, mainly for pumps, compressors, conveyers and fans. The MVD3000 is also marketed for hoists. According to Delta electronics (2014a, 2014b, 2013) all the MVD products are designed for drive systems which use either synchronous or asynchronous motors.

3.4 General Electric

General Electric has two different medium voltage drive systems which are MV7000 and MV6. The MV7000 has two different versions, a flat pack and a press pack. The MV7000 flat pack version has a power range of 0.7 to 10 MW and output voltage is from 3.3 to 6.6 kV (General Electric 2018a). The press pack version has a power range from 3 to 81 MW and an output voltage capability of 3.3 kV to 13.8 kV (General Electric 2018b). General Electric seems to use either the NPC or the ANPC type inverters in their MV7000 products according to General Electric (2018a, 2018b, page 7) where they present the topology of their converter. The flat pack and the press pack both have connection from the inverter into the dc bus, which suggests that either the NPC or the ANPC topology is used. General Electric (2018a, 2018b, page 14) brochures say that the inverter can create three or five voltage levels for output voltage waveform. This means that General Electric uses the ANPC topology which can be chosen as a three-level ANPC or hybrid five-level ANPC depending on the application and the needs of the customer. General Electric is using a vector control in both of the MV7000 products and they are capable of four quadrant operations, because both can be configured either with a diode or an active front end, which make it possible to use these products in regenerative applications according to General Electric (2018a, 2018b, page 14). The MV7000 press pack is only available with water cooling according to General Electric (2018b) and the flat pack is available with air- or water-cooled versions according to General Electric (2018a, page 5).

The other medium voltage drive systems General Electric has is MV6 which uses a nested neutral-point piloted inverter topology in their converter. The MV6 has an output power range from 0.16 to 3.15 MW with an output voltage range from 2.3 kV to 6.9 kV. The MV6 is capable of creating output voltage waveform from three, five, or nine levels. As a control method General Electric uses vector control. The MV6 is also capable of four quadrant operations, because it can be configured with a diode or an active front end. (General Electric 2014)

General Electric has chosen to use the IGBT as a switching device in all of their medium voltage drive systems. The MV7000 products are designed for drive systems which use synchronous, induction or permanent magnet motors (General Electric 2018a, 2018b). General Electric is marketing their products for multiple different industries. The main applications these drive systems are marketed to are pump, fan and compressors. The MV7000 and the MV6 are also marketed for wind turbines. The MV7000 is also marketed for marine use in different applications in a variety of vessels.

3.5 Siemens

Siemens is one of the major manufactures in the medium voltage drive markets and they have a wide range of different products in their medium voltage drive portfolio. Siemens uses a variety of different inverters in their drives. They have products that use multi-cell inverters, which are Sinamics Perfect Harmony GH180 and GH150 (Siemens 2018a). Siemens also has products that use three level NPC voltage source inverters and they are SM150 and GM150 (Siemens 2018a).

The Sinamics Perfect Harmony family has power range from 0.12 MVA to 47 MVA. The GH180 has a cascaded H-bridge voltage source inverter topology according to Siemens (2018c, page 10). The GH180 has power range of 0.12 MVA to 24.4 MVA. The power range of the GH180 depends on which cooling system is used. The air-cooled drive has a power range up to 10 MW and the water-cooled drive has power range up to 24 MW according to Siemens (2019a) table of technical data overview. The GH180 has an output voltage range of 2.3 kV to 11 kV (Siemens 2019a). The other converter in the Perfect Harmony family is the GH150 and it has a modular multilevel converter topology according to Siemens (2018c, page 10). The GH150 has power range of 4 MVA to 47 MVA and an output voltage range of 4.16 kV to 11 kV (Siemens 2017). According to Siemens (2017, page 2) the GH150 is only available with water cooling. Both products in Perfect Harmony family use low voltage IGBTs as a switching device according to Siemens (2018c, page 10).

Siemens has two versions of Sinamics GM150. One with the IGBT and one with the IGCT as the switching device. These two versions differ in the power and output voltage range. The GM150 with the IGBTs has power range from 1 MVA to 13 MVA. The power of the IGBT version depends on how cooling is arranged. The air cooled version has a power range from 1 to 10.1 MVA and the water cooled has power range from 2 to 13 MVA. The IGCT version has a power range from 10 to 21 MVA (Siemens 2019b). The output voltage of the GM150 is form 2.3 kV to 4.16 kV with IGBTs and 3.3 kV with IGCT (Siemens 2019b). The Sinamics GM150 does not have a capability for regenerative applications, because it is only available with a diode front end configuration (Siemens 2016a).

Siemens Sinamics SM150 has also two versions, one with the IGBT and one with the IGCT. The difference between these two versions is the output power. With the IGBT the SM150 has output power form 3.4 MVA to 7.2 MVA. Power range of the drive with the IGBT depends on the cooling system. With air cooling, the power range is from 4.6 to 5.8 MVA and the power range with water cooling is 5.7 to 7.2 MVA. The IGCT version has only water-cooled version and it has a power range from 10 MVA to 30 MVA according to Siemens (2019c). The output voltages with the IGCT are 3.3 kV and with the IGBT 3.3 KV to 4.16 kV (Siemens 2019c). The SM150 has a capability for four quadrant operations, which means that it can be used in regenerative applications. The SM150 can be configured with an active front end or a diode front end (Siemens 2018a).

All the Siemens Sinamics products discussed above are designed for applications where there is a need to drive induction or synchronous motors. Siemens also uses vector control in every product in Sinamics family discussed above (Siemens 2018b, 2017, 2016a, 2016b). According to Siemens (2018c, page 10) the GH180, the GH150 and the GM150 are marketed for pump and fan applications, the GH180 and the GH150 are also marketed for compressor applications. Siemens (2018c, page 10) also says that the SM150 and the GM150 can be used and are marketed for conveyer and mill applications. The GM150 is also marketed for marine applications according to Siemens (2018c, page 10).

3.6 Summary

The medium voltage drive markets today have many different manufactures and many different products are available for a vast range of different applications. Table 6 summarises whole market review which was conducted as a part of this study. From the Table 6 it can be said that the power range different medium voltage drives are capable is very wide. For example, the ABB ACS2000 has a capability from 2 to 36 MW and the General Electric MV7000 press pack has a power range of 3 to 81 MW. According to this study the inverter topologies most used is the NPC and the ANPC. As a switching device according to this study the IGBT is the most used in the market. The only company that prefers to use the IGCTs in most of their products is ABB. Siemens also offers an option to get their GM150 and SM150 product with the IGCTs. Smaller companies in the medium voltage drive markets use the IGBTs in their products and from Table 6 it can be said that Siemens also prefers to use the IGBTs as a switching device in most of their products.

Table 6 Summary of manufacturers and products from the market review.

Manufacturer	Model	Output power	Output Voltage	Topology	Switching device	Control
ABB	ACS 1000	0.315 - 5 MW	2.3 - 4.16 kV	3L-NPC-VSI	IGCT	DTC
	ACS 2000	0.25 - 3.68 MW	4.16 - 6.9 kV	5L-ANPC-VSI	HV-IGBT	DTC
	ACS 5000	2 - 36 MW	6.0 - 13.8 kV	5L-ANPC-VSI	IGCT	DTC
	ACS 6000	5 - 36 MW	2.3 - 3.3 kV	3L-NPC-VSI	IGCT	DTC
Danfoss	Vacon 3000	2 - 3 MW	3.3 - 4.16 kV	3L-NPC-VSI	HV-IGBT	Vector
Delta electric	MVD 1000	0.16 - 12.8 MW	3.3 - 11 kV	CHB	IGBT	Vector
	MVD 2000	0.183 - 10.2 MW* 0.23 - 12.8 MW**	3.3 - 11 kV	CHB	IGBT	Vector
	MVD 3000	0.315 - 5.3 MW***	3.3 - 11 kV	CHB	IGBT	Vector
General electric	MV7000 flat pack	0.7 - 10 MW	3.3 - 6.6 kV	ANPC	IGBT	Vector
	MV7000 press pack	3 - 81 MW	3.3 - 13.8 kV	ANPC	IGBT	Vector
	MV6	0.16 - 3.15 MW	2.3 - 6.9 kV	NPP	IGBT	Vector
Siemens	GH180	0.12 - 24.4 MVA	2.4 - 11 kV	CHB	LV-IGBT	Vector
	GH150	4 - 47 MVA	4.16 - 11 kV	M2C	LV-IGBT	Vector
	GM150	1 - 13 MVA	2.3 - 4.16	3L-NPC-VSI	HV-IGBT	Vector
		10 - 21 MVA	3.3 kV		IGCT	
	SM150	3.4 - 7.2 MVA	3.3 - 4.16 kV	3L-NPC-VSI	HV-IGBT	Vector
		10 - 30 MVA	3.3 kV		IGCT	

* = Constant torque
** = Variable torque
*** = With rated voltage 6 - 10kV

According to this study, the main applications where medium voltage drives are used and marketed for are applications where the load is either a pump, fan, conveyer or compressor. Most of the manufacturers also have products that are used in the marine industry.

4. THE FUTURE TOPOLOGIES UNDER RESEARCH AND DEVELOPMENT

Medium voltage drive market is constantly developing. A lot of money and effort is used in the research and development of medium voltage drives and new studies are constantly conducted in the field of control schemes, topology structures and switch components. This section looks at one inverter topology called the nested neutral point clamped inverter which has been studied a lot in recent years. This topology seems to be developed to the point that it looks possible that it could someday reach into the electrical drive markets.

4.1 Nested neutral-point clamped inverter

The Nested neutral-point clamped (NNPC) inverter topology is a hybrid topology which combines a flying capacitor and a neutral point clamped inverter topology. Four level NNPC topology is illustrated in Figure 9. In the NNPC the FC topology makes the outer layer of the inverter and the NPC makes the inner part of the inverter in each phase leg as can be seen from Figure 9. From Figure 9 it can be observed that the FC part of the NNPC inverter is composed of four switching devices S_{a1}, S_{a2}, S_{a5} and S_{a6} and from two flying capacitors C_{a1} and C_{a2}. The NPC part of the inverter is composed of four switching devices the S_{a2}, S_{a3}, S_{a4} and S_{a5} and from two clamping diodes, which are connected in the middle of the flying capacitors. The NNPC does not need connection between capacitors in the dc circuit of the converter as the traditional NPC topology. (Wu et al. 2017)

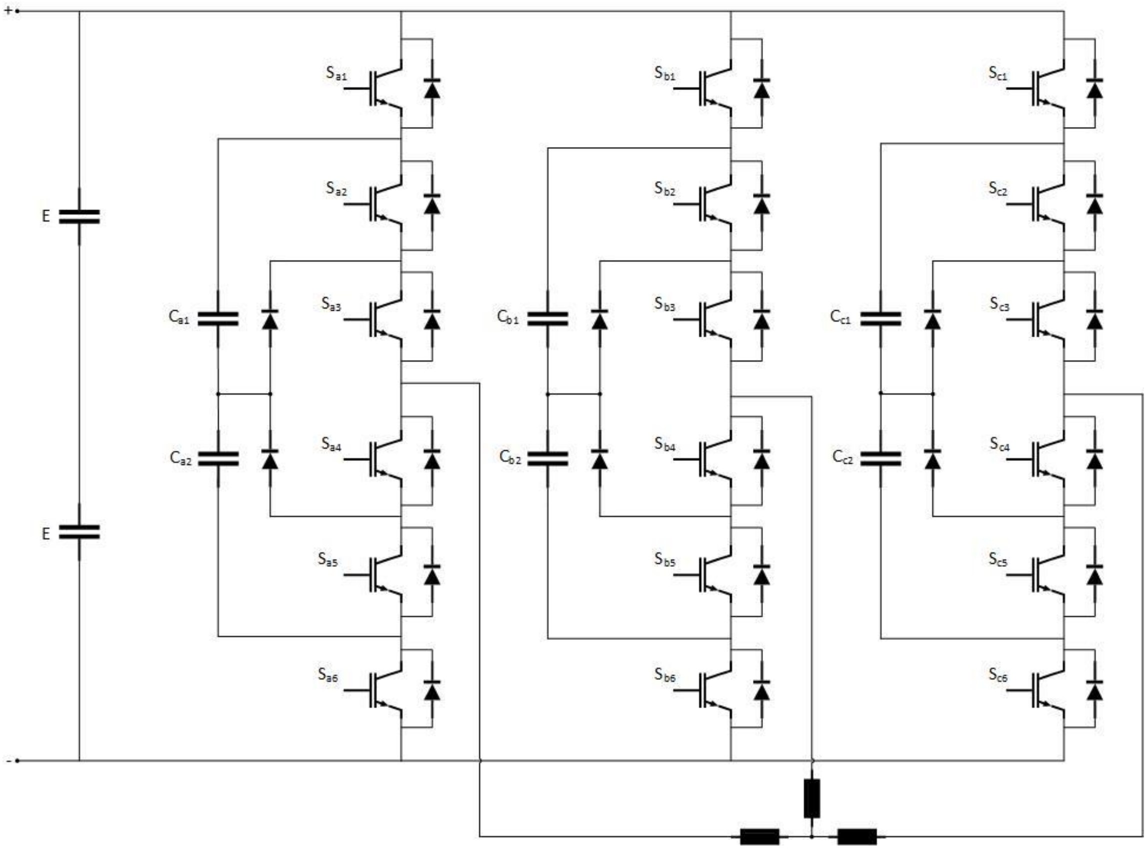

Figure 9 Four level nested neutral point clamped inverter topology

The flying capacitor voltages in the four level NNPC must be kept at 2E/3, where E is half of the voltage between the positive and the negative bar of the inverter. The switching states and output voltages of the four level NNPC are illustrated in Table 7. The control of the switching devices is arranged so that the three switching devices get complementary gate signals. The outer switches S_{a1} and S_{a6} are getting complementary gate signals (Wu et al. 2017). From the inner switches S_{a2} and S_{a4} are complementary to each other also S_{a3} and S_{a5} gets complementary gate signals (Wu et al. 2017). From the Table 7 it can be observed that there are two redundant states to create voltage levels ±E/3. These redundant states make the control of the flying capacitor voltage possible (Wu et al. 2017).

Table 7	Switching states of four level nested neutral pint clamped inverter and corresponding output voltage levels and charge of the flying capacitor. Number 1 represents on state and number 0 represent off state, C represents charging and D discharging.

Output Voltage	Switching device						Charge			
V_{aN}	S_{a1}	S_{a2}	S_{a3}	S_{a4}	S_{a5}	S_{a6}	C_{a1}		C_{a2}	
							i > 0	i < 0	i > 0	i < 0
+E	1	1	1	0	0	0	-	-	-	-
E/3	1	0	1	1	0	0	C	D	-	-
	0	1	1	0	0	1	D	C	D	C
-E/3	1	0	0	1	1	0	C	D	C	D
	0	0	1	1	0	1	-	-	D	C
-E	0	0	0	1	1	1	-	-	-	-

The redundant states make it possible to choose the right switch combination when chancing from one voltage level to another to keep the voltage of the flying capacitor voltage in the preferred value. Table 7 illustrates how the capacitor voltage changes with the different switching states and how the direction of the current flow effects the charge in the flying capacitor. The NNPC switching devices can be controlled with a carrier-based pulse width modulation or space vector modulation, but to keep the flying capacitor voltages on balance these methods must be modified with a voltage balancing control unit. The voltage balancing unit gets a signal which has a reference voltage waveform from the PWM or the SVM and chooses the proper switching state via comparing measured voltages from the capacitors and the dc bus of the inverter and the output currents from the inverter. The unit chooses the best switching state and creates a voltage waveform which is defined by the PWM to keep the flying capacitor voltages balanced.

There are few benefits that the NNPC topology offers. It has more voltage levels than more traditional three level topologies, which leads to lower du/dt and THD. This topology has the structural capability to be used in higher voltage medium voltage drives (Wu et al. 2017). According to Wu (page 2017) voltages up to 7.2 kV are possible without the need to put more switches in series. The voltage stress is evenly distributed between switching devices in the inverter (Wu et al. 2017). The NNPC topology does not require as many components as the NPC which has equivalent amount of levels (Wu et al. 2017).

5. CONCLUSIONS

The use of multilevel inverters in the medium voltage drives answers the challenges that the medium voltage drive systems have. Especially multilevel inverters help to reduce harmonic distortion in the output voltage and the du/dt. The different topologies allow to increase the output voltage and power, which makes it possible to use variable speed drives in many applications. The use of multilevel inverters also makes voltage waveforms fed from the MV drive more sinusoidal, which makes the motors more energy efficient and increases the energy efficiency of the whole drive system.

The medium voltage drive markets have evolved and there are lots of different options for choosing the right kind of converter type for the different solutions. The NPC, the ANPC and the CHB seem to be the most common inverter topologies in the market today. It seems that the FC topology has not found that much popularity in the medium voltage drive market on its own. It seems that the FC is more useful and widely used as a part of hybrid inverters. It can be observed that new topologies are breaking through in the markets. Especially the development of modular multilevel converters and the active neutral point clamped inverter topology have reached the point where those topologies have been able to get into the market.

The market study in this thesis is not comprehensive and does not investigate all the manufacturers in the industry. However, it is possible to see the bigger picture and the trends in the market. The picture which this thesis gives about products in the medium voltage markets is enough to draw conclusions and generalisations about what has and what is happening in the market today.

Because different manufactures do not give all the information about their products in their brochures and websites it is hard to compare different products from different manufacturers with each other, especially the inverter technology they are using. This makes it sometimes hard to say which topology is used in specific product. There is no standardised way of presentig electrical specifications of products between manufactures, which makes it hard to compare different products at a deeper level. Some manufacturers do not tell openly which kind of inverters they are using. This leaves the possibility of doubt because it is hard to say if manufacturer is using the NPC or the ANPC inverter if certain information is not openly available such as voltage levels or a picture of the inverter topology. This also leaves the possibility of error while analysing different products from different manufacturers.

From this bachelor’s thesis there are many different options to make more studies in the future. There is the possibility to study one of the inverter topologies discussed in this study and take a closer look at it and for example make mathematical or computerized model from it and simulate it. There is also the possibility to study and simulate medium voltage drive system driving processes, for example in pumps or fans, and study how the systems effect the process. There is also the possibility to study the different types of components used in the inverters or the modulation methods which are used in the multilevel inverters.

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